ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Volume 13, Issue 05, May 2026

Airborne Particulate Matters Impact on Health and Environment

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Abstract— Airborne particulate matter (APM) embodies the most critical environmental and public health challenges worldwide. This study reviews the characteristics, sources, chemical composition, and impacts of particulate matters (PM) like PM10, PM2.5, and PM0.1 with a explicit focus on associated heavy metals (HMs). PM are generated from both natural sources like volcanic activity, dust, vehicular emissions, fossil fuel combustion, industrial processes, and agricultural practices. Heavy metals like lead, cadmium, mercury, arsenic, chromium and nickel are frequently adsorbed fine particles, enhancing their atmospheric transport and bioavailability. Due to very small size and high reactive surface area, the ultrafine particles can penetrate deep into respiratory system, enter systemic circulation, and induce oxidative stress. Prolonged acquaintance is strongly linked with respiratory diseases, cardiovascular disorders, neurological impairments etc. The populations with pre-existing health conditions, including children, elderly, and individuals face elevated risks. Beyond human health, this study significantly highlights the atmospheric deposition of PM-bound heavy metals affects on the terrestrial and aquatic ecosystems through bioaccumulation, soil acidification, eutrophication, and disruption of nutrient cycles. A multidisciplinary research approach is essential to better understand long-term exposure risks, bioaccumulation pathways, and integrated environmental-health impacts.

Keywords— Airborne Particulate Matter, Environmental Toxicology, Health Hazards, Heavy Metals.

I. INTRODUCTION

Over the decades, a dramatic increase in the levels of particulate matter in the air has been observed. Vehicle emissions, manufacturing processes, raw material use, domestic combustion appliances, and wildfires are the main causes of particulate matter in the air [1]. PM, ozone, nitrogen dioxide, sulphur dioxide, heavy metals, black carbon, and persistent organic pollutants are among the most common air contaminants. Asthma, heart disease, and stroke are some of the health problems that these pollutants exacerbate. An estimated 0.24 million people in the EU lost their lives each year to air pollution; 0.07 million die due to ozone and 0.048 million from nitrogen dioxide (NO2). PM is a major health hazard because it contains inhalable tiny particles or liquid droplets that may cause serious problems. It has been shown in certain research that smaller particles like PM10 have the potential to penetrate the lungs and potentially reach the circulation. Very small size particles, PM2.5 may float in the air for long periods of time and travel great distances from its point of emission, endangering large areas. Other particles like nitrates, sulphates, organic and elemental carbon etc. found in different concentrations depending in the environment [2]. To reduce pollution, it is essential to characterize and analyse the chemical composition of particulate matter. Soil, water, and higher plant surfaces attracts the particulate matters, which can have long-term negative effects on ecosystems and biodiversity.

Heavy metals (HMs) in metropolitan areas may come from a variety of places, including car repair businesses, combustion processes, and worn tires. These may travel across the biosphere via long-distance transboundary air pollution and end up in many ecosystems. Their ability to survive in ecosystems raises the possibility of bioaccumulation at many stages of the food web [3]. There is a decrease in particulate matter (PM) concentration in wooded regions, which is evidence that plants clean the air by absorbing HMs and particulate matter (PM) indirectly [4]. As a result, plants may help filter the air and retain particulate matter and heavy metals by virtue of their leaf characteristics [5]. Heavy metals accumulate in marine organisms due to their atmospheric precipitation into aquatic environments. Nine harmful particles were detected in marine organisms between 2010 and 2021, above the limits set to protect human health [6]. Mercury pollution affects over half of the world's surface rivers. Lead and cadmium concentrations in agricultural soils are 47% and 31% higher than the limits, respectively, due to atmospheric deposition of metals. Also, HMs are elements that are already part of the Earth's crust. Anthropogenic activities involving metals and their compounds are the main cause of environmental and human contamination [7]. Metal oxidation, air deposition, soil erosion, leaching, and evaporation from soil and groundwater resources are other potential causes of environmental pollution [8].

Not all metals are necessary for plant life like aluminium, cadmium, etc., do not have any known biological functions [9]. As a metalloid that shows toxicity even at low exposure levels, arsenic is one of many heavy metals (HMs) whose weight and toxicity are supposedly connected [10]. Researching the bioavailability of heavy metals at values below 10 ppm across different environmental compartments

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is crucial since these substances are categorized as nutrients or trace elements. Temperature, sequestration, and adsorption processes are physical parameters; lipophilicity, kinetics, and complexation are chemical features; and biological elements pertaining to species characteristics are biological variables that impact their bioavailability [7]. Enzymes that participate in redox reactions include HMs, which are essential for many metabolic activities in animals and plants. The mechanisms by which heavy metals cause toxicity and carcinogenicity are also poorly understood. For reasons related to public health, it is important to note that different metals have different toxicological characteristics and physicochemical properties. These metals are hazardous and carcinogenic because they produce reactive oxygen species and cause oxidative stress [11]. When heavy metals bind to proteins in the nucleus, they cause damage and changes in protein structure, which may lead to cancer or cell death.

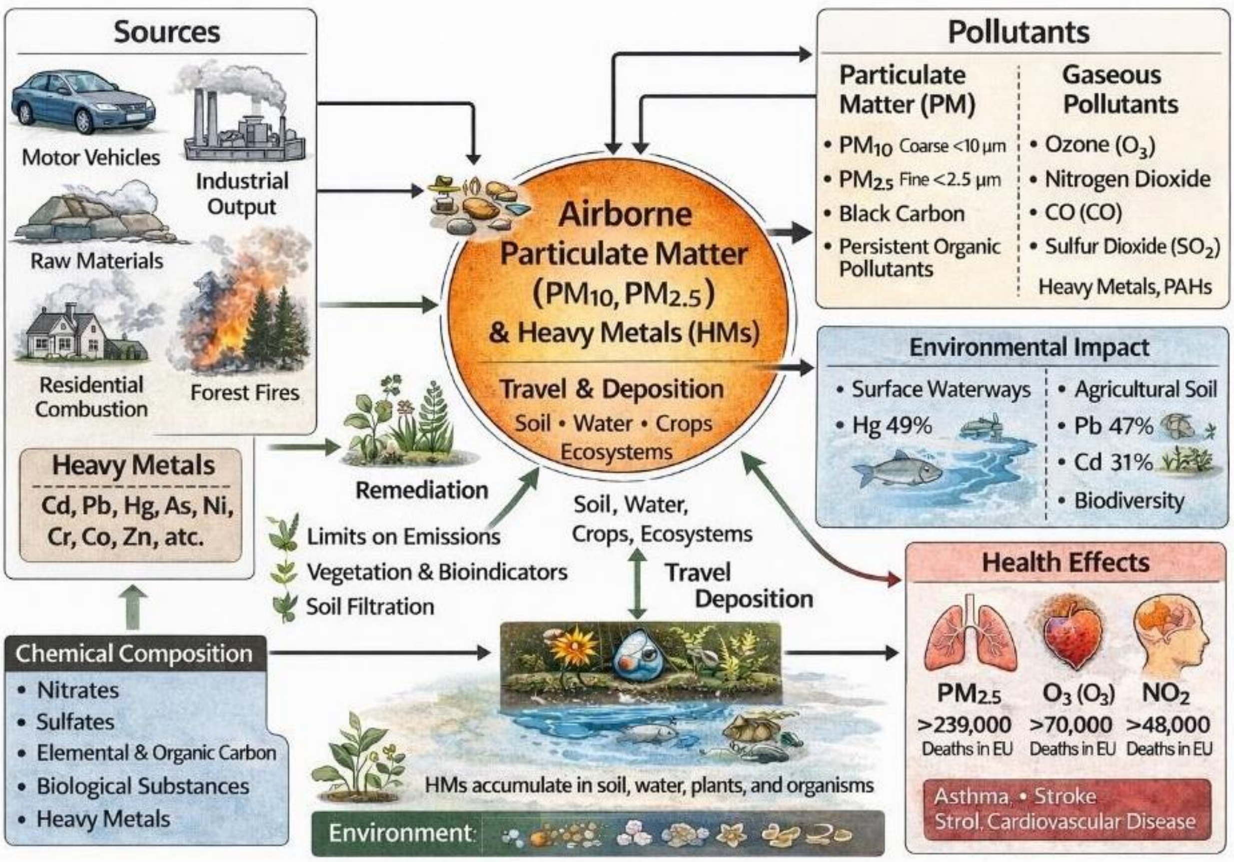

Figure 1. Schematic block diagram representing airborne particulate matter and associated heavy metals

Heavy metals may build up in the environment via atmospheric deposition, which can then contaminate groundwater, crops, and people's bodies through the food chain. Figure 1 represents airborne particulate matters and associated heavy metals. Plants and animals alike rely on copper, an essential mineral for enzymes involved in oxidative stress. Therefore, it is a metalloenzyme, which means it is involved in making haemoglobin, metabolizing glucose, making catecholamines, and cross-linking proteins like elastin, collagen, and hair keratin. There are two possible oxidation states for it, and it takes part in redox reactions [12]. The current state of knowledge on the global distribution of heavy metals in PM2.5 is to be filled in by this study, which also seeks to pinpoint their sources, monitoring techniques, potential health effects, and areas where more research is needed. This study discusses the types of the airborne particulate matters and sources of the particulate matters. Further, the impact of the particulate matters on the health and environment is represented.

II. PRIMARY TYPES OF AIRBORNE PARTICULATE MATTERS

There is a wide range in the size, shape, and chemical properties of the solids and liquids that make up particulate matter (PM). Based on their size, the particles are categorized as follows: coarse particles (PM10), tiny particles (PM2.5) and ultrafine particles (PM0.1) [13]. Nanotoxicology provides a prism through which to view the latter, which may originate in nature, combustion processes, cosmetics, medicines, and catalysts. Combustion, dust, and soot are examples of major sources of particulate matter, whereas emissions of sulphur dioxide, nitrogen oxides and ammonia are examples of secondary sources. Black carbon, salt aerosols, and mineral dust are examples of primary PM,

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 13, Issue 05, May 2026

which is more stable than secondary PM. However, due to its hygroscopic nature and tendency to mix with other atmospheric components, it may cause aging processes to occur while traveling. As more pollutants are introduced during transportation, the risks to human health are magnified. Secondary pollutants may be produced when particulate matter interacts with various atmospheric components [2]. By oxidizing NOX, secondary particulate matter may produce HNO3 as aerosols and nitrate particles. To a lesser extent than NOx, SO2 is converted to sulphate in particulate form, leading to the production of sulphate particles. In addition, oxidants such OH, NO3, and O3 may react with volatile organic compounds (VOCs) and secondary organic aerosols (SOAs) [14]. Figure 2 represents the primary and secondary sources of the particulate matters.

III. AIRBORNE PARTICULATE MATTERS SOURCES OF EMISSIONS

The emission of PM in atmosphere arises from natural sources as well as gasses produced by different chemical processes. A primary cause of these emissions is human activity. The particles emitted unswervingly from sources are classified as primary particles, whilst those derived from gas emissions are categorized as secondary particles. Significant natural and anthropogenic sources of PM emissions include aerosols, vehicular traffic, forest fires, fossil fuel combustion, coal cooking, gas grilling, cigarette smoking, pollutants from domestic, industrial, and agricultural activities. Vehicular emissions contribute to the augmentation of particulate matter in the atmosphere [15]. Light duty gasoline vehicles contribute to the emission of particulate matter which typically consists of carbonaceous elements with a minimal presence of water-soluble ions [16]. Motor vehicles contribute to PM emissions, mostly due to the frictional contact among components of the braking system. PM10 emissions into the atmosphere result from tire wear. Additionally, road wear and road dust contribute to PM emissions [17].

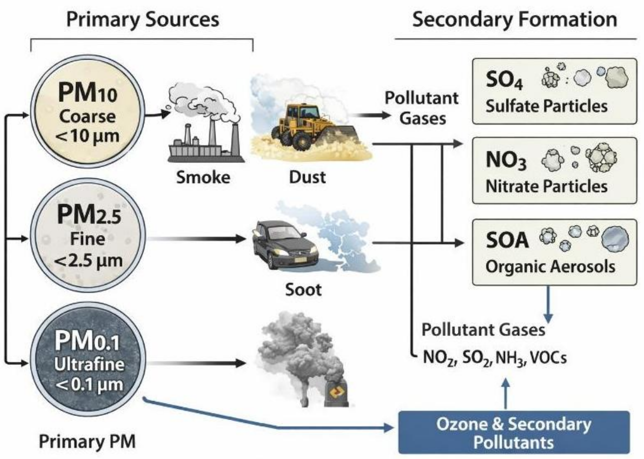

Figure 2. Primary sources of Airborne Particulate matters

Sea salt contributes to the emission of sodium, chlorine, and magnesium; secondary aerosols are sources of NO3, SO4, and NH4+ emissions; and the burning of mixed fuel or industrial oil results in the emission of SO4 and nickel [18]. Automobile catalytic converters are responsible for the emission of palladium, rhodium, and platinum as a result of their function as catalysts in these devices [19]. In Hong Kong, mobile vehicles and super regional transit are regarded as the primary sources of PM emissions [20]. Ammonia released from fertilizers or animal manure serves as a restraining factor in the transformation of acidic components into their corresponding salts. Gaseous sulphur emitted from volcanic activity or rotting plants may subsequently generate secondary sulphate particles in the atmosphere. Other sources like windblown dust and road dust, constitute seventy percent of PM2.5 emissions. Furthermore, the industrial processing of metals, the combustion of coal for power generation and industrial fuel may also be a contributing factor [21].

IV. IMPACT OF AIRBORNE PARTICULATE MATTERS ON HEALTH

Air Quality Guidelines have been released on a quarterly basis by the World Health Organization (WHO) since the mid-1980s. The health risks posed to workers by exposure to aerosols and fine particulate matter vary with the concentration and composition, which are affected by factors such as geographical location, weather, and emission sources [22]. Millions of people die each year because of exposure to fine particulate matter, which has negative effects on human health and is a major environmental cause of premature mortality. Over 1.6 billion people who work outside are at increased risk due to workplace air pollution, which is expected to be a major occupational exposure [23]. Also, chronic exposure to indoor particulate matter and other pollutants increased risk of dementia [24]. A person's occupation has a significant impact on their health. Air pollution is a major problem for outdoor workers, since it is responsible for the untimely deaths of almost 0.86 million people every year around the globe. Emission control and reduction measures must be put into place since air quality affects health and quality of life [25]. There was still a lot of work to do to protect forestry and agricultural workers, notwithstanding legal advances [26]. As a result, regulatory and preventative measures are being strengthened.

4.1. Impact of Heavy Metals on Health

One out of every eight deaths on Earth is attributed to air pollution [27]. Since many cities have low PM levels, the concentration of PM in urban areas varies with population density, activity, and geography. Particulate matter levels, especially those of heavy metals, may vary in both amount and composition depending on one's location. Those with preexisting respiratory or cardiovascular diseases are more vulnerable to the negative health effects. In humans in particular, heavy metals may cause toxic accumulation by producing compounds that are difficult to breakdown [28]. Organometallic compounds are synthesized when stable oxidation states interact with biomolecules in the body. This accumulation occurs because of this interaction. While certain metals are required for plant and animal metabolism, their redox potential disrupts homeostasis and transport by potentially damaging cells when they bind to proteins instead of the intended target [29]. While certain heavy metals are considered essential (copper, nickel, iron, zinc) and others are considered non-essential (cadmium, mercury, lead) [30], toxicity may occur at quantities above acceptable limits for any of these elements [31].

Figure 3 represents the effects of particulate matters of the human health.

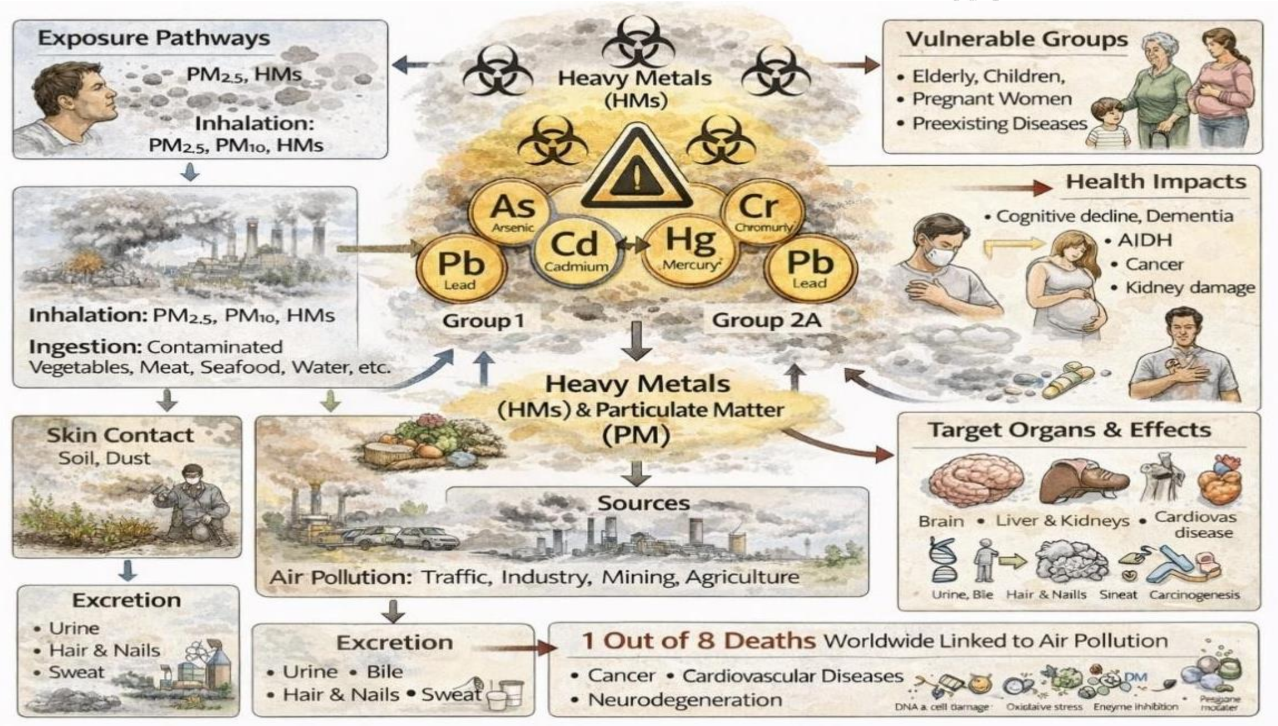

Figure 3. Impact of heavy metals

The neurological system, circulatory system, kidneys, and liver are the most harmfully impacted by heavy metals [32]. The neurological and gastrointestinal tract are vulnerable to the effects of mercury, arsenic, and lead pollution, which may enter the body via skin, lungs, or digestive tract. In addition to interfering with DNA and proteins, heavy metals affect and block metabolic processes and enzyme activity, which may lead to cancer or cell death. Urine and bile are the primary excretion routes for heavy metals. Hair, nails, milk production, and sweating are some of the other organs that help remove them, but to a lesser extent.

Attention deficit hyperactivity disorder in children is a consequence of lead's neurotoxic effects. Lead poisoning is a major issue in public health, particularly for children, since lead mostly shows up in the brain [33]. Cadmium is known to cause cancer and is harmful to several organs, such as the pancreas, kidneys, bones, prostate, and lungs [32]. In addition, cadmium has been associated to heart issues, especially in smokers. Vegetables, nuts, meat, organs, and oilseeds are potential entry points for it into humans. Acute exposure causes accumulation in the liver, which in turn causes necrosis and apoptosis [33]. Several human disorders like oxidative stress, DNA damage etc. have been linked to cadmium. Furthermore, chromium causes hyperkeratosis, ulcers, neoplasms, and mental and respiratory problems. Adducts, chromosomal anomalies, and DNA transcription are all outcomes of induced DNA damages.

Another particulate matter, mercury, irritates the gastrointestinal tract, causes psychological problems, and impairs children's brain development. Eating too many fish, whether they're marine or freshwater, may expose humans to methylmercury, which can affect brain function. Most of the mercury is breathed, with just around 15% being absorbed, according to the literature.

Tungsten is a carcinogenic material that causes gastrointestinal problems, allergies, and effects on the respiratory system when workers inhale it. Skin allergies, lung fibrosis, and heart problems are all brought on by nickel. Anaemia, irritability, diarrhoea, nausea, vomiting, and stomach pain are among symptoms that zinc may bring on [27]. Lead damages bone tissue and impacts child growth. Depending on the location and kind of HM deposition, poisoning may cause brain related issues like brain damage, cognitive impairment, memory loss and even dementia. Observations have shown that Alzheimer's patients have plasma levels of mercury, cadmium, and manganese that are higher [34]. While manganese acts as a neuroprotector at low concentrations, it causes apoptotic cell death and Alzheimer's disease at high concentrations. Despite being essential elements created in minute amounts during synaptic firing, copper and zinc may impact neurodevelopment and add to diseases like Wilson's disease and schizophrenia.

4.2. Combined impact of Heavy Metals and Particulate Matter

Involvement of HM in oxidative processes that cause oxidative stress occurs when they are bound to particulate matter. When organic compounds like quinones and metals (like iron and copper) undergo Fenton-type reactions, which produce reactive species [35]. Particulate matter may cause a host of health problems when it enters the respiratory system via the airways and the digestive tract when swallowed. They may be partially expelled by mucociliary processes after inhalation into the trachea and bronchi. Acute respiratory tract infections, chronic obstructive pulmonary disease, and cardiovascular disease are among the respiratory illnesses that may lead to mortality when exposed to particulate matter [36]. The average concentration of fine particles, PM2.5 is set at 5 mg/m3 by the WHO's air quality guideline, whereas the maximum exposure limit for more than three to four days in a year is 15 µg/m3.

Ambient and interior sources of PM2.5 exposure may be attributed to the combustion of solid fuels in cooking. The half of world's population is affected by the solid fuels of cooking, with a particularly high incidence in Africa and Asia [28]. Even in parts of the US, Canada, and Europe where pollution levels are below 4 µg/m3, people's health has been negatively impacted by long-term exposure to PM2.5, unlike other air pollutants. There has been a global trend toward lower or stabilizing PM2.5 values in some areas. The impact on human well-being is also sensitive to the size of the particles. Soil and biological components are thought to be the source of heavy metals in PM10. Heavy metals and polycyclic hydrocarbons may be detected in high quantities in PM2.5, and the large reactive surface area of PM0.1 nanoparticles allows them to cross biological barriers, affecting internal organs. Studies on PM2.5 monitoring have shown negative outcomes, including metabolic disruptions, cell death and the worsening of cellular lesions. Prolonged exposure's effects are still unknown, despite the plethora of studies evaluating health status in connection to PM2.5 [9].

Particulate matter and heavy metals enter people mostly via the respiratory system, although they may also enter from skin and food. Dermatitis develops when the skin responds to pollutants. Inflammation and immune system dysfunction may result from a compromised epidermal barrier. Antioxidants and vitamin C may lessen its impact [37]. While in the atmosphere, PM2.5's chemical composition could change. Also, it might be in the same aerosol as ultrafine PM0.1, which has been linked to direct damage to the lungs and brain in studies. Chemicals soluble in water, organic and mineral carbon, and heavy metals make up PM0.1 aerosols. Additionally, dry eyes, conjunctivitis, and allergies are all symptoms of ocular surface dysfunction that have been linked to particulate matter exposure in preclinical studies [38].

V. IMPACT OF AIRBORNE PARTICULATE MATTERS ON ENVIRONMENTS

Many ecosystems, plants and animals have difficulties due to particulate matter. The chemical makeup of the particulate matter has little bearing on the effect it has on vegetal surfaces; size alone determines this. Their size distribution may therefore reveal the loading of these components. Dust and other particulate particles may abrade and overheat plants, which hinders their ability to photosynthesize [7]. The dust that settles on leaves reduces the amount of light that reaches their surfaces, which slows down the process of photosynthesis. Acidic and alkaline compounds may damage leaf surfaces, and plants can absorb some particle debris via their cuticles. Plants absorb materials in the rhizosphere, which has far-reaching ecological consequences. Contaminating the rhizosphere with these contaminants has a negative effect on important nutrient cycles, especially on the nitrogen cycle, which is facilitated by the bacteria and fungi that live around plant roots.

Deposition of varied particulate matter is one way in which the presence of cations like aluminium and certain alkaline cations, affects the environment. Because various forms of particulate matter reduce the amount of radiation plants need to grow, which in turn reduces precipitation, PM impacts ecosystems in terms of climate change. When PM accumulates in one area, it has a negative effect on the air quality in the surrounding areas [8]. Miniature particles further complicate matters since they are difficult to see. There were several haze episodes in China caused by PM2.5 particles, and the resulting fog had very high PM2.5 concentrations. At some concentrations, nitrogen dioxide has the potential to absorb light, which might cause vision problems. Furthermore, these problems are caused by large quantities of ozone, carbon dioxide, and water vapor. Human-emitted volatile organic compounds react with nitrogen dioxide to produce photochemical haze, which has a negative effect on ecosystem aesthetics and poses problems for living things. The acidity of water bodies is accelerated by nitrogen oxides. Some aquatic animals cannot survive in environments with a lower pH, therefore a decrease in pH is bad for them.

In addition to hastening eutrophication, it causes an explosion of algae, which blocks out light from the sky and reduces oxygen levels in the water, killing out aquatic life [39]. The interplay between particulate matter and sulphur dioxide also affects plant growth. In addition, animals suffer injuries when harmful compounds like fluorine or arsenic contaminate plants that they eat. Because of the presence of important building components, leaves are crucial to several physiological processes; nonetheless, leaves can have negative effects on plants. After its deposition on leaves, sulphur dioxide is absorbed and converted into sulphate, a less toxic form. Damage to the structure, seen as discoloured or brittle leaf surfaces, occurs when their ability to convert sulphur dioxide to sulphate is impaired due to an increase in concentration. Because of being exposed to selenium, plant surfaces acquire dark, patchy regions; clouds are formed in response to atmospheric trace chemicals. Global warming is caused by the greenhouse effect, which is exacerbated by an overabundance of atmospheric particulate matter, especially carbon dioxide and water vapor. Some areas may experience floods because of hot weather, while others may experience drought. The shrinking of ice sheets threatens fish populations and the human activities that depend on permafrost, which might have a negative impact on northern ecosystems that are already under management.

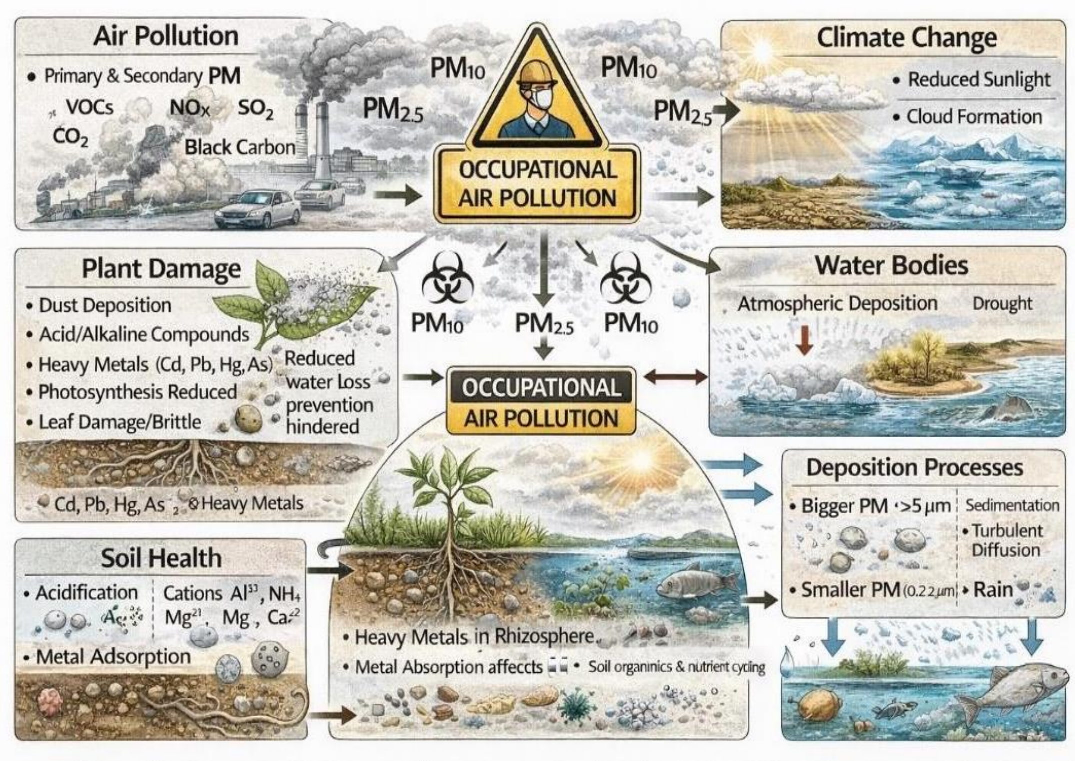

Figure 4. Impact of Airborne Particulate matters on Environment

Particulate matter containing heavy metals (copper, iron, aluminium, cobalt, lead, manganese, and zinc) may be absorbed by aquatic environments regardless of their source. The combustion of fossil fuels, emissions from vehicles, and metallurgical operations all contribute to the formation of these four elements. Initially present in water as insoluble forms, heavy metals may undergo metal-organic complexation reactions that transform them into soluble or colloidal forms [40]. Coarse particle matter often contains less soluble metals than tiny particulate matter. Factors affecting metal solubility include composition and source, atmospheric deposition mechanism, particle aging during long-distance flight, and particle dissolution tendency. Since heavy metals in PM2.5 are soluble in water, it's possible that the low pH of precipitation aids in their degradation before they reach the ocean surface. Both wet and dry processes may lead to the atmospheric deposition of particulate particles. The process of particulate matter being naturally absorbed by water in the atmosphere and then deposited on land and water surfaces is known as wet deposition. The solubilities of the PM constituents vary according to the size of the PM. For particles larger than 5 μm in size, the slow process of dry deposition includes turbulent diffusion or Brownian motion in addition to gravity sedimentation. Both approaches show decreased effectiveness for small particles with a size between 0.2 and 2 μm [34].

Agricultural practices, emerging pollutants, and climate change have all contributed to a multitude of pollution phenomena that affect soil. The specifics of the site and the kind of pollution will determine the extent of the cleaning. Human activities at the ground and water levels, as well as the atmospheric deposition of various pollutants, are the sources of heavy metals (HMs). Various land uses result in varying degrees of soil pollution. There is a relationship between the kind of soil and the plants grown there, as well as between the city of study and the organs tested there. Pollution from a variety of sources, including vehicles, poor air quality, and inadequate urban planning may expose people to heavy metals in cities [41]. Soil contains heavy metals that have important physiological functions like copper, iron, nickel and zinc. Dangerous outcomes may occur at higher concentrations. Despite a reduction in translocation at greater soil concentrations, the concentrations of lead and zinc in wild blackberry roots and leaves increased with rising soil levels [42].

These patterns provide more precise information about where pollution is coming from. Heavy metals in ecosystems are ingested by organisms via many pathways, including the digestive system through food, skin through touch and the respiratory system through inhalation [43]. Zinc and other heavy metals have an indirect effect on soil enzymatic or microbial activity by lowering pH or organic matter content; this is also true for lead, cadmium, and mercury. The presence of nickel and tungsten might have additional implications since it could hinder the nitrogen cycle activity of soil microorganisms [27].

VI. CONCLUSIONS

According to the Earth Organization, air pollution is the most crucial environmental concerns, closely linked to the most pressing threat of all: global warming. The characteristics of atmospheric particulate matter that absorbs heavy metals, particles assessments, sources, effects transported from air to water and land are all included in this research. Dust and heavy metal compositions in the air are directly impacted by the kind of industry, the means of transportation, and daily activities. Heavy metals in particulate matter assessments are sensitive to several factors, include industrial processes, vehicle emissions, weather, and the proximity of sample locations to pollution sources. Improvements in result quality, reductions in analytical instrument maintenance demands, promotion of environmentally friendly procedures, and protection of staff health and safety are the current trends in heavy metal sample preparation.

Explanation of their transmission from natural and anthropogenic sources, investigation of adsorption mechanisms, and investigation of new materials for efficient removal should be the foci of future research on heavy metals adsorbed onto particulate matter. Future studies should enrol a larger number of participants to better understand the risks to people's health. The air pollutant that poses the greatest threat to human health is particulate matter. Various analytical detection and monitoring methods exist, but there is still a noticeable lack of understanding of health impacts, policies, and laws. Therefore, new approaches are needed to find effective solutions that match with scientific progress and other environmental problems. The linked health problems will prompt further epidemiological studies to investigate the link between heavy metal exposure and respiratory, cardiovascular, and neurological diseases. To further understand the mechanisms of bioaccumulation and to find long-term infrastructure solutions for storing heavy metals and, therefore, PM, studies into the risks of bioaccumulation in soil, water, and food chains are essential. There is growing worried about ultrafine particulate matter and non-exhaust sources, as shown by recent trends in particulate matter and heavy metal air pollution. Simultaneously, there has been progress in monitoring, stricter restrictions, and ecofriendly alternatives such urban infrastructure built on plants that are rising to the top of the heap to lessen their impact on people's health and the planet.

REFERENCES

[1] E. G. Pacyna *et al.*, "Current and future emissions of selected heavy metals to the atmosphere from anthropogenic sources in Europe," *Atmospheric Environment,* vol. 41, no. 38, pp. 8557-8566, 2007/12/01/ 2007, doi: https://doi.org/10.1016/j.atmosenv.2007.07.040.

[2] F. Bilo, P. Cirelli, and L. Borgese, "Elemental analysis of particulate matter by X-ray fluorescence methods: A green approach to air quality monitoring," *TrAC Trends in Analytical Chemistry,* vol. 170, p. 117427, 2024/01/01/ 2024, doi: https://doi.org/10.1016/j.trac.2023.117427.

[3] A. Nadgórska-Socha, M. Kandziora-Ciupa, M. Trzęsicki, and G. Barczyk, "Air pollution tolerance index and heavy metal bioaccumulation in selected plant species from urban biotopes," (in eng), *Chemosphere,* vol. 183, pp. 471-482, Sep 2017, doi: 10.1016/j.chemosphere.2017.05.128.

[4] J. Shi, G. Zhang, H. An, W. Yin, and X. Xia, "Quantifying the particulate matter accumulation on leaf surfaces of urban plants in Beijing, China," *Atmospheric Pollution Research,* vol. 8, no. 5, pp. 836-842, 2017/09/01/ 2017, doi: https://doi.org/10.1016/j.apr.2017.01.011.

[5] S. Yin, Z. Shen, P. Zhou, X. Zou, S. Che, and W. Wang, "Quantifying air pollution attenuation within urban parks: an experimental approach in Shanghai, China," (in eng), *Environ Pollut,* vol. 159, no. 8-9, pp. 2155-63, Aug-Sep 2011, doi: 10.1016/j.envpol.2011.03.009.

[6] W. de Vries, J. Kros, J. C. Voogd, and G. H. Ros, "Integrated assessment of agricultural practices on large scale losses of ammonia, greenhouse gases, nutrients and heavy metals to air and water," *Science of The Total Environment,* vol. 857, p. 159220, 2023/01/20/ 2023, doi: https://doi.org/10.1016/j.scitotenv.2022.159220.

[7] P. B. Tchounwou, C. G. Yedjou, A. K. Patlolla, and D. J. Sutton, "Heavy metal toxicity and the environment," (in eng), *Exp Suppl,* vol. 101, pp. 133-64, 2012, doi: 10.1007/978-37643-8340-4_6.

[8] Z. L. He, X. E. Yang, and P. J. Stoffella, "Trace elements in agroecosystems and impacts on the environment," (in eng), *J Trace Elem Med Biol*, vol. 19, no. 2-3, pp. 125-40, 2005, doi: 10.1016/j.jtemb.2005.02.010.

[9] S. Wang and X. Shi, "Molecular mechanisms of metal toxicity and carcinogenesis," (in eng), *Mol Cell Biochem,* vol. 222, no. 1-2, pp. 3-9, Jun 2001.

[10] D. Baldantoni, F. De Nicola, and A. Alfani, "Air biomonitoring of heavy metals and polycyclic aromatic hydrocarbons near a cement plant," *Atmospheric Pollution Research,* vol. 5, no. 2, pp. 262-269, 2014/04/01/ 2014, doi: https://doi.org/10.5094/APR.2014.032.

[11] C. G. Yedjou and P. B. Tchounwou, "OXIDATIVE STRESS IN HUMAN LEUKEMIA (HL-60), HUMAN LIVER

CARCINOMA (HepG2), AND HUMAN (JURKAT-T) CELLS EXPOSED TO ARSENIC TRIOXIDE," (in eng), *Met Ions Biol Med,* vol. 9, pp. 298-303, 2006.

[12] B. R. Stern, "Essentiality and toxicity in copper health risk assessment: overview, update and regulatory considerations," (in eng), *J Toxicol Environ Health A,* vol. 73, no. 2, pp. 11427, 2010, doi: 10.1080/15287390903337100.

[13] A. Benabed and A. Boulbair, "PM10, PM2.5, PM1, and PM0.1 resuspension due to human walking," *Air Quality, Atmosphere & Health,* vol. 15, no. 9, pp. 1547-1556, 2022/09/01 2022, doi: 10.1007/s11869-022-01201-3.

[14] K. Qu *et al.*, "The effect of cross-regional transport on ozone and particulate matter pollution in China: A review of methodology and current knowledge," (in eng), *Sci Total Environ,* vol. 947, p. 174196, Oct 15 2024, doi: 10.1016/j.scitotenv.2024.174196.

[15] R. M. Harrison and J. Yin, "Particulate matter in the atmosphere: which particle properties are important for its effects on health?," (in eng), *Sci Total Environ,* vol. 249, no. 1-3, pp. 85-101, Apr 17 2000, doi: 10.1016/s0048-9697(99)00513-6.

[16] M. A. Robert, S. VanBergen, M. J. Kleeman, and C. A. Jakober, "Size and composition distributions of particulate matter emissions: part 1--light-duty gasoline vehicles," (in eng), *J Air Waste Manag Assoc,* vol. 57, no. 12, pp. 1414-28, Dec 2007, doi: 10.3155/10473289.57.12.1414.

[17] A. Thorpe and R. M. Harrison, "Sources and properties of non-exhaust particulate matter from road traffic: a review," (in eng), *Sci Total Environ,* vol. 400, no. 1-3, pp. 270-82, Aug 1 2008, doi: 10.1016/j.scitotenv.2008.06.007.

[18] M. Viana *et al.*, "Source apportionment of particulate matter in Europe: A review of methods and results," *Journal of Aerosol Science,* vol. 39, no. 10, pp. 827-849, 2008/10/01/ 2008, doi: https://doi.org/10.1016/j.jaerosci.2008.05.007.

[19] C. L. Wiseman and F. Zereini, "Airborne particulate matter, platinum group elements and human health: a review of recent evidence," (in eng), *Sci Total Environ,* vol. 407, no. 8, pp. 2493-500, Apr 1 2009, doi: 10.1016/j.scitotenv.2008.12.057.

[20] D. Wu, J. C. H. Fung, T. Yao, and A. K. H. Lau, "A study of control policy in the Pearl River Delta region by using the particulate matter source apportionment method," *Atmospheric Environment,* vol. 76, pp. 147-161, 2013/09/01/ 2013, doi: https://doi.org/10.1016/j.atmosenv.2012.11.069.

[21] C. I. Davidson, R. F. Phalen, and P. A. Solomon, "Airborne Particulate Matter and Human Health: A Review," *Aerosol Science and Technology,* vol. 39, no. 8, pp. 737-749, 2005/08/01 2005, doi: 10.1080/02786820500191348.

[22] W. Yu *et al.*, "Estimates of global mortality burden associated with short-term exposure to fine particulate matter (PM_{2·5})," *The Lancet Planetary Health,* vol. 8, no. 3, pp. e146-e155, 2024, doi: 10.1016/S2542-5196(24)00003-2.

[23] T.-L. Tsai *et al.*, "Fine particulate matter is a potential determinant of Alzheimer's disease: A systemic review and meta-analysis," *Environmental Research,* vol. 177, p. 108638, 2019/10/01/ 2019, doi: https://doi.org/10.1016/j.envres.2019.108638.

[24] R. Peters, I. Mudway, A. Booth, J. Peters, and K. J. Anstey, "Putting Fine Particulate Matter and Dementia in the Wider Context of Noncommunicable Disease: Where are We Now and What Should We Do Next: A Systematic Review," *Neuroepidemiology,* vol. 55, no. 4, pp. 253-265, 2021, doi: 10.1159/000515394.

[25] M. Cork, D. Mork, and F. Dominici, "Methods for estimating the exposure–response curve to inform the new safety standards for fine particulate matter," *Journal of the Royal Statistical Society Series A: Statistics in Society,* vol. 188, no. 4, pp. 961-983, 2025, doi: 10.1093/jrsssa/qnaf004.

[26] K. P. Josey, P. deSouza, X. Wu, D. Braun, and R. Nethery, "Estimating a Causal Exposure Response Function with a Continuous Error-Prone Exposure: A Study of Fine Particulate Matter and All-Cause Mortality," *Journal of Agricultural, Biological and Environmental Statistics,* vol. 28, no. 1, pp. 20-41, 2023/03/01 2023, doi: 10.1007/s13253-022-00508-z.

[27] A. K. Singh *et al.*, "Agroecosystem contamination with heavy metals due to road transportation: A global threat to safe food security," *Process Safety and Environmental Protection,* vol. 194, pp. 1265-1282, 2025/02/01/ 2025, doi: https://doi.org/10.1016/j.psep.2024.12.046.

[28] S. Das, R. Raj, N. Mangwani, H. R. Dash, and J. Chakraborty, "2 - Heavy Metals and Hydrocarbons: Adverse Effects and Mechanism of Toxicity," in *Microbial Biodegradation and Bioremediation*, S. Das Ed. Oxford: Elsevier, 2014, pp. 23-54.

[29] I. Salahshoori *et al.*, "Navigating the molecular landscape of environmental science and heavy metal removal: A simulation-based approach," *Journal of Molecular Liquids,* vol. 410, p. 125592, 2024/09/15/ 2024, doi: https://doi.org/10.1016/j.molliq.2024.125592.

[30] M. Jaishankar, T. Tseten, N. Anbalagan, B. B. Mathew, and K. N. Beeregowda, "Toxicity, mechanism and health effects of some heavy metals," (in eng), *Interdiscip Toxicol,* vol. 7, no. 2, pp. 60-72, Jun 2014, doi: 10.2478/intox-2014-0009.

[31] S. B. Mayegowda, V. Chikkud, S. Barua, and N. G. Manjula, "13 - Heavy metal detection by nanotechnology-based sensors," in *Nanotechnology-based Sensors for Detection of Environmental Pollution*, F. M. Policarpo Tonelli, A. Roy, M. Ozturk, and H. C. A. Murthy Eds.: Elsevier, 2024, pp. 237-263.

[32] G. L. Daly and F. Wania, "Organic Contaminants in Mountains," *Environmental Science & Technology,* vol. 39, no. 2, pp. 385-398, 2005/01/01 2005, doi: 10.1021/es048859u.

[33] M. Lisiak-Zielińska *et al.*, "How polluted are cities in central Europe? - Heavy metal contamination in Taraxacum officinale and soils collected from different land use areas of three representative cities," *Chemosphere,* vol. 266, p. 129113, 2021/03/01/ 2021, doi: https://doi.org/10.1016/j.chemosphere.2020.129113.

[34] A. B. Fulke, S. Ratanpal, and S. Sonker, "Understanding heavy metal toxicity: Implications on human health, marine ecosystems and bioremediation strategies," *Marine Pollution Bulletin,* vol. 206, p. 116707, 2024/09/01/ 2024, doi: https://doi.org/10.1016/j.marpolbul.2024.116707.

[35] V. Vilas-Boas, N. Chatterjee, A. Carvalho, and E. Alfaro-Moreno, "Particulate matterinduced oxidative stress – Mechanistic insights and antioxidant approaches reported in in vitro studies," *Environmental Toxicology and Pharmacology,* vol. 110, p. 104529, 2024/09/01/ 2024, doi: https://doi.org/10.1016/j.etap.2024.104529.

[36] J. Chen and G. Hoek, "Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Volume 13, Issue 05, May 2026

and meta-analysis," (in eng), *Environ Int*, vol. 143, p. 105974, Oct 2020, doi: 10.1016/j.envint.2020.105974.

[37] G. Liu *et al.*, "Unlocking high-rate O3 layered oxide cathode for Na-ion batteries via ion migration path modulation," *Journal of Energy Chemistry*, vol. 83, pp. 53-61, 2023/08/01/ 2023, doi: https://doi.org/10.1016/j.jechem.2023.04.029.

[38] S. Iqbal, A. Ramini, and S. Kaja, "Impact of particulate matter and air pollution on ocular surface disease: A systematic review of preclinical and clinical evidence," (in eng), *Ocul Surf*, vol. 35, pp. 100-116, Jan 2025, doi: 10.1016/j.jtos.2024.12.003.

[39] T. L. Greaver *et al.*, "Ecological effects of nitrogen and sulfur air pollution in the US: what do we know?," *Frontiers in Ecology and the Environment*, vol. 10, no. 7, pp. 365-372, 2012/09/01 2012, doi: https://doi.org/10.1890/110049.

[40] P. Grennfelt and H. Hultberg, "Effects of nitrogen deposition on the acidification of terrestrial and aquatic ecosystems," *Water, Air, and Soil Pollution*, vol. 30, no. 3, pp. 945963, 1986/10/01 1986, doi: 10.1007/BF00303359.

[41] B. Giles-Corti *et al.*, "City planning and population health: a global challenge," (in eng), *Lancet*, vol. 388, no. 10062, pp. 2912-2924, Dec 10 2016, doi: 10.1016/s01406736(16) 30066-6.

[42] L. F. Steingräber, C. Ludolphy, J. Metz, H. Kierdorf, and U. Kierdorf, "Uptake of lead and zinc from soil by blackberry plants (Rubus fruticosus L. agg.) and translocation from roots to leaves," *Environmental Advances*, vol. 9, p. 100313, 2022/10/01/ 2022, doi: https://doi.org/10.1016/j.envadv.2022.100313.

[43] G. Goudarzi *et al.*, "Health risk assessment on human exposed to heavy metals in the ambient air PM(10) in Ahvaz, southwest Iran," (in eng), *Int J Biometeorol*, vol. 62, no. 6, pp. 1075-1083, Jun 2018, doi: 10.1007/s00484-018-1510-x.