Chapter

Particulate Matter and Human Health

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Abstract

This chapter provides an introduction to particulate matter by discussing various ways of categorisation, characterisation and their health effects. The natural and anthropogenic sources of atmospheric particulate matter are discussed. The chapter also introduces qualitatively some aerosol concepts, such as their chemical composition and size distribution. Some examples are provided to illustrate how particulate matter, despite being microscopic particles, can manifest themselves in the atmosphere. Finally, the various pathways by which particulate matter impacts the health system are reviewed along with their interactions to understand concept behind the PM-associated health effects.

Keywords: Aerosol, PM, Health effects, Chemical constituents, Heavy metals

1. Introduction

Air pollution has become a major environmental and health concern worldwide. Even though, the effect of air pollution has been recognised since classical times yet the studies correlating human health and air pollution came into existence in near twentieth century. According to WHO, air pollution refers to contamination/or changes in the natural environment by physical, chemical or biological agent (pollutants), which may be contributed by natural or anthropogenic sources. In reality, some of these pollutants are naturally present but are of least concern because of their lower levels. Once, their level cross prescribed levels they are harmful for humans including other living organisms and natural environment. National Ambient Air Quality Standards (NAAQS), sets limits for six criteria air pollutants viz. carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM) and sulphur dioxide (SO_2).

Particulate matter refers to a complex mixture of solid particles and liquid droplets (EPA). In general, they may vary in size and composition depending upon its location and time of its source e.g., PM emitted from mining activities will have metal contaminants associated with them whereas sea aerosols will mainly contain organic contaminants. Depending on these it might contain nitrates, sulphates, elemental and organic carbon, organic compounds (PAH), biological compounds (endotoxin, cell fragments) and heavy metals (Fe, Ca, Ni, Zn etc.). PM are becoming increasingly ubiquitous but the disease burden related to PM pollution is quite high in low- or middle-income nations as compared to developed countries. According to WHO every nine out of ten people breathe polluted air worldwide. The State of Global Air Report in 2020 reported that more than 90% of the world's population were exposed to $PM_{2.5}$ level that exceeds WHO guideline limits, with

Figure 1.
Dust event at Safdarjung Tomb Delhi, India (Image Courtesy: Shubham).

developing countries more at risk. Also, studies on particulate matter exposure have explained the various health associated problems including heart attacks, asthma, decreased lung capacity, respiratory symptoms such as irritation of airways, difficulty in breathing and premature death (**Figure 1**) [1–4].

The size of PM can be related to their sources, due to the physical processes that form these particles and the atmospheric processes that control the fate and evolution of particle size distributions in the ambient atmosphere. PM_{10} (particles with aerodynamic diameters less than or equal to 10 μm) is generated largely by physical processes, including resuspension of soil and road dust, sea spray, agricultural tilling, vehicular abrasion (i.e. tyre and brake wear), and fugitive dust emission from industrial sources (**Figure 1**). $PM_{2.5}$ (particles with aerodynamic diameters less than or equal to 2.5 μm) comprise predominantly the condensation of secondary inorganic and organic compounds and $PM_{0.1}$ (particles with aerodynamic diameters less than or equal to 0.1 μm) particles comprise predominantly secondary sulphate and bisulphate ion, secondary nitrate ion, secondary ammonium ion, and carbonaceous PM from primary and secondary sources, but also include some crustal materials. The origin of $PM_{0.1}$ is attributed to combustion sources and atmospheric nucleation. They have short atmospheric lifespan as they grow to form accumulation particles. They get enriched in carbonaceous aerosols and metals from combustion of oil and other fuel, also from high temperature processing of metals. However, smaller particles can affect and damage the body organs to the greater extent; although the impact is variable depending upon the concentration and composition of particulate matter. For example, heavy metals like lead, arsenic and cadmium are well known to cause toxicity in the human body, whereas sulphur aerosols which form sulphuric acid are corrosive and can damage the tissues; PAHs are potent carcinogens and can cause cancer (**Table 1**).

1.1 Air quality standards

Air pollution levels in most of the urban areas have been a matter of concern. To improve air quality, WHO is working with different countries to understand the problem related with air pollution. It has revised guidelines for key air pollutants in the ambient environment: particulate matter, nitrogen dioxide, sulphur dioxide,

Category	Size range (μm)	Respiratory system permeability
Smog/Atmospheric dust/Tobacco smoke	0.01–1	Alveolar penetration/ Bronchial penetration
Fly ash/cement dust	1–100	Nostril to Bronchial area
Pollen/Household dust	0.1–100	Nostril to Alveolar area
Bacteria/Bacterial spores	0.7–10	From larynx to bronchial area
Viruses	0.01–1	Alveolar penetration/ Bronchial penetration

Table 1.
Particulate matter (PM); size attribution and penetration to human respiratory system [5–7].

Sl no.	Pollutant	Time weighted average	Ambient air quality standards for the European Union	Guideline values prescribed by WHO (2005)
1	Particulate matter (size less than 10 μm) μg/m^3	Annual Avg	40	20
		24 hours	50	50
2	Particulate matter (size less than 2.5 μm) μg/m^3	Annual Avg	25	10
		24 hours	—	25
3	Sulphur Dioxide(SO2) μg/m^3	24 hours	125	20
4	Oxides of Nitrogen as NO2 μg/m^3	Annual Avg	40	40
		hours	200	200
5	Ozone μg/m^3	8 hours	120	100

Table 2.
Air quality standards.

carbon monoxide and ozone. The concentration limits for these air pollutants along with prescribed European Union Ambient Air Quality Standards are given in **Table 2**.

2. PM: sources and classification

Depending on their origin, aerosols may be natural or anthropogenic. The main sources of anthropogenic particulate matter in the atmosphere lie in urban and industrial areas, e.g., vehicular exhaust emission, wear and tear mechanism on roadways, industrial emissions, construction sites and household emissions. On the other hand, main source of particulate matter in rural areas is dominated by agricultural activities and biomass burning.

Aerosol sources are classified into primary and secondary types on the basis of their origin. Primary particulate matter are those emitted into the atmosphere directly, whereas secondary particulate matter are formed in the atmosphere from pre-existing precursors. Thus it is clear that sea salt, mineral dust and soot particles are primary particulate matter, whereas organic particles formed from the oxidation of volatile organic compound and sulphates from the oxidation of SO_2 or other sulphur containing gases are secondary particulate matter. It is also noted that there is distinct zone, called as "grey zone" between primary and secondary particulate matter formed in case of some low volatile organic compounds that

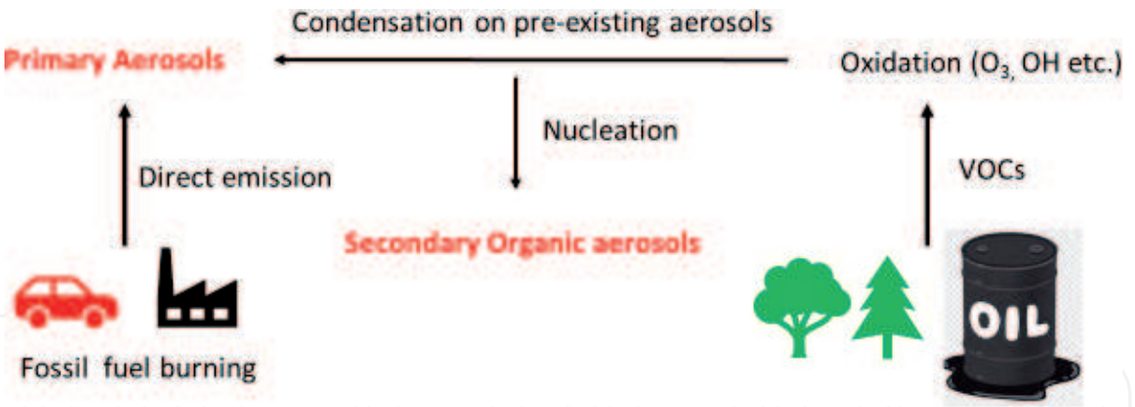

Figure 2.
Sources and formation process of PM.

condense onto particulate matter but not directly within emitting sources, such as some hydrocarbons in vehicular exhaust. In general, secondary particulate matter formation involves chemical transformation from volatile precursors (**Figure 2**) [8].

2.1 Primary natural sources of PM

Significant natural sources of primary particulate matter are dominating in nature due to the mass emissions of sea salt, which is the biggest contributor [7, 8]. Other natural sources of primary particulate matter is soil dust or rock debris generated through physical action, emission of smoke from biomass burning and debris from volcanic eruptions. Primary biogenic PM consists of pollen, spores and plant waxes.

2.2 Secondary natural sources of PM

Major source of natural secondary particulate matter are sulphates and nitrates. They are formed in atmosphere due to gas to particle conversion processes. The major chemical species responsible for this conversion process, involving the natural gaseous compound are nitrogen, sulphur, carbonaceous and organic molecules. Although, various organic substances derived from plants can add larger contribution to the total PM mass. The major generation of particulate matter occurs via condensation of sulphates and nitrogen containing gases. The amount of particulate matter generated by gas to particle conversion process is usually same as PM generated through direct emission of natural particulate matter and greater amount of PM is generated via this process in comparison to direct emission from anthropogenic action [9].

2.3 Primary anthropogenic sources of PM

A significant amount of atmospheric PM is contributed through the anthropogenic activities. It consists of both primary and secondary particulate matter. The primary particulate matter are sourced mainly from the fossil fuel burning, industrial activities, transportation activities and other nonindustrial activities. These particulate matter contains sulphate, nitrate, ammonium, trace elements, carbonaceous matter and water vapour. The carbonaceous portion of this particulate matter consists of elemental carbon and organic carbon and sourced from the combustion process and from condensation process.

2.4 Secondary anthropogenic sources of PM

Secondary anthropogenic PM is formed in the atmosphere by the chemical reactions of gaseous precursors such as sulphur dioxide, nitrogen oxides and ammonia during the transport process. During night, primary oxides of sulphur and nitrogen may get converted to secondary PM in the presence of nitrate radicals. Their origin and growth occur from pre-existing particles, that may grow via matter condensation and thereby leading to new particles formation through homogeneous nucleation. These processes regulate the mass transfer from the gas phase to the particulate phase which is being controlled by sulphur, nitrogen or organic and carbonaceous species.

3. Chemical constituents of PM

3.1 Sulphur containing species

The most sulphate particles in atmosphere are secondary and formed through nucleation and condensation processes due to the oxidation of its gaseous precursor (sulphur dioxide and dimethyl sulphide). Major portion of sulphate particles are contributed by emission from combustion process and found to be in the size range of 0.1 μm to 2 μm. The formation of sulphate are attributed to several mechanisms such as liquid-phase reactions within cloud droplets or oxidation of sulphur dioxide with hydroxide in gaseous phase reactions [10]. SO_2 is emitted to the atmosphere from both anthropogenic and natural sources, although it has been estimated that more than 70% of SO_2 global emissions are released by anthropogenic sources [11], and fossil fuel combustion is responsible for the majority of these emissions. Other SO_2 sources are biomass burning, shipping, metal smelting, agricultural waste burning, pulp and paper processing, and a modest volcanic source [12, 13]. While considering the historic point of view, sulphur dioxide emission from anthropogenic sources have soared from approximately 7.2 fold from 1890 to 2000 [14]. Anthropogenic emission of sulphur dioxide was maximum in early 1970s and decreased until 2000. However, there has been rapid increase in their emissions due to the developmental activities in the underdeveloped countries [12, 15, 16]. Study indicates the growing importance of international transport as a major factor in the increase of sulphur dioxide emissions [13].

3.2 Nitrogen containing species

As in the case of sulphates, nitrogen compounds are mainly of secondary origin and mainly arise from the reaction of natural and anthropogenic gaseous precursors. These aerosols generally have diameters smaller than 2.5 μm [17, 18]. Nitrate ion and ammonium ion are the two main nitrogen containing compounds in particulate matter. The major precursor gases released by natural and anthropogenic activities are NO, NO_2, N_2O and NH_3. Moreover, nitric acid is the main product generated by oxidation in the atmosphere.

The major anthropogenic addition of secondary nitrate precursor gases is mainly due to power generation and other combustion processes producing high temperature, such as those occurring in the vehicular motors and in biomass burning [19]. On the other hand, agricultural activities such as land fertilising are the main source of atmospheric NH_3, although it is emitted by other sources as well, including waste collection, vehicles and a number of production processes [20]. Natural nitrogen compounds come mainly from soil emissions (nitrification, N_2O), wildfires (NO_2, NO), electrical discharges (NO) and biogenic emissions (NH_3).

The production of secondary nitrate is heavily dependent on the amount of gaseous NH_3 and HNO_3 and of particulate SO_4, as well as on temperature and humidity [21]. Homogeneous (gas-phase reaction of NO_2 + OH) and heterogeneous (hydrolysis of N_2O_5 on aerosol surfaces) reactions are involved in the formation of nitric acid during the daytime and night time, respectively. In normal conditions, the gaseous nitric acid dissolved in liquid microparticles reacts with the ammonia in the atmosphere forming particulate ammonium nitrate [22]. Sometimes larger particles of sodium nitrate and calcium carbonate are formed due to high concentration of sodium and calcium ion, sourced from sea salt and mineral dust and due to acidic environment. These particles are larger than the particles of ammonium nitrate [23].

3.3 Carbonaceous particles

Carbonaceous particle are in a significant fraction of atmospheric particulate matter and constitutes a wide range of compounds. It has been estimated that carbonaceous fraction contributes 20–50% of the $PM_{2.5}$ mass fraction in urban and rural areas depending on source and 70% of the PM_1 mass fraction [24, 25]. The carbon fraction of particulate matter could be categorised into three main groups: carbonates, organic carbon and elemental carbon or black carbon.

The carbon found in the form of carbonates (mainly $CaCO_3$ and $MgCO_3$) occurs usually as super micrometric particles resuspended from the ground. This fraction is neglected because of the size and also, there is no straight forward technique for determining it (it is usually identified by acidifying the sample and determining CO_2). Organic carbon constitutes the non-absorptive fraction of the carbonaceous particles that may be of either primary or secondary origin. Sources of organic carbon are not well known, especially those formed by secondary atmospheric processes [26]. Studies related to the organic carbon formation have suggested that a significant fraction is formed by water soluble compounds. This is a crucial finding as it may responsible for the radiative balance of the atmosphere and influence the hydrological cycle [27]. Black carbon is the most refractory and polymerised part of the particulate matter, is generated mainly by fossil-fuel combustion and biomass burning [28]. Black carbon particles have diameter in the range of 10–100 nm and the mass ratio (H/C) of around 0.1 [29]. Black carbon fraction contributes less to overall particulate matter but absorbs incoming and outgoing radiation very actively [30, 31].

3.4 Elemental components

The main elemental components associated with PM are described in accordance of particle sizes measured. For $PM_{2.5}$ and PM_1 there are many components that are

Composition	Particulate matter diameter range (μm)		
	10–2.5	2.5–1.0	< 1.0
Elemental Components	Na, Mg, Al, Si, S, Cl, K, Ca, Fe, Zn, Pb, Cr, V, Ni, Cu,	Na, Mg, Al, Si, S, Cl, K, Ca, Fe, Zn, Pb, Cr, V, Ni, Cu,	Na, Mg, Al, Si, S, Cl, K, Ca, Fe, Zn, Pb, Cr, V, Ni, Cu,
Ionic Components	Cl^-, NO_3^-, SO_4^{--}, Na^+, K^+, Ca^{++}	NO_3^-, SO_4^{--}, NH_4^+, Na^+, K^+, Ca^{++}	Cl^-, NO_3^-, NO_2^- SO_4^{--}, NH_4^+
Origin	Terrestrial and sea salt	Secondary generated particles	Secondary generated particles

Table 3.
Size-resolved elemental composition of particulate matter [32–34].

thought to contain secondary generated particles. There are several elements that are identified by researchers [32–34] based on locations and it is considered that the atmospheric PM elemental compositions are source based, **Table 3** (viz. Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Se, Br, As, Rb, Sr., Y, Nb, Mo, Hg, Pb etc.). Also, it is noted that hydrogen ion is obviously included in PM components.

4. PM associated human health

4.1 Health impacts resulting from PM and its constituents

Growing number of studies in the last few years provided evidence linking disease and adverse effects to extremely low levels of PM and its toxic components. Many components for instance organics such as PAHs, inorganics such as heavy metals are known carcinogens and are responsible for numerous adverse health effects in humans. Apart from this, exposure to PM has been linked to increased hospital admissions, carcinogenicity, developmental disorders, nervous system effects, respiratory symptoms, cardiovascular diseases, decreased lung function and premature mortality [35–40]. Recent finding showed the presence of nanoparticles on the foetal side of the placenta indicating that the placenta barrier can be easily penetrated by the PM resulting in exposure to foetus [41]. This indicates that the extent of toxicity of PM is not only limited to the adults but also to the foetus as well. Moreover, long term exposure to PM pollution renders a population more vulnerable to COVID-19, increased hospitalisations of patients with predisposed asthma or other respiratory ailments were also reported. Hence, the impact and toxicity of PM and its components depend on various factors

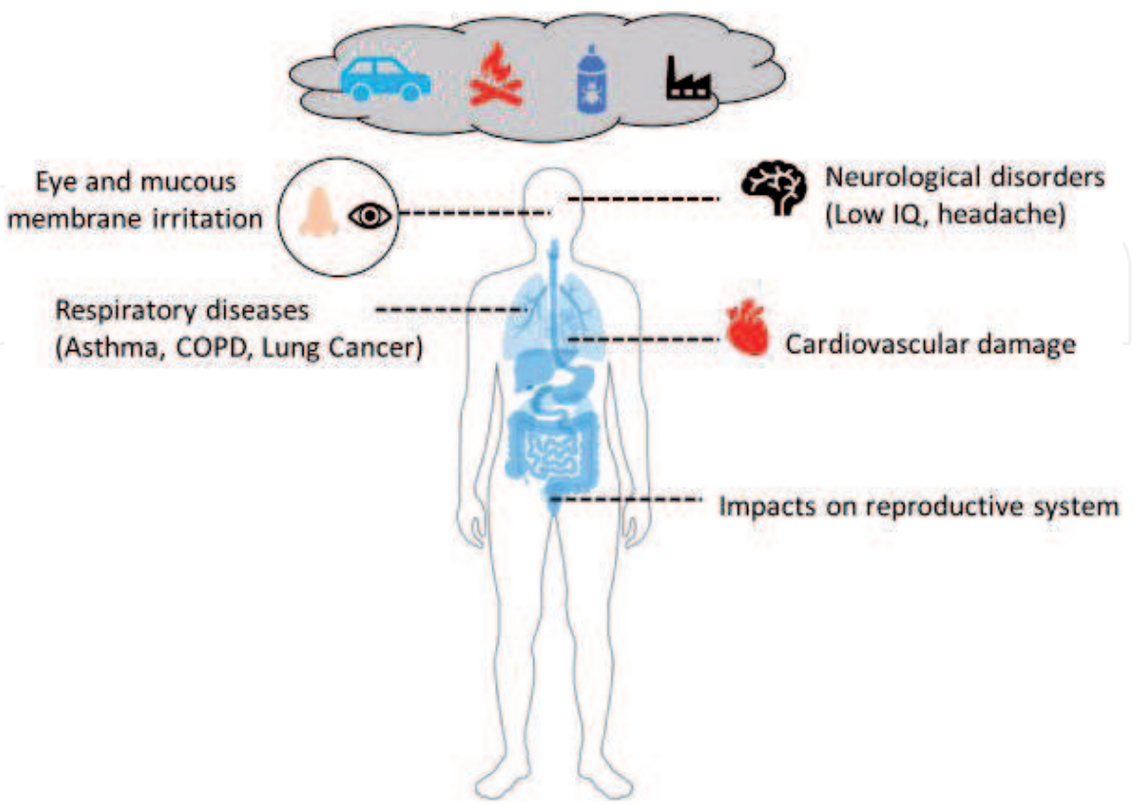

Figure 3.
PM and human health impacts.

Components	Health effects
Heavy metals	Respiratory infections, Neurological effects, Carcinogenicity, Renal disorders
PAH	Decreased immune function, carcinogenic effects, lung function abnormalities

Table 4.
PM component and its health effect.

including their solubility in water, residence time, elemental composition, particle size and chemical reactivity; local environmental conditions- season, wind speed, topography etc.

At present, research studies based on population data do not provide enough evidence to identify differences in the effects of particulate matter with different chemical constituents [37]. However it should be noted that the evidence for hazardous nature of particulate matter generated through the combustion process, from mobile and stationary sources, are more consistent than that from other sources [38]. The black carbon fraction of $PM_{2.5}$ that is resulted from incomplete combustion has great concern towards their contribution to detrimental effects on human health as well as on climate. Other constituents of particulate matter attached to black carbon are seen as responsible for various health effects, such as PAHs that are well known carcinogens and toxic to the cells, also metals and inorganic salts. It has to be noted that diesel engines exhaust, consisting mostly particulate matter, has been classified as carcinogen (Group 1) to humans by the International Agency for Research on Cancer [39]. This also includes some PAHs as well as some solid fuels used in household (**Figure 3** and **Table 4**) [40, 42].

4.2 Respiratory effects

Respiratory system is mainly affected by all types of air pollutants. High levels of sulphur dioxide, nitrogen oxides and ozone are linked to symptoms such as nose and throat irritation, cough, chest discomfort due to narrowing of airways, increased mucous production on the walls of upper airways following which inflammatory reactions may occur leading to asthma and more severe condition COPD [42, 43]. People with respiratory ailments are more sensitive to air pollution exposure.

The human health risks of PM are attributed to their deposition and transportation in the human body. The particles are deposited in the lungs by the process of impaction, interception, sedimentation and diffusion. In general, larger PM fractions (> $PM_{2.5}$) are mostly deposited in the upper respiratory tract by means of impaction. Smaller size PM (< $PM_{2.5}$) can deposit deeper into the lower airways and alveoli depending on the flow rates and diffusion, and may be transported to other tissues and organs via bloodstream. Several studies have also provided the evidence that exposure to smaller particles can result in serious health effects. Although, the impact is variable depending upon the composition (heavy metals, PAHs act as carcinogens), concentration and duration of exposure to the particles. Exposures to PM bound heavy metals (arsenic, nickel, lead etc.) are responsible for asthma, emphysema and even lung cancer [44].

Although in vitro studies on human health due to PM pollution are numerous, there are relatively few that focus on the epidemiological aspects. Studies are scarce regarding investigation focusing on the mechanism of PM toxicity at cellular and molecular levels (**Figure 4**).

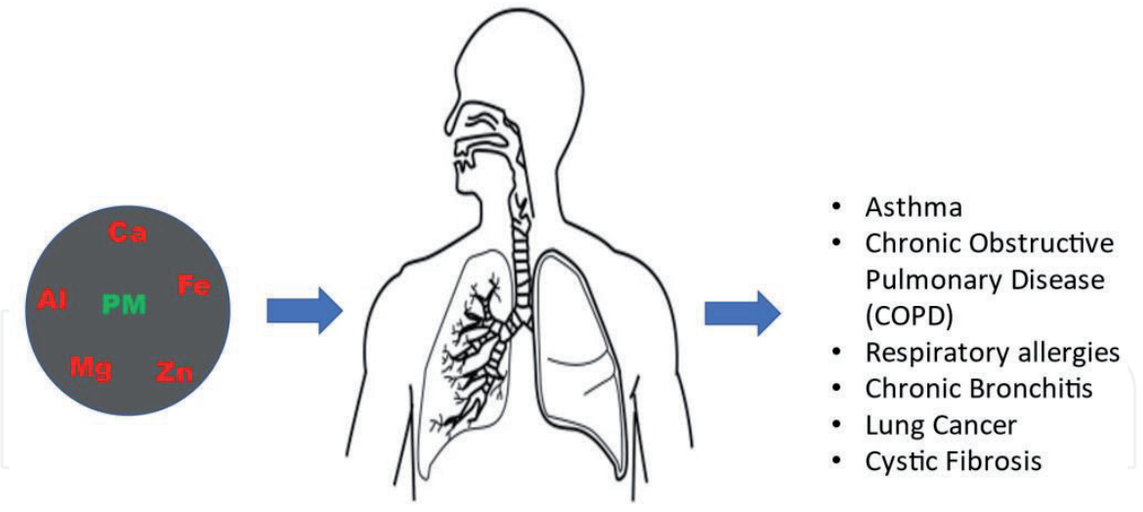

Figure 4.
PM and associated respiratory effects.

4.3 Cardiovascular effects

In recent studies, multiple cardiovascular effects have been documented due to the exposure of air pollutants. According to Global Burden of Disease report, 2018 air pollution was responsible for 19% of cardiovascular deaths in 2015. It was also the cause of about 21% of deaths due to stroke and 24% of deaths from coronary heart disease.

Carbon monoxide has high affinity for haemoglobin and thus it displaces the oxygen and binds with haemoglobin to form carboxyhaemoglobin. It is a stable compound which cannot bind and deliver oxygen to tissues leading to tissue hypoxia (decrease oxygen carrying capacity). Increased risks of ischemic heart disease and myocardial infarction have been demonstrated among occupational groups exposed to gaseous emissions whereas short term exposure studies have reported changes in vasomotor function among healthy individuals as well as increase in prothrombogenic effects. Increased hospital admissions due to myocardial infarctions, increased congestive heart failure among the elderly population as a result of elevated PM concentration were also reported. Long term exposure to traffic emissions have been linked to coronary arteriosclerosis while, short term exposure is related to hypertension, stroke, myocardial infarctions and heart abnormalities [44, 45]. In vitro studies in experimental animals exposed to PM results in systematic inflammation and oxidative stress in the cardiovascular system and may enhance the progression of atherosclerosis in animals predisposed to this disease. In addition to this, chronic exposure to nitrogen oxide may result in ventricle hypertrophy [45].

4.4 Neurological effects

Exposure to heavy metals (e.g., lead, mercury) and dioxins have been corelated with several neurological effects in humans. Lead exposure occurs through inhalation, ingestion and dermal absorption. Conditions such as neurological damage (mimics Ca and disrupts Ca homeostasis), lower IQ and attention impairment of hand-eye co-ordination and encephalopathy has been associated with chronic exposure of lead [40]. It is well recognised teratogen can easily pass through placenta and can cross blood–brain barrier. Therefore, it can cause more harm to the foetus. Mercury (methyl mercury) is another heavy metal that effects the nervous system. Organic mercury is fat soluble and can be distributed in the central nervous system where it is oxidised to Hg^{2+} and causes neurological damage. Symptoms include

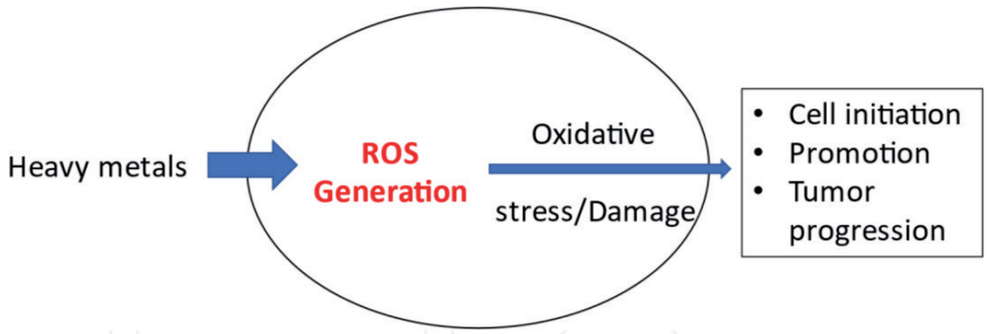

Figure 5.
Mechanism of toxicity of PM bound heavy metals.

memory loss, narrowing of vision, loss of muscle coordination and emotional instability [46].

4.5 Carcinogenicity

Presence of heavy metals, dioxins etc. have detrimental effect as they bioaccumulate and interfere with the normal functioning of the cell [40, 47]. Chemically, metals in their ionic form are more reactive and can interact with biological systems in different ways such as cadmium and mercury can readily attach to sulphur in proteins. Apart from this, they are known to mimic and replace essential metals, for instance cadmium can replace zinc and arsenic mimics phosphate. Furthermore, they are known to induce oxidative stress, producing oxidative modification of biomolecules; which might be a key step in the initiation of cancer cells (**Figure 5**) [47].

5. Conclusions

Particulate matter being the contributor for human health burden poses a major challenge globally. For comprehensive understanding and involved process and their interactions requires continuous investigation. The broad range study associated with atmospheric aerosols requires that integrate approaches be used for their investigation. As the impacts are high in developing countries as compared to developed nations where major cities are under development that poses major pollution burden. However, policies governing the same should be more stringent to control the menace of pollution burden.

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