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Air pollution and roadside trees: A comprehensive review with a special reference to foliar dust deposition

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Abstract
Air pollution in cities is increasingly intensifying, exerting inevitable impacts on all living organisms, including trees. Urban trees are vital for cities because the improve air quality and regulate the climate: in metropolitan areas, the predominant inorganic atmospheric pollutants include Nitrogen oxide (NOx), Sulphur oxide (SOx), Carbon oxides (COx), Ozone (O_3), and suspended Particulate matter ($PM_{2.5}$ and PM_{10}). Each of these contaminants poses significant risks to public health, while simultaneously including a range of physiological and structural alterations in urban tree species and plants also can indicate the level of pollution in the respective areas. Vegetation captures gases, particulates and aerosols from the atmospheric more effectively than other land surfaces. Particulate matter deposition in different plants not only depends upon the sources and amount of pollutants in the environment but also depends on morphological characteristics of plants like leaf size and surfaces, texture, hair, wax, length of petiole, weather condition and wind direction. Hence plants can be used as bio monitors and bio indicators of air pollution. Dust interception capacities of plants can be exploit to use them as sinks for atmospheric particulate pollutants. Literature available on these aspects are reviewed and the highlights are depicted in this review paper.

Keywords: Air pollution, foliar dust deposition, leaf traits, pollutants, roadside trees

Introduction

Air pollution had spread around the world like an evil with rapid urbanization and industrialization, it has resulted in various health problems for men such as respiratory cardiovascular and ophthalmic diseases (Brunekreef and Holgate, 2002; Miller *et al.,* 2007; Nandasena, 2010; Giles *et al.,* 2011; Gudmundsson, 2011; Jamrozik and Musk, 2011) [5, 15, 16, 26, 30]. Urban air quality degradation is primarily driven by increasing vehicular emissions, construction activities, industrial discharge and resuspension of road dust. Particulate matter ($PM_{2.5}$ and PM_{10}) is especially hazardous due to its ability to penetrate respiratory system and carry toxic compounds such as heavy metals. Ambient air pollution has become a matter of great concern particularly in mega cities and urban areas and rapid industrial development coupled with emission from transport sector are recognized as the primary source the situation is alarming and gradually becoming more severe and it is expected to increase in near future to cope up with the population expansion (Banerjee *et.al.,* 2011) [4]. Therefore, development of an adequate management plan is one of the most basic requirements for the well beings of human, animals as well as for plants.

Roadside vegetation places a crucial role as a natural filter by capturing dust particles on leave surfaces and offers a cost- effective, sustainable method to mitigate these pollutants (Ahmed *et.al*., 2009) [1]. Leaves act as effective pollution receptor and serve as passive filter, capturing airborne particles through foliar dust deposition (Lorenzini *et al.*2006; Saebo *et.al*. 2012) [23]. Various trees and shrubs along with specific leaf traits have been identified, which can serve as practical tools in air pollution biomonitoring and mitigating the increased urban dust pollution (Fusaro *et al* 2021; Rodriguez - Santamaria *et al* 2022; Steinparzer *et.al*. 2023) [14, 50]. Dust pollution is a major problem in cities of developing countries. Many developed cities and nations including London, UK (Metham 1964), Russia (Novoderzhikina *et.al*., 1969) [31], and Ohio USA (Dochinger 1980) [11], have embraced the utilization of vegetation to combat dust pollution. Several researchers, such as Varshney and Mitra (1993) [57], Rai and Panda (2014) [38], and Devkota *et.al*., (2023) [9] have conducted studies on plants employed for monitoring dust loads. Vegetation along road side, comprising trees, shrubs, and hedges, has been found to play a crucial role in effectively mitigating the detrimental impact of gaseous and particulate pollutants (Ahmed *et.al*., 2009) [1]. Additionally, many tree species have evolved morphological and physiological traits that enhance their pollution capture efficiency. Morphological features of leaf are important in determining the dust capturing potential of the leaves. Foliar features such as leaf roughness stickness, presence of grooves and trichomes facilitate more dust retention then smooth non-sticky leaves without grooves and trichomes. (Kardel *et.al*., 2012; Ram *et.al*.,2014; Saebo *et.al.,* 2012) [18, 39]. Leaf characteristics such as leave orientation style nons assignment are also important in affecting the study position on plant leaves. This review explores the interrelationship between road side air pollution and tree physiology, emphasizing species prevalent in India.

Impact of Air pollution on Trees

Trees are organism that are directly affected by pollution, adsorbing or accumulating plants mainly in their leaves as the most exposed part. Visible changes in leaves may therefore be the first indication of injury, depending on tree sensitivity (Kaur and Nagpal, 2017) [17].The contaminants present in air enter trees through leaf stomata; when encountering the water found in leaves, a series of chemical reactions are activated that contribute to decreasing the pH, generating and acidic environment, and triggering a series of metabolic conditions ranging from changing stomatal activity to reactions with enzymes inhibiting processes such as the conversion of hexose into ascorbic acid (Sen *et.al.,* 2017). The emissions produced by motor vehicles affect tree health (Table 1). The loss of foliage in *Tilia cordata* has been evaluated in sites with low and high vehicular loads; in sites where there was less traffic, the loss of foliage was lower while in sites with high traffic levels, the loss of leaves in the crowns was more significant. A Scale from 1 to 5 was established, with 5 representing the best condition, characterized by a foliage loss of 10%, and 1 representing a foliate loss of 90% or more. The authors obtained scores of 4.5 and 3.6 for trees in areas with less traffic and more traffic respectively (Pietras- Couffignal *et.al.,* 2019) [32]. Some species of trees are greatly affected by environmental pollutants, other some species show tolerance and adaptation to them. In 2020, Roy *et.al*. studied 3 species of trees with a high capacity for tolerance to air pollution, metal accumulation, and particle capture namely *Mangifera Indica and Azadirachta indica and Ficus religiosa* and the authors observed no differences in this adaptation due to seasonal changes. Other trees like *Betula pendula, Tilia cordata, Salix alba, Robinia pseudoacacia, Populus alba, Populus simonii and Populus nigra* have been reported to be tolerant to and to accumulators of SO_2 (Sklyarenko *et.al*., 2018) [51]. The microstructures of tree leaves, such as the grooves, trichomes, glands and epicuticular wax layer, are associated with the tree's particle retention capacity. Some trees reduce their accumulation of particulate matter by self-cleaning their leaves through washing with precipitation, as is the case for *G. biloba* (Kawak *et.al.,* 2019).

Table 1: type and source of air pollutants (li *et al.,*2017)

S. No.	Pollutant	Type	Source
1.	Particulate Matter ($PM_{2.5}$ & PM_{10})	Suspended particles	Burning fossil fuel, Road dust, fires, and Land burning
2.	Sulfur dioxide (SO_2)	Gas	Coal and Oil and oil power plants, oil refineries, metallurgical industry and volcanic eruption
3.	Nitrogen dioxide (NO_2)	Gas	Motor Vehicles, Industries and Power generation.
4.	Carbon monoxide (CO)	Gas	Internal Combustion engines, Forest fires, and Industrial process
5.	Ozone (O_3)	Secondary Gas	Chemical reactions between Nox and VOCs in the presence of sunlight.
6.	Methane (CH_4)	Green house gas	Agriculture, Waste decomposition and oil and gas extraction
7.	Volatile Organic Compounds (VOCs)	Gases	Emissions from solvents, paints, gasoline and Diesel combustion.
8.	As, Cd, Cr, Co, Cu, Hg, Ni, Pb, V, Zn and Fe	Heavy Metal	Metallurgical industries, the combustion of leaded gasoline (in some countries), Electronic waste and the mining industry.

Quantitative study of atmospheric dust retention by plant

The quantitative study of atmospheric dust retention by plants focuses on measuring and analyzing how much data is captured, retained and accumulated by different plant species. This involves measuring the dust load per unit leaf area (g/m^2), chemical composition of retained particles, and assessing how leaves surface morphology, environmental conditions, and pollution level influence dust accumulation. Quantitative analysis helps to identify the most efficient species for air-quality improvement and can be used to design Green belt and roadside plantation for pollution control. In China Guangzhoug the urban vegetation retained approximately 8012.9 tons of dust annually showing the large-scale ecosystem service of green cover. Yang *et al.,* (2015) compared 12 urban trees species and reported dust retention capacities changing from 1.5 to 12 g/m^2 of leaf area depending on season and species. Shu *et al*., (2019) found that species with hairy, rough and folded leaves like *Ficus Benjamina* and *Magnolia grandiflora* retained significantly more dust compare to smooth leafed species such as *Cinnamomum camphora*. Zhao *et al.,* in Zhengzhou studied evergreen species and found that Eriobotrya japonica retained 5.45 g/m2, while Pittosporum tobira retained 1.53g/m2 under high pollution conditions. In India, Pandey *et al.,* (2016) observed that *Terminalia arjuna* and *Morus alba* accumulated more dust in industrial zones of Delhi than in residential areas with the industrial site showing 2.5 times higher dust load. A recent Gujarat study (Dinesh Kumar *et al.,* 2024) quantified Indoor plant dust retention and highlighted that indoor foliage also captures significant dust, demonstrating the filtering role of vegetation even in enclosed environments. The estimations of removal of atmospheric particulate matter by plants have been done by several researchers. For example, trees in Beijing, China captured 1261.4 tons of pollutants that resulted in reduction of 772 tons of PM_{10} per annum from the air (Yang *et al*., 2005). Nowak *et al.,* (2006) have demonstrated the variation in pollution removal by urban trees in several US cities and estimated that the total annual air pollution removal by urban trees is approximately 7,11,000 metric tons. Removal of approximately 4% and 3% of PM_{10} annually by urban plant canopies in West Midland and Glasgow, United Kingdom respectively has been reported McDonald *et al., (*2007). Cavanagh, (2008) reported removal of around 300 tons of air pollutants annually by trees in Christchurch, New Zealand. Nowak *et al.,* (2013) through a modeled based study estimated te total amount of $PM_{2.5}$ removed annually by trees to be between 4.7 tons to 64.5 tons in different states of USA.

Foliar traits affecting dust deposition efficiency

The efficiency of dust deposition largely depends on foliar traits such as surface roughness, trichome density, wax content and leaf orientation. Studies have shown that rough, hairy and uneven leaf surfaces trap more particles compared to smooth and glossy ones (Rai & Panda, 2014; Zhu *et al.,* 2021) [38, 59]. The role of leaf surface character in dust capturing by the plant foliage and the significance of micro morphological leaf surface characters of plant in indication and mitigation of automobile exhaust pollution has been described by Pal *et al,* (2002) [35]. Verma *et al.,* (2003) [58] also suggested that the morphological characteristics in combination with orientation of leaf on the main axis, shape, size and wax deposition etc, play significant role in the interception of air born dust by plants (Table 2). Prusty *et* *al., (*2005) [34] have observed significant variations in dust int erception ability among the plant species and implied that dust interception capacity of plants depends on their canopy, shape and size leaf phyllotaxy and leaf surface characteristics such as hairs and cuticle. They have also stated that except leaf morphology, dust interception ability of plants depends on leaf orientation and the sessile or semi sessile nature of leaves. Leaves with long petioles are easily put into motion by minor air movement and such leaves can hold lesser amount of dust. In contrast, leaves with short petioles can resist the air movement and can hold relatively more amount of dust Chakre *et al.*, (2006) [7]. Trichomes and grooves on the leaf surface enhance mechanical interception, while leaf size, margin type and venation patter further influence the accumulation of coarse a fine particle (Turner,2013; Singh *et al*., 2023) [49, 54]. Mandal *et al.,* (2025) [24] further reported that the presence of trichomes, higher leaf thickness and increased cuticular wax contain significantly improved particulate retention efficiency, particularly under high pollution conditions in urban areas. Zhang *et al*. (2023) Demonstrated that species with higher surface roughness and micro structural irregularities accumulated up to 2.5-3.4 g/m2 of dust under urban conditions. Similarly, plants with dense pubescence, such as *Ficus religiosa and Nerium oleande*r, exhibited significantly higher dust capture efficiency compared to smooth leaved species (Bisht *et al*.,2022) [3]. The interaction of structural (trichomes, waxes, veins) and physiological (leaf age, orientation, stomatal opening) traits determine the total dust load on foliag (Zhu *et al.,* 2021; Singh *et al.,* 2023 [49,59] Zhang *et al*.,2025) [30]. Except leaf morphology the structure and composition of wax particles may also contribute toward the dust capturing capacity of plants. Epicuticular wax layers of different thickness and composition influence the deposition of dust on plant foliage (Dzierzanowski *et al.,* 2011) [10]. Significant differences in accumulation of particulate matter where observed between tree species commonly cultivated in Poland and the variations were attributed to the dis similarity in wax properties of different plant species (Popek *et al*.,2013) [33].

Table 2: Comparative Foliar Dust Deposition and Leaf Traits of Selected Indian Roadside Trees

S. No	Tree Species (Scientific Name)	Common Name	Average Foliar Dust deposition (mg/cm2)	Leaf Type	Leaf Teture	Dust Retention Capacity	Remark/References
1.	Ficus religiosa	Peepal	2.85±0.18	Broad, Deciduas	Smooth	Moderate	Smooth leaves hold less dust, tolerant to air pollutant (Rai & Panda, 2014) [38]
2.	Azadirachta indica	Neem	4.20±0.20	Pinnate, Evergreen	Rough	High	Rough Surface traps more dust, High tolerance (Kaler *et al*., 2016)
3.	Saraca asoca	Ashoka	3.75±0.22	Narrow, evergreen	Smooth	Moderate	Linear leaves collect dust along midrib (Singh & Pal, 2017)
4.	Mangifera indica	Mango	3.20±0.15	Broad, Evergreen	Leathry, Waxy	Very High	Waxy cuticle enhances particulate retention (Sharma *et al*., 2016)
5.	Cassia fistula	Amaltas	2.45±0.19	Pinnate, Deciduas	Smooth	Low-moderate	Seasonal leaf shedding reduces annual dust load (Rai & panda, 2014) [38]
6.	Delonyx regia	Gulmohar	2.80±0.20	Binnate, Deciduas	Rough	High	Rough, Compound leaves effective dust collectors (Singh & Pal, 2017)
7.	Alstonia scholaris	Saptparni	3.95±0.25	Broad, Evergreen	Leathery	High	Good Pollution tolerant tree leathery leaves (Kaler et. al., 2016)
8.	Cassia siemea	Kasod	2.60±0.18	Pinnate, deciduas	Smooth	Moderate	Modern retention, Hairy roadside species (Singh & Pal, 2017)
9.	Zizyphus mauritiana	Ber	2.40±0.21	Broad, Semi-deciduas	Rough, Hairy	Moderate	Effective under dry roadside conditions (Rai & Panda, 2014) [38]
10.	Hibiscus rosa sinensis	Gudhal	1.85±0.14	Broad, shrub	Smooth	Low-moderate	Shrub; Shows Biochemical adaptation to dust (Prajapati & Tripathi,2008)
11.	Calotropis gigantia	Madar	3.70±0.19	Broad, succulant	Rough, Waxy	High	Dust tolerant, survives in industrial areas (Sharma et. al., 2016)
12.	Nerium oleander	Kaner	2.95±0.14	Narrow, Evergreen	Leathery, Smooth	Moderate-High	Shows tolerance & morphological changes under dust (Kumar *et al*.,2018)
13.	Ficus benghalensis	Banyan	5.35±0.22	Broad, Evergreen	Hairy, Rouigh	Very High	Traps fine dust due to trichomes & large surface area (Rai & Panda,2014) [38]

Factors influencing dust deposition efficiency

In addition to foliar traits (leaf size, shape, trichomes density, surface roughness and waxy or pubescent) environmental and atmospheric conditions (Wind speed, direction, humidity and rainfall intensity) strongly influence dust deposition efficiency. Metrological parameters such as wind speed, rainfall, humidity and seasonal variation determine both the rate of deposition and the potential for resuspension or wash off. Liu *et al.,* (2022) [21]. found that particulate accumulation was significantly higher during dry seasons with lower rainfall while frequent precipitation reduced surface dust loads. Similarly, Lokshin *et al.,* (2025) [20] emphasized that particle size and chemical composition also affect how effectively dust adheres to leaf surfaces, with finer particles showing greater retention due to electrostatic and surface chemical interaction. A study of Bridhikitti *et al*, (2023) [2]. demonstrated that canopy structure and leaf area index influence over all deposition efficiency as denser canopies create aerodynamic resistance, reducing wind speed and promoting dust settling.

Mechanisms of Foliar dust deposition

Foliar dust deposition occurs via multiple Aerodynamic and surface interaction mechanisms like Sedimentation (Larger particles settle bye gravity on horizontal or rough surfaces), Impaction (moving particles collide with leaf surfaces due to momentum), Interception (particles following air flow paths are intercepted by leaf edges and tricomes), Diffusion (Ultra fine particles attach due to Brownian motion, Electrostatic attraction (charged particles adhere to oppositely charged surfaces). Farmer *et al.,* 2021) [13]. Course particles settle directly under gravity, while finer particles move irregularly due to Brownian motion and turbulence, increasing their chances of contact with leaves. Inertial impaction occurs when particles deviate from air flow path and collide with the surface, and interception happens when particles following air streams come close in a to be captured. Once particles reach the leaf, adhesive forces such as electrostatic and wonderwaal interactions help them stick until removed by wind or rain. Wet deposition also contributes when particles are incorporated into raindrops or do and settle on foliage sometimes dissolving to form soluble films on the leaves surface (Raza *et al.,* 2021; Lokshin *et al.,* 2025) [20, 36].

Air pollution tolerance index (APTI) of Plants

APTI is a quantitative tool used to assess the tolerance level of plants to air pollution. It helps identify plant species that can withstand and mitigate air pollutants (such as SO_2, No_2, Co and particulate matter).

$$APTI = [A(T+P) +R] / 10$$

A (Ascorbic acid content mg/g) - act as an antioxidant; higher A - Higher pollution tolerance

T (Total chlorophyll content mg/g) - indicates photosynthetic activity

P (pH of leaf extract) - Affects stomatal behaviour and pollutant absorption

R (Relative water content) - Indicates the water balance and stress tolerance of the plant

APTI provides an indication of tolerance level of plant species exposed to air pollution (Singh *et al.*,1991; Escobedo *et al*., 2008) [12, 53.].Assesment of APTI of plants exposed to air pollution have been carried out by several researchers (Radhapriya, *et al*.,2012) [44] and depending on the APTI score many plants have been classified as tolerant or sensitive species (Lalitha *et al*., 2013) [22].Nayak *et al.*, (2011) have estimated the APTI of Shorea robusta, Alstonia scholaris, Peltophorum pterocarpum, Albizia lebbeck, Tectona grandis, Lagerstroemia speciosa and Delonix regia near industrial sites and reported the former four plants as tolerant in those industrial zones. This, sensitive plant can be used for urban greening as suggested by Miria and Khan (2013) [25]. (Table 3)

Table 3: Interpretation of APTI values

S.No.	APTI Value Range	Plant Category	Pollution Tolerance
1.	>17	Tolerant	Can be used for green belt development
2.	12-16	Intermediate	Moderate Tolerance
3.	1-11	Sensitive	Act as a bio indicator of air pollution

Conclusion

It is concluded that the accumulation of atmospheric dust on plants is influenced by species specific traits such as height, leaf structure, orientation and arrangement, petiole length, and presence/ absence of surface hairs. Plants exhibiting folded leaves with rough texture. Roadside plants can function as effective natural filters for mitigating dust pollution in urban areas. Identifying plant species with greater tolerance to dust and pollution stress can help urban planners select suitable species for roadside plantations. Integrating these plants into urban landscape can improve air quality and minimize the harmful effects of particulate matter on human health and ecosystems.

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