The Research of Medical Science Review

Received: 24 November, 2024
Accepted: 24 December, 2024
Published: 02 January, 2025

ISSN: 3007-1208 | 3007-1216
Volume 3, Issue 1, 2025

IMPACT OF AIR BORNE PARTICULATE MATTER ON PLANTS, CLIMATE, ECOSYSTEMS, AND HUMAN HEALTH: A COMPREHENSIVE REVIEW

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ABSTRACT

Particulate matter (PM) is an intricate blend of airborne solid and liquid particles. A combination of inorganic and organic substances, such as carbon, metals, sulfates, nitrates, acids, and semi-volatile compounds, make up these particles in most cases. Natural sources, such as soils, sea salt, and volcanic eruptions, emit particulate matter. PM in the air has diameters ranging from 0.005 to 100 micrometers (µm), which is equivalent to the thickness of a human hair and only a few atoms in size. For these particles, researchers have established various size categories. The three broad categories that the U.S. Environmental Protection Agency (U.S. EPA) frequently uses to characterize PM are coarse (10 to 2.5 µm), fine (2.5 µm or smaller), and ultrafine (0.1 µm or smaller). Studies indicate that the size of the particles has a significant impact on how they settle. Due to the discovery that particulate matter exposure has caused health repercussions in thousands of premature death rate, particulate matter has garnered public attention in the last several years. Because it contributes to cloud formation, particulate matter not only has an impact on health but also has an impact on global warming and the greenhouse effect. This review article explores the detrimental effects of PM on plants, climate, ecosystems, and human health. By understanding the multifaceted impacts of PM, we can develop effective measures to mitigate its detrimental effects and protect human health and the environment.

Keywords: *Particulate Matter, Deposition Processes, Greenhouse Effect and Global Warming, Environmental Biotechnology*

INTRODUCTION

Particulate matter (PM), a complex mixture of solid and liquid particles dispersed in the atmosphere, has become a significant environmental contaminant with extensive implications. Particulate matter (PM) can arise from many sources, such as emissions from industries, exhaust from vehicles, construction operations, and natural phenomena (Souza et al. 2021). Natural sources, such as soils, sea salt, and volcanic eruptions, emit particulate matter. Based on particle size, three distinct categories of particulate matter are identified: Road dust and particles from worn-out engines and brakes make up PM10, which has a diameter of 2.5-10 µm. Diesel engine exhausts are the source of PM2.5, which have a diameter less than 2.5 µm (Shields et al. 2007).

There's also a differentiation between primary and secondary particles. The difference is dependent on how airborne particles originate. Primary particles are created by wind, friction, or burning fossil fuels. When acidic compounds react with salts in the air, secondary particles are created. Secondary particles may absorb primary particles (Tomasi and Lupi 2017). Because bigger percentages stick to tiny hairs in the respiratory system and are then released when one clears their throat, only PM2.5, according to the US Environmental Protection Agency (EPA), is hazardous to human health (Sosa et al. 2017). Thus, regulations pertaining to particulate matter with a size of 2.5 or less are more stringent than those governing bigger particles. Particulate matter emissions in industry have decreased throughout the last 20 years as a result of the installation of dust and soot filters. However, rising emissions in other industries offset the decline to some extent. Particulate matter standards are rather harsh due to the health risk (Davidson et al. 2005).
The accumulation of PM on the surfaces of plants can disrupt photosynthesis, diminish leaf area, and hinder the growth and development of the plants (Chen et al. 2015). Furthermore, PM has the capacity to modify soil characteristics, which in turn influences nutrient accessibility and microbial functions, ultimately resulting in the degradation of ecosystems. Particulate matter significantly impacts climate change by affecting cloud development, radiative forcing, and the patterns of atmospheric circulation (Yang et al. 2022). Exposure to particulate matter (PM) has been associated with numerous negative health outcomes, such as respiratory illnesses, cardiovascular issues, and a heightened risk of mortality (Thangavel et al. 2022). Grasping the relationship between particulate matter, environmental systems, and human health is essential for formulating effective strategies to reduce its detrimental impacts (Odubo and Kosoe 2024). The primary objective of our review is to provide a comprehensive and up-to-date overview of the detrimental effects of airborne particulate matter (PM) on various aspects of our environment and human health. We aim to assess PM sources, types, and impacts on plants, climate, ecosystems, and human health, identify knowledge gaps, and propose strategies for mitigating PM's negative consequences. By examining the impacts of PM on plants, climate, ecosystems, and human health, we hope to inform the development of effective strategies to mitigate its negative consequences and create a healthier and more sustainable future for all.

1. Global Efforts to Reduce PM Exposure

The Environmental Protection Agency (EPA) regulates particulate matter. The Clean Air Act contains two different limits for fine particles. Primary requirements are determined by the health consequences that certain pollutants produce, whereas secondary criteria are determined by the welfare impact of particulate matter, which includes preventing vision impairment and damage to buildings, crops, and animals (Saxena et al. 2019). For PM2.5, the 24-hour threshold was lowered to 35 micrograms per cubic meter this year, while PM10 was set at 150 micrograms per cubic meter (Mutua 2022). The World Health Organization (WHO) regulates particulate matter in Europe, and PM2.5 guidelines are 40 micrograms per cubic meter. The reduction to 20 micrograms per cubic meter is planned for 2010. Particles of solid or liquid substances that are small and part of the Earth's atmosphere are known as atmospheric particulates. As atmospheric aerosol, they float in the atmosphere (Smirnov and Smirnov 2021).
In addition to having negative effects on precipitation and climate, they can have a negative influence on human health. Soot, suspended particulate matter (SPM), respirable suspended particles (RSPs; particles with a diameter of 10 micrometers or less), tiny particles (diameter of 2.5 micrometers or less), and ultrafine particles are subtypes of atmospheric particle matter (Kemp 2004). Group 1 carcinogen status is given to particles by the WHO and IARC. The potential of particulates to enter the bloodstream and lungs deeply and unfiltered, leading to heart attacks, irreversible DNA alterations, and early death makes them the deadliest type of air pollution. There is no safe threshold of particles, according to a study that included 312,944 participants from nine European nations. The study also found that the rate of lung cancer increased with each 10 μg/m3 in PM10 (Valavanidis et al.).

1. Particulate matter in the atmosphere

Certain particles are produced by natural processes such as dust storms, sea spray, forest and grassland fires, volcanoes, and living vegetation. Particulates from human activity are also produced in large quantities by the burning of fossil fuels in power plants, automobiles, and other industrial processes (Mohapatra and Biswal 2014). The main energy-producing and home-heating technique in emerging nations is coal combustion. Currently, anthropogenic aerosols—those produced by human activity—account for roughly 10% of the total mass of aerosols in our atmosphere, primarily due to the fact that salt spray over the oceans is the most prevalent type of particle in the atmosphere (Haywood 2021). Particulate matter is emitted by natural processes including soils, sea salt, and volcanic eruptions. Airborne particulate matter concentrations are rising in many places due to anthropogenic sources such industry, shipping, car exhausts, and the production of coal and ore. Particulate matter emissions from power plants are increased (Hopke et al. 2020). Fire pits and barbecues are the primary sources of emissions from residential homes. The biggest threat to human health, according to Dutch epidemiologists, is traffic-related pollution, especially those from diesel engines. The diagram 1 illustrates the various natural and anthropogenic sources of particulate matter (PM). These sources contribute to the increasing levels of PM in the atmosphere, which has significant implications for human health and the environment.

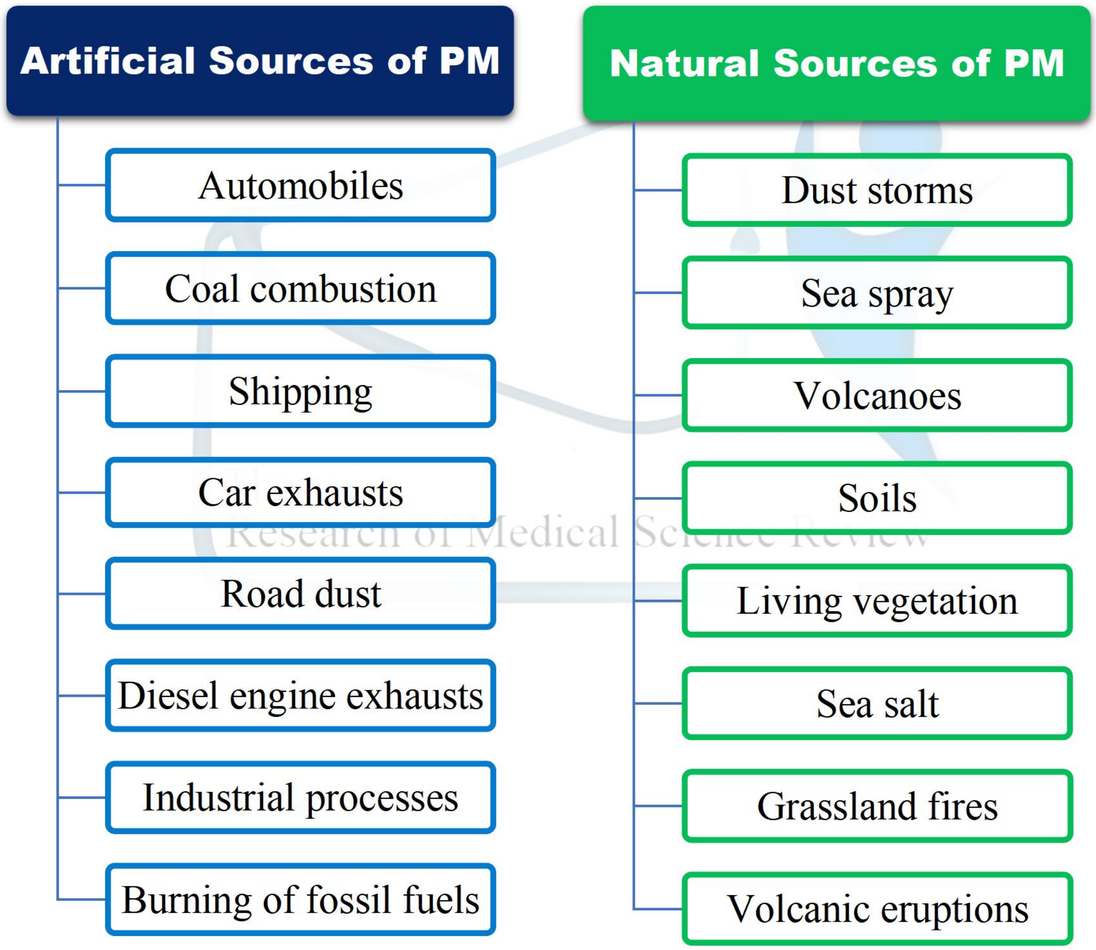

Diagram 1: Natural and artificial sources of particulate matter (PM) in the atmosphere

2. Processes of Deposition

Particles in the air tend to stay in the air longer when they are lighter and smaller. While smaller particles (less than 1 micrometer) can remain in the atmosphere for weeks before being mostly eliminated by precipitation, larger particles (more than 10 micrometers in diameter) usually gravitationally drop to the ground in a matter of hours. Near the emission source, diesel particulate matter concentrations are higher (Heal et al. 2012). To assess the effects on health, any information about DPM and the environment, vegetation, height, and distance from significant sources would be helpful. All exposed surfaces are impacted by the practically constant action of dry deposition of air particles, despite its significantly slower rate of occurrence when compared to wet or occult deposition (Lüers et al. 2017).

Particulate matter (PM) can be classified into three main categories based on their size: coarse, fine, and ultrafine. Coarse particulate matter (PM10) is of a larger size compared to fine particulate matter (PM2.5) and ultrafine particulate matter (UFP) (Huang et al. 2011) (Teixeira et al. 2023). PM10 can be effectively trapped by the nasal passages and throat, whereas PM2.5 and UFP can infiltrate deeper into the respiratory system, leading to more significant health issues. UFP, being the smallest particles, are frequently produced by combustion activities and have the potential to enter the bloodstream via the lungs (Lekkas 2008). Although all three categories of particulate matter can adversely affect health and the environment, ultrafine particles are typically regarded as the most detrimental because of their capacity to penetrate deeply into the respiratory tract and possibly enter the bloodstream.

Table 1: Comparison of coarse, fine and ultrafine particulate matter

Particle size and specific gravity are significant dust physical parameters that affect the weight of the

PM fraction	Size range	Source	Life time in atm	References
Coarse PM RSPM **(Respirable suspended particulate Matter)** PM 10	<10um diameter	▪ Soil dust ▪ Farming ▪ Mining ▪ Industrial dust ▪ Construction material ▪ Coal, oil ▪ Combustion ▪ Ocean spray	Mins-hours	(Mansor et al. 2022)
Fine PM RPM **(respirable particulate matter)** PM 2.5	<2.5um diameter	▪ Combustion of coal, oil and gasoline ▪ transformation products of NOx, SO2 and organics e.g terpenes ▪ high temperature process, ▪ smelters and steel mills	Days-weeks	(Gadkari 2010)
Ultrafine particles **(UFP)**	0.1um	▪ Metal fumes ▪ Sea salts nuclei, Oil ▪ smoke, ▪ Diesel etc.	Weeks-months	(Viitanen et al. 2017)

particles

and their possible transit distance from a source. For particles larger than 1 µm in diameter, the primary depositional process is gravitational sedimentation; however, for particles smaller than 0.001 µm in diameter, or respiratory suspended particulate matter, the impact of the particle on surfaces is more affected by its intrinsic properties (Abbasi et al. 2021). Even if mass loading in this size fraction may be low in comparison to fine PM, coarse PM frequently dominates the dry deposition of organic compounds (such as dioxins, dibenzofurans, and polycyclic aromatics) to vegetated surfaces. The factors that affect dust interception and subsequent retention are leaf orientation, age, surface roughness, and wettability. Dust retention is also affected by wind speed and consistency as well as vegetation porosity in relation to air movement. When it's dry outside, it can be challenging to gauge how quickly dust is lost from vegetal surfaces. Comparable cement dust loads and deposition rates (3.7 g m-2 d-1) were observed on tamarind and coconut leaves by (Prajapati 2012). The range of 1–15 cm s_1 has been observed for fine particle deposition velocities to forest surfaces. According to Neitlich et al. 2022 assessment, over the most of the summer growing season in Alaska, dust levels near the Dalton Highway were rather constant, and over 85% of the dust that falls on vegetation surfaces may be eliminated (Neitlich et al. 2022).

Certain types of gaseous pollutants can dissolve in the water droplets that are suspended in clouds and fog. Fine particles that already exist may absorb water and condense into droplets of fog or clouds. By accumulating and eliminating particles from the air, promoting particle development through aqueous oxidation processes, and boosting deposition, fog formation affects both the overall atmospheric burden and the deposition of particulate matter (Xue et al. 2016). Compared to high height clouds or coastal fogs, low altitude radiation fogs differ in their generation and deposition properties. In these fogs, smaller droplets contain significantly higher concentrations of important polluting species (such as NO3-, SO42-, and organics) than bigger droplets do. High quantities of acids and other ions are sometimes found in clouds, including sulfate (SO4 2-), hydrogen (H+), ammonium (NH4 +), and nitrate (NO3 -), in decreasing order of concentration (Hill et al. 2007). The decrease of forests in industrialized areas has been connected to acidic cloud water deposition. Particulate-derived material concentrations in cloud or fog water are frequently many times higher than those in nearby precipitation or ambient air. PM is delivered to foliar surfaces in a hydrated and thus bioavailable state by fog and cloud water.

3. Effects of Particulate Matter on Climate

By altering the quantity of energy of sun that enters the system of earth and the quantity of long-wave radiation that leaves, atmospheric aerosols have an impact on the planet's climate. A number of unique processes, divided into direct and indirect impacts, are responsible for this. The primary cause of doubt in projections for climate of future is the effects of aerosols on the climate (Kremser et al. 2016). While the force of radiative caused by gases of greenhouse might be estimated with a fair precision degree, according to the Third Valuation Report of the panel of Intergovernmental group on alteration of weather. Aerosol radiative forcings are still associated with significant uncertainties, most of which stem from estimates derived from global modeling studies that are still impossible to validate. Monthly average aerosol concentrations worldwide as determined by data made with NASA's Terra satellite using the Moderate Resolution Imaging Spectroradiometer (MODIS) (Shokr et al. 2017). Because aerosols bring change and alter the mechanism of the atmosphere to reflect and absorb noticeable and infra-red light, satellite used for the measurements of types of aerosols—known as aerosol-optical thickness—are built on this phenomenon. A number of 1 denotes extremely cloudy conditions, whereas depth of optical less than 0.1 recommends a absolutely vibrant atmosphere with range of extreme distinguishability (Sivaprasad 2015).

5.1 Direct effect of Aerosol

Any direct radiation-aircraft interaction, including absorption and scattering, is referred to as the "direct aerosol effect." Inducing a net negative radiative forcing, it impacts both short- and long-wave radiation. The amount of sunlight absorbed or dispersed into space is influenced by the albedo of the surface beneath, which determines the degree of the resulting force of radiative resulting from the aerosol effect directly (Braslau and Dave 1973). The radiative forcing of a strongly scattering aerosol, for instance, is higher above a low-albedo surface than it is above a high-albedo surface. On the other hand, when an aerosol absorbs large amounts of light, it causes a surface with high albedo to experience the maximum radiative forcing. Since the aerosol direct-effect is a first type of order effect, the IPCC (Intergovernmental Panel on Climate Change) has categorized it as a radiative forcing. The system of Single Scattering Albedo (SSA) is a measure of an aerosol's interaction with radiation; it is the tendency of sprinkling to scattering involving absorption (extinction) of radiation through particle (Tegen and Heinold 2018). With relatively little absorption, the SSA leads to unify if smattering outweighs. As absorption grows, the SSA declines and becomes zero for immeasurable captivation. Aerosol of sea-salt, for instance, has an SSA of 1, indicating that it is merely a scattering particle; in contrast, soot has an SSA measurement of 0.23, indicating if it is a significant climatic aerosol absorber (Valentini et al. 2020).

5.2 Indirect effects of Aerosol

Any alteration to the budget of Earth's radiative resulting from atmospheric aerosols modifying clouds is referred to as the "indirect aerosol effect," which encompasses multiple separate impacts. Cloud condensation nuclei (CCN) are atmospheric particles that already exist when cloud droplets form on top of them. There are more cloud droplets for every given set of meteorological conditions when there is a rise in CCN (Fanourgakis et al. 2019). The terms used to describe the increased scattering of shortwave radiation that results from this, called Twomey Effect (Stevens et al. 2016). There is evidence to support the cloud albedo effect from the differences in cloud albedo between ambient clouds and the effects of biomass burning and ship exhaust plumes. Since the Cloud Albedo Aerosol Effect is a first order effect, the IPCC has categorized it as a radiative forcing. Because more droplets are distributing the same quantity of water, a growth in droplet of cloud amount brought on by aerosol introduction reduces cloud droplet size (Bellouin et al. 2020). The effect of dropping snowfall and lengthening the lifespan of cloud, sometimes referred to as the Albrecht effect, secondly indirect effect, or cloud lifetime aerosol effect. This has been seen as reduced precipitation in biomass burning plumes and reduced shower in ship deplete columns as associated to adjacent clouds. The dependency between this cloud lifespan impact and the hydrological system leads the IPCC to classify it as climatic feedback rather than a radiative forcing (Murphy and Ravishankara 2018).

Table 2: Comparing the direct and indirect effects of aerosols on the Earth's radiative balance and climate.

Sr No	Feature	Direct Aerosol Effect	Indirect Aerosol Effect
1	**Mechanism**	Direct interaction of aerosols with radiation	Aerosols influencing cloud formation and properties
2	**Radiative Forcing**	First-order effect	First-order effect (Twomey effect), second-order effect (Albrecht effect)
3	**Impact on Radiation**	Influences both shortwave and longwave radiation	Primarily affects shortwave radiation through cloud albedo changes
4	**Key Factors**	Aerosol type, size, and concentration; surface albedo	Cloud condensation nuclei (CCN), cloud droplet size, cloud lifetime
5	**Examples**	Scattering and absorption of sunlight by aerosols	Increased cloud droplet concentration, changes in cloud albedo and lifetime

4. Effect of Particulate Matter on Human health

The EPA states that only PM2.5 is hazardous to human health since bigger percentages cling to tiny hairs in the respiratory tract are expelled when one clears their throat. Human caused (Anthropogenic) PM of atmospheric pollution is consistently and independently related to the most serious effects, including lung cancer and other cardiopulmonary mortality, according to an increase in fine particle concentrations in the air (Zheng et al. 2015). The high death toll and additional health issues linked to particulate matter pollution were initially shown in the early 1970s and have been repeatedly confirmed since then. According to estimates from 2000, PM pollution killed 22,000–52,000 people annually in the US and was a factor in about 370,000 early deaths in Europe in 2005 (Mohapatra and Biswal 2014). Asthma, lung cancer, heart-related problems, disorders of respiratory system, abnormalities of birth, and early death rate are among the impacts of particulate matter inhalation that have been extensively researched in both people and animals (Tasneem 2020). Particle shape and chemical makeup also affect a particle's ability to penetrate; size is not the only factor. The various levels of comparative saturation of a PM particle into the circulatory system are denoted by straightforward nomenclature in order to prevent this issue.

Where in the respiratory system a particle will settle after being breathed is mostly determined by its size. Particles measuring no more than 10 micrometers (PM10) are so small that they can possibly reach the innermost area of the lungs, such as the bronchiole or alveoli (Rathi et al. 2024). Although mucus and cilia in the nose and throat filter larger particles, PM10, or particulates smaller than 10 micrometers, can penetrate in the lungs and bronchi and cause issues of health (Zlotkowska 2015). The majority of regulatory agencies have decided to monitor airborne particulate matter at a size of 10 micrometers, which does not strictly define a boundary between respirable and non-respirable particles. The lungs' gas exchange areas are often penetrated by particles smaller than 2.5 micrometers, or PM2.5, and smaller particles (less than 100 nanometers) have the potential to go through the lungs and impact other organs (Chen et al. 2016). Since the cilia filter out inhalable particles, they only enter the bronchi. While pulmonary particles can enter terminal bronchioles and reach the lungs, respirable particles are those that can reach alveoli and ultimately the system of circulation. Inhalable particles are limited to the bronchi because they are removed by the cilia.

The portion of dust that can accumulate anywhere in the respiratory system and enter the mouth and nose is known as the inhalable dust fraction (Ali et al. 2023). What enters the thorax and settles in the gas exchange areas and lung airways is known as the thoracic fraction. In the gas exchange zones (alveoli), this is known as the respiratory fraction. Their solubility in water determines the location and degree of captivation of breathable vapors and gases. In addition, rates of air stream and the limited pressure of the gases in the moved air affect absorption. The shape that a particular pollutant takes (particulate or aerosol) determines its destiny (Mathew et al. 2022). The rate at which the patient breathes affects inhalation as well. During the previous five years, the rate of respiratory sickness has increased by 45%, according to a Mongolian government body. A 13% greater threats of heart attacks were associated with growth in predicted annual exposure to PM 2.5 of just 5 µg/m3, according to the study's findings (Alexeeff et al. 2021). Heart disease may be considerably exacerbated by even brief exposure to high quantities, according to research. Traffic emitted particles is the only greatest serious avoidable reason of heart attacks in the general population, accounting for 7.4% of all attacks, according to a study published in The Lancet. Less than 100 nanometer particles, or nanoparticles, have the potential to cause considerably more harm to the cardiovascular system (Kim et al. 2017).

It has been demonstrated that particles smaller than 100 nanometers can migrate into other organs, including the brain, by slipping past cell membranes. According to several theories, brain damage by particulate matter is comparable to that observed in Alzheimer's patients (Peters 2023). The Diesel Particulate Matter (DPM) particles that are released by contemporary diesel engines are generally particles with a size range of 100 nanometers (0.1 micrometer). Furthermore, the particles of soot include cancer-causing substances such as benzo-pyrenes that have been adsorbed onto their surface. It is becoming more and more obvious that the engine emission limitations set by law are not a reliable indicator of the risk of health. A single unit measuring 10 µm in thickness possesses roughly the similar form as a million of particles with a diameter of 100 nm (Hinds and Zhu 2022).

Table 3: Health impacts associated with different sizes of particulate matter

Sr No	Particle Size	Respiratory Effects	Cardiovascular Effects	Other Effects	References
1	**PM10**	Irritation, coughing, bronchitis	Increased risk of heart attack and stroke	-----	(Shahriyari et al. 2022)
2	**PM2.5**	Asthma, COPD, reduced lung function	Increased risk of heart attack, stroke, heart failure	Increased risk of premature death	(Alexeeff et al. 2021)

3	**Ultrafine particles**	Increased risk of respiratory infections	Increased risk of cardiovascular disease	Potential brain damage, impaired cognitive function	(Flood-Garibay et al. 2023)

5. Plants and Particulate Matter stress

Depending on the particle of specific type composition dumped, exposure to a given mass quantity of aerial PM might cause vastly different phytotoxic reactions. Particulate deposition and its impacts on plants invariably involve two things: (1) trace elements and heavyweight metals, such as lead; (2) nitrogen oxide and sulfuric acid and their relationships in the acidic-form and acidic concentrations (Zhai et al. 2018). According to Benetti et al. 2021 , size can serve as an effective stand-in for chemical composition due to its correlation with the mechanism and amplitude of deposition (Benetti et al. 2021). Granted that human caused (anthropogenic) acid-forming sulfate and nitrogenous particles are fewer reactants and soluble-mineral dust particles in general. Particles of dust with pH values less than 9 can damage leaf tissues directly when they land on them or indirectly through changing the pH of the soil (Ali et al. 2024). Dusts that contain toxic salts-soluble substances can also damage plants. According to Sen 2008, energy exchange in between plant and the atmosphere through the absorption, alteration, and discharge of radiations of short-wave as well as radiation of long-wave (Sen 2008). The surface reflectivity in the observable and infrared radiation of short-wave spectrum, as well as the number of light waves obtainable for the process of photosynthesis, all are transformed when dust particles are deposited on a surface of leaf (Varotsos and Krapivin 2020).

Particles of dust can change the ocular features of surfaces of snow-covered, which can cause in changes to the internal structure and variation of the community of plants, temperatures of vegetative surfaces 4 to 11.5 ^{o}C above ambient environments, and patterns of grazing of animals. Dust loads of road of 40 g m^{-2} increases leaf temperatures by 2 to 3^{o}C in environment of desert (Dubey et al. 2018). Gases diffusion in between the leaf and air possibly hindered by constructing up of dust on surfaces of leaf. While particles of fine size cause influence on the inferior surfaces, deposit of medium-sized particles more strictly disturbs the superior surfaces of leaves. When it originates to dusty surroundings, plants having stomata in channels may be less affected by covering of wax than plants having stomata are on the outer surface of leaf (Barthlott et al. 2017).

6. Ecosystem and Particulate matter stress

First, populations of individual susceptible organisms at single or many trophic levels must adapt in order to mount a defense against particle stress. In order for plants and particulates to interact biologically, at least three levels must be considered: (a) the specific plant and its atmosphere, (b) inhabitants and its atmosphere, and (c) organic categories of different populations and relevant atmosphere (Luo et al. 2019). Based on their genetic constitution, developmental stages, availability of resources, and micro-habitat, specific type of organisms react inversely to pressure. The ecological succession process can enhance ecosystem resilience to particle deposition by fostering competition between individuals and species. In an uncontaminated (desirable) environment, succession proceeds forward; in difficult mode of environments, however, energy is provided from growth and reproduction to conservation as a result of sporadic natural disturbances, which pushes succession backward to an earlier stage (Brauer 2009). The regular plant physiology and plant biochemistry, the features that measure energy flow and cycling of nutrients, the structure of food chain, and the list of nutrients are all disordered by these interruptions (Irfan et al.). Nevertheless, such disturbances generate the situations for reborn, which enables the disordered ecosystem to survive to its changing surroundings. As a result, these disorders may result in a short-lived hindrance and rapid recovery. Conversely, human-caused tensions, like those brought on by particulates and other man-cause deposition, can be more disastrous and shattering, causing strained ecosystems which leads to slow recovery and frequently experiencing further deprivation. For example, exposure to heavy metals damages trees and plays a role in the reduction of forests in the north-eastern United States (Malunguja et al. 2022).

Natural selection favors tolerance individuals because tolerant members of a crop population display a broad area of sensitivity. There has been evidence of the quick evolution of some resistant species populations at sites with presence of important nitrate and other trace element deposits (He et al. 2005). Grassland ecosystems are experiencing pollution along-term damages that is the main reason of the extinction of most-sensitive type of species, the removal of tree covering, and the conservation of a cover of residues cover of plants known as successional species, herbs or shrubs that can withstand pollution. Farmer (1993) suggests that the chemistry of the dust particles on plant surfaces is likely to have a greater impact on the impacts of the dust than just the mass of the particles (Farmer 1993). According Soheili et al. 2023, alkaline particles, like limestone particles, can harm plant surfaces. The development of crusts on leaves has inhibited photosynthesis, resulting in early leaf fall and the breakdown of leaf tissues, which has caused a decrease in the growth of the dominating trees (Soheili et al. 2023).

It is reported that alkaline dust with elevated MgO levels that was applied to leaf surfaces caused disruption of the epicuticular waxes (Fatima et al. 2021). When cement dust is hydrated, it releases calcium hydroxide, which in certain situations can increase alkalinity of surface area to pH 12. This degree of alkalinity has the ability to analyze fatty and components of wax, the cuticle penetration, and proteins denaturation, plasmolyzing the leaf. The lichen thallus's photosynthetic system was harmed by a coating of limestone dust (Kochhar and Gujral 2020). All of this causes the structure and function of communities to shift. According to reports, the microbial population that resides in the phyllo-sphere is impacted by particulates deposition. This microbial category of microbes is crucial to the breakdown of litter fall (Bani et al. 2018). Since fungi are crucial to the decomposition process, altering the community of fungi on the spikes will ultimately weaken the decomposer community and slow down the degree at which disorder decomposes. Each of type of these procedures modifies the cycle of nutrients (Conery 2021). The deposition of C-H compounds and different nutrients of mineral caused by slowly decaying litter affects the ecosystem's nutrition availability. Due to their dietary requirements and continuous exposure to particle matter, epiphytic lichens and mosses are vulnerable. Particulate matter affects ecosystems in a number of important and indirect ways (Çobanoğlu Özyiğitoğlu 2020). The most interesting indirect plant responses are essentially soil-mediated and mostly dependent on the individual elemental chemical makeup of particulate matter. The biological interactions that occur in the soil environment are poorly understood but nonetheless occur (Smith et al. 2018). According to Fazeli-Nasab et al. 2022, rhizosphere are essential for transforming organic matter through chemical and biological processes as well as for releasing inorganic minerals for plant uptake (Fazeli-Nasab et al. 2022).

Table 4: Impact of Particulate Matter on Ecosystems

Sr No	Ecosystem Component	Effects of Particulate Matter	References
1	**Plants**	Reduced photosynthesis, leaf damage, stunted growth, early senescence	(Khan et al. 2022)
2	**Soil**	Altered pH, reduced nutrient availability, disrupted microbial communities	(Naz et al. 2022)
3	**Ecosystem Succession**	Delayed succession, hindered recovery from disturbances	(Pérez-Hernández and Gavilán 2021)
4	**Biodiversity**	Loss of sensitive species, reduced species richness	(Rai 2020)
5	**Nutrient Cycling**	Disrupted nutrient cycling, altered soil fertility	(Liu et al. 2018)

7. Advanced monitoring and control systems

Studies on particulate matter in Bangkok, Thailand, showed that for every 10 micrograms per cubic meter, there was a 1.0% chance of all diseases and a 1.9% greater hazard of dying from heart disease (Hongthong et al. 2022). The change from diesel burning to methane gas as well as improved measures may be the cause of the declining emissions (Chen et al. 2019). Prompt mortality, persistent bronchitis, and heart-related disorders are all rising quickly. In addition to having an impact on health, particulate matter contributes to cloud formation, which in turn causes the greenhouse effect and global warming (Gupta 2014). Most developed nations have strict regulations governing the emissions of particulate matter. Because of environmental concerns, most firms have to run some sort of dust collection system to keep particulate emissions under control. These systems consist of wet scrubbers, electrostatic precipitators, fabric filter collectors (baghouses), and inertial collectors (cyclone collectors) (Diao and Yang 2021). In order to remove larger, coarse particles, cyclone collectors are frequently used as a "precleaner" or initial step before using other, more efficient collectors (Friedlander 1952). The most widely used in general industry are fabric filters or baghouses. They function by pushing air that is heavy with dust through a fabric filter in the shape of a bag. The particulate is then left to gather on the bag's outside, and the clean air is then allowed to flow through and either be released into the atmosphere or, in certain situations, recirculated inside the building (Maduna and Tomašić 2017). Polyester and fiberglass are typical textiles, while PTFE (often referred to as Teflon2) is a common fabric coating. After that, the collector's bags are cleansed of any remaining dust accumulation (Shah and Rawal 2016). With the help of wet scrubbers, particle matter can adhere to liquid molecules by passing the contaminated air through a scrubbing solution, which is often a blend of water and other substances. As the contaminated air goes through, electrostatic precipitators charge it electrically. After that, the charged air travels over enormous electromagnetic plates, which draw in and collect the charged particles in the airstream, sending the now-clean air for exhaustion or recirculation (Sell 1992).

Conclusions

Airborne particulate matter (PM) poses a significant and multifaceted threat to environmental and human systems. Its impacts on plant physiology, ranging from impaired photosynthesis to reduced growth, highlight the vulnerability of vegetation to airborne pollutants. Ecosystems are equally affected, experiencing biodiversity shifts, soil degradation, and altered nutrient cycles. Moreover, PM influences climate dynamics, exacerbating global warming and altering weather patterns through changes in radiative forcing and cloud formation. Particulate matter (PM), a pervasive environmental contaminant, poses significant threats to human health, ecosystems, and climate. This review has comprehensively explored the diverse impacts of PM, highlighting its sources, types, and detrimental effects. PM exposure is linked to respiratory illnesses, cardiovascular diseases, and increased mortality rates. PM can disrupt plant growth, alter soil characteristics, and impair ecosystem functions. Governments must implement and enforce stringent PM emission standards. Promoting the development and adoption of cleaner technologies and emission control systems. Raising awareness about the health and environmental risks associated with PM exposure. Fostering collaboration among nations to address global PM pollution issues. The health consequences of PM are profound, with increased risks of respiratory and cardiovascular diseases, as well as premature mortality. Mitigating these effects requires coordinated strategies across environmental management, public health, and policy frameworks to reduce PM emissions, improve air quality, and protect both ecological and human health. The urgency of addressing PM's far-reaching impacts cannot be overstated, making further research and global collaboration essential for developing effective solutions.

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