

Roadside Plant Species and Their Role in Traffic-Pollution Mitigation: An Indian Perspective

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ABSTRACT

Rapid urbanization, increasing road traffic, and expansion of transport infrastructure have intensified air-pollution problems in Indian cities. Vehicular activity contributes directly and indirectly to particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon, and metal-containing road dust. Roadside vegetation represents a comparatively low-cost nature-based intervention capable of intercepting particulate matter, absorbing selected gaseous pollutants, modifying local airflow, reducing resuspended dust, and providing additional ecosystem services. However, the effectiveness of roadside vegetation depends strongly on plant species, leaf morphology, canopy structure, vegetation density, meteorological conditions, road geometry, and the surrounding urban form. This review examines the role of roadside plant species in mitigating traffic-related pollution with particular emphasis on Indian cities. Evidence from studies conducted in Delhi, Pune, Bathinda, Kanpur, Varanasi, Lucknow, Uttarakhand and other Indian locations is synthesized. Species such as *Ficus benghalensis*, *Ficus religiosa*, *Mangifera indica*, *Delonix regia*, *Polyalthia longifolia*, *Azadirachta indica*, *Saraca asoca*, *Grevillea robusta*, *Millettia pinnata*, *Terminalia arjuna*, *Nerium* spp. and other locally adapted species have demonstrated varying degrees of pollution tolerance and pollutant accumulation. Particular attention is given to leaf traits, Air Pollution Tolerance Index (APTI), Anticipated Performance Index (API), particulate deposition, heavy-metal accumulation, physiological responses, and the design of vegetation barriers. The review emphasizes that roadside plantation should not be based simply on the number of trees planted; rather, species selection and spatial configuration should be integrated with traffic intensity, street geometry, pollutant characteristics, local climate, pedestrian exposure, and maintenance requirements. Vegetation should complement—not replace—emission reduction, public transport, road-dust management, and regulatory measures. A species-selection framework for Indian urban roads is proposed, together with research priorities involving standardized PM-removal measurements, native species evaluation, plant–pollutant interactions, and city-specific vegetation planning.

Keywords- roadside vegetation, vehicular pollution, particulate matter, PM_{2.5}; PM₁₀; phytoremediation, Air Pollution Tolerance Index, India.

I. INTRODUCTION

Air pollution has become one of the major environmental challenges associated with rapid urbanization and motorization. Indian cities are characterized by high population density, expanding road networks, increasing private and commercial vehicle use, construction activity, road-dust resuspension and complex mixtures of local and regional pollution sources. Road transport is particularly important because

emissions are released close to the ground and therefore near pedestrians, cyclists, roadside workers and residents living adjacent to busy corridors. The International Energy Agency has reported that road transport is a key contributor to urban air pollution in India, with transport-related pollution occurring close to populated areas; India introduced Bharat Stage VI vehicle-emission standards nationally in 2020 as part of broader efforts to reduce emissions (IEA, 2023). Traffic-related pollution is not restricted to exhaust emissions. Road vehicles

contribute to a mixture of exhaust particles, brake and tyre wear particles, resuspended road dust and gaseous pollutants. The relative importance of individual sources varies among cities, seasons and locations. For example, source-apportionment studies in Delhi-NCR have demonstrated substantial contributions from transport as well as dust, industry, biomass burning and secondary particulate formation. TERI-ARAI assessments have reported transport-sector contributions to Delhi PM_{2.5} that vary considerably depending on season and methodology. India's National Ambient Air Quality Standards specify annual standards of 40 $\mu\text{g m}^{-3}$ for PM_{2.5} and 60 $\mu\text{g m}^{-3}$ for PM₁₀, with 24-hour standards of 60 and 100 $\mu\text{g m}^{-3}$, respectively. The standards also specify limits for gaseous pollutants including SO₂ and NO₂ (CPCB, 2009).

Against this background, vegetation along roads has received increasing attention as a nature-based approach for reducing pollutant exposure. Leaves, branches and stems provide surfaces on which airborne particles can deposit, while plants can also take up certain gaseous pollutants through stomata. Vegetation can modify turbulence and pollutant dispersion and can create a physical interface between emission sources and exposed populations. Reviews of urban green infrastructure have demonstrated that trees, shrubs, hedges and other vegetation can influence local air quality, although the magnitude and direction of the effect depend strongly on vegetation configuration and urban morphology (Abhijith et al., 2017; Barwise & Kumar, 2020).

The potential of roadside plants is particularly relevant to India because urban roadside landscapes commonly contain a mixture of avenue trees, shrubs, hedges, climbers and naturally occurring vegetation. However, planting decisions have historically been influenced by aesthetic considerations, availability of nursery material and general urban landscaping requirements rather than quantitative pollution-mitigation criteria. Consequently, a scientifically based approach to species selection is necessary. This review therefore examines the role of roadside plant species in traffic-pollution mitigation from an Indian perspective. It synthesizes evidence on pollutant interception, plant tolerance, leaf characteristics, physiological adaptation, heavy-metal accumulation and vegetation-barrier design, while identifying species and planting strategies that have been investigated under Indian urban conditions.

II. TRAFFIC RELATED AIR POLLUTION IN INDIAN URBAN ENVIRONMENTS

Vehicular pollution is a complex mixture whose composition varies according to vehicle type, fuel, engine technology, traffic congestion, driving conditions and road environment. Major pollutants of concern

include PM₁₀, PM_{2.5}, ultrafine particles, NO_x, CO, VOCs and black carbon. Non-exhaust sources additionally contribute particles containing metals and mineral material.

The significance of road traffic is particularly apparent in large metropolitan regions. The Delhi-NCR source-apportionment literature illustrates the complexity of the problem: transport, dust, industry, biomass burning and secondary particulate formation can all contribute significantly, with relative contributions changing between summer and winter. Thus, roadside vegetation should be viewed as one component of a broader air-quality-management system rather than a stand-alone solution.

Roadside pollution is also spatially heterogeneous. Concentrations are generally highest close to emission sources and decline with increasing distance, although atmospheric stability, wind direction, street geometry, traffic volume and surrounding buildings strongly affect this pattern. Vegetation located between a road and a sensitive receptor may therefore have a different effect from vegetation planted within a densely enclosed street canyon.

This distinction is important in Indian cities where roads range from relatively open highways to narrow streets surrounded by multistorey buildings. A planting arrangement that improves dispersion and particle interception along an open arterial road may have a different effect in a narrow urban canyon. Abhijith et al. (2017) concluded that vegetation effects differ according to urban configuration and that inappropriate high-level vegetation in street canyons can potentially impede pollutant dispersion.

III. ROADSIDE VEGETATION AS A POLLUTION-MITIGATION MECHANISM

1. *Particulate-matter interception-*

The most direct pollution-control function of roadside plants is the interception of particulate matter. Particles transported by air collide with and adhere to leaves, branches and stems. Some particles subsequently remain attached to the plant surface, while others may be removed through rainfall, wind or leaf turnover. The efficiency of particle capture depends on particle size and plant morphology. Leaf roughness, grooves, ridges, hairs, waxes, stomatal characteristics and surface area can influence deposition. A review of urban forests found that foliar characteristics are particularly important at the individual-tree scale, whereas vegetation density, meteorology and surrounding urban design become increasingly important at larger scales (Han et al., 2020). Small leaves, complex foliage and rough or hairy surfaces can provide numerous deposition sites. However, no single leaf trait guarantees high overall pollution-removal performance because aerodynamic

conditions and canopy structure also influence particle deposition. Research on roadside vegetation has demonstrated that vegetation can reduce near-road PM concentrations under appropriate conditions. One study examining a roadside hedge reported reductions of approximately 2–9% behind the hedge compared with an adjacent clear area, with the magnitude varying by particle size and location. Traffic-facing foliage also showed greater particle deposition at lower sampling height, highlighting the importance of barrier position and human breathing height (Abhijith et al., 2020).

2. Absorption of gaseous pollutants-

Plants may also remove certain gaseous pollutants through stomatal uptake. NO₂, SO₂ and ozone can interact with leaf surfaces and enter plant tissues, where they may be metabolized, detoxified or incorporated into biochemical processes. The magnitude of gaseous-pollutant removal varies substantially among species and environmental conditions. Stomatal conductance is therefore important. Plants with active gas exchange may have greater opportunity for gaseous uptake, but excessive pollutant loading can itself cause stomatal closure and physiological damage. Consequently, a species that is highly effective under moderate pollution may not necessarily remain effective under extreme pollution.

3. Modification of airflow and dispersion-

Vegetation acts as a porous aerodynamic structure. A vegetation barrier can intercept particles while simultaneously changing turbulence, wind velocity and plume dispersion. The effects therefore depend on barrier height, width, porosity, leaf area density and continuity. Research has demonstrated that dense roadside vegetation can reduce downwind particulate concentrations when appropriately designed, while poorly configured vegetation can sometimes reduce ventilation and increase pollutant concentrations locally. Vegetation barriers should therefore be sufficiently dense to intercept pollutants but should not create an unnecessarily impermeable obstruction in situations where ventilation is critical (Abhijith et al., 2017; Barwise & Kumar, 2020).

4. Reduction of resuspended road dust-

Road traffic contributes to the mechanical resuspension of deposited road dust. Roadside vegetation can reduce the movement of coarse dust by acting as a physical barrier. Vegetation does not remove the original source of road dust, however. Dust that accumulates on roads can be repeatedly resuspended, particularly under dry conditions and heavy traffic. This distinction is important in Indian cities. Vegetation can intercept a portion of the resuspended material, but effective road-dust management, street cleaning, control of construction dust and maintenance of paved surfaces remain necessary.

IV. LEAF CHARACTERISTICS GOVERNING POLLUTANT CAPTURE

The effectiveness of a roadside species is strongly related to leaf morphology and canopy architecture.

1. Leaf roughness-

Rough leaves generally provide more microsites for particle attachment than smooth leaves. Surface irregularities can physically trap particles, particularly larger particles. Leaf grooves and depressions can act as temporary reservoirs for dust.

2. Trichomes and hairs-

Leaf hairs increase the effective surface area and can enhance particle retention. Species possessing dense pubescence may therefore be useful components of vegetation barriers. However, the persistence of captured particles depends on wind, rainfall and leaf orientation.

3. Epicuticular wax-

Waxy surfaces can retain fine particles and hydrophobic compounds. Differences in wax structure among species can therefore influence PM accumulation. Studies of roadside vegetation have demonstrated that leaf-surface properties influence particle capture across different size fractions (Weber et al., 2019).

4. Leaf area and canopy density-

A plant with a high total leaf area can provide a greater deposition surface. Dense foliage also increases the physical interaction between moving air and plant surfaces. However, excessively dense barriers can affect airflow and should therefore be evaluated in relation to road geometry.

5. Evergreen versus deciduous species-

Evergreen species can provide relatively continuous interception throughout the year, whereas deciduous species may provide strong seasonal services but lose much of their foliar surface during leaf fall. In Indian cities, combinations of evergreen and seasonally deciduous species may provide more consistent year-round functions.

V. INDIAN EVIDENCE ON ROADSIDE PLANT SPECIES

Indian research has increasingly demonstrated the potential of roadside and urban plant species to tolerate, accumulate, and mitigate pollutants associated with vehicular traffic. Considerable variation has been reported among plant species in their physiological responses, particulate deposition capacity, biochemical characteristics, and ability to accumulate heavy metals. Among the species frequently investigated under Indian urban conditions are *Ficus benghalensis*, *Ficus religiosa*, *Ficus glomerata*, *Polyalthia longifolia*, *Azadirachta indica*, *Mangifera indica*, *Delonix regia*, *Saraca asoca*,

Grevillea robusta, *Terminalia arjuna*, *Millettia pinnata*, *Morus alba* and *Nerium* spp. Their performance, however, varies according to climatic conditions, traffic intensity, pollutant composition, soil characteristics, season, plant age and local urban morphology.

Ficus benghalensis has attracted considerable attention because of its large canopy, high leaf biomass and reported tolerance to polluted urban environments. Studies conducted in Varanasi identified *F. benghalensis* among the species showing strong performance under polluted conditions, suggesting its potential for greenbelt development. *Ficus religiosa* has similarly been reported as a pollution-tolerant species and has also demonstrated potential for biomonitoring atmospheric pollution because its leaves can accumulate deposited particulate matter and associated contaminants. Prajapati and Tripathi (2008), in their assessment of 29 tree species in Varanasi, identified *F. benghalensis* and *F. religiosa* among the better-performing species when physiological tolerance and landscape characteristics were considered together. Other species, including *Polyalthia longifolia*, *Ficus glomerata*, *Anthocephalus indicus* and *Mangifera indica*, were also categorized as promising candidates for greenbelt development.

Azadirachta indica is another important species in the Indian roadside landscape because of its adaptability to relatively dry conditions, tolerance of urban stresses and widespread availability. A study conducted in Bathinda, Punjab, evaluated *A. indica*, *F. benghalensis*, *Melia azedarach* and *Polyalthia longifolia* using the Air Pollution Tolerance Index (APTI) and Anticipated Performance Index (API). The study reported considerable seasonal variation in APTI, with *F. benghalensis* showing the highest APTI during summer among the investigated species, while *A. indica* showed relatively lower tolerance during winter (Sharma et al., 2020). Such findings demonstrate that pollution tolerance is not a fixed characteristic but may vary with environmental conditions and physiological status.

Polyalthia longifolia is particularly important in Indian urban landscaping because of its tall, narrow and vertically oriented canopy. This growth form allows it to be planted along roads where horizontal space is limited. Its pollution tolerance has been reported in studies conducted in several Indian cities, making it a potentially useful avenue species. Nevertheless, its value for pollution mitigation should be considered together with its actual particulate-deposition capacity, because physiological tolerance alone does not necessarily indicate the amount of atmospheric pollution removed by a plant.

Mangifera indica has also demonstrated considerable potential under Indian roadside conditions. Kandpal and Rai (2024) investigated the air-pollution sensitivity and tolerance of common tree species in the industrial zone of Kumaun Himalaya, Uttarakhand, and reported relatively high APTI for *M. indica* at the polluted site. The results suggested that *M. indica*

possessed physiological characteristics that enabled it to withstand atmospheric pollution. Its large leaf area and substantial canopy additionally provide considerable surface area for particulate deposition. However, because mango is a large tree, its use along roads should be restricted to locations where adequate space is available for canopy and root development.

Delonix regia has also been investigated for its tolerance to vehicular pollution. Research conducted in Pune evaluated several common roadside tree species using APTI and related biochemical characteristics and reported *D. regia* among the more tolerant species under the studied conditions. Its broad canopy and substantial foliage make it potentially useful for roadside green infrastructure where sufficient planting space is available. Similarly, *Saraca asoca* has shown promising pollution tolerance. A study of plants growing along a national highway in Kanpur evaluated 17 species and identified *S. asoca* as a highly resistant species based on APTI. *Ficus elastica*, *Ficus religiosa* and *S. asoca* were subsequently identified as potential species for greenbelt development in that study (Singh et al., 2022).

Grevillea robusta represents another species investigated specifically under roadside vehicular exposure. Singh et al. (2020) evaluated *G. robusta* and *Mangifera indica* in an urban environment in Dehradun and observed changes in physiological characteristics associated with vehicular pollution. The study demonstrated alterations in photosynthetic performance, transpiration, stomatal conductance, water-use efficiency and biochemical responses in roadside plants. At the same time, the species demonstrated adaptive characteristics and dust-removal potential, indicating that roadside plants can simultaneously experience pollution stress and contribute to pollution mitigation. Such dual responses are important when selecting species for long-term roadside plantation programmes.

In addition to gaseous pollutants and particulate matter, roadside vegetation can accumulate heavy metals originating from vehicular and non-exhaust sources. Species such as *Terminalia arjuna*, *Millettia pinnata*, *Morus alba* and *Ficus religiosa* have been examined for their capacity to accumulate metals including lead, cadmium, copper and zinc. A study conducted in Delhi demonstrated considerable differences among plant species in their accumulation of heavy metals across residential, commercial and industrial environments (Patel et al., 2023). Such plants may therefore have value as biomonitors of urban pollution in addition to their potential role in pollutant interception. However, accumulation of contaminants in foliage should also be considered from the perspective of leaf-litter management because metals deposited or accumulated in leaves may eventually enter urban soils following leaf fall.

Potential Indian roadside shrubs include *Nerium oleander*, *Hibiscus rosa-sinensis*, *Duranta erecta*, *Bougainvillea* spp. and other locally adapted species,

although their selection should be based on empirical pollutant-capture data, water requirements, maintenance, ecological suitability and safety. Recent research has further expanded the list of potentially useful species. Kandpal and Rai (2024) examined five common tree species in an industrial region of Uttarakhand and found differences in pollution sensitivity and tolerance based on leaf traits and APTI. *Mangifera indica* exhibited comparatively high tolerance at the polluted site, while *Nerium* also demonstrated relatively high tolerance. These results emphasize the importance of evaluating species under actual local pollution conditions rather than relying exclusively on data obtained from other geographical regions. Overall, Indian studies indicate that roadside plant species differ substantially in their capacity to tolerate vehicular pollution, accumulate particulate matter and heavy metals, and maintain physiological functioning under polluted conditions. Species such as *Ficus benghalensis*, *Ficus religiosa*, *Azadirachta indica*, *Polyalthia longifolia*, *Mangifera indica*, *Delonix regia*, *Saraca asoca* and *Grevillea robusta* have demonstrated useful characteristics in different Indian environments. However, these findings should not be interpreted as a universal ranking of species. The performance of each plant depends on local climate, traffic intensity, pollutant composition, soil conditions, vegetation structure and maintenance.

VI. AIR POLLUTION TOLERANCE INDEX AS A TOOL FOR SPECIES SELECTION

The Air Pollution Tolerance Index is one of the most frequently used approaches in Indian studies for evaluating plant response to air pollution. APTI incorporates four biochemical parameters: ascorbic acid content, total chlorophyll, relative water content and leaf-extract pH.

The index is commonly represented as:

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

where **A** is ascorbic acid content, **T** is total chlorophyll, **P** is leaf-extract pH and **R** is relative water content. The biological rationale is that ascorbic acid contributes to antioxidant protection, chlorophyll reflects photosynthetic status, relative water content reflects plant hydration and pH can influence physiological tolerance. More recently, Kandpal and Rai (2024) evaluated five common species in the industrial region of Rudrapur, Uttarakhand. *Mangifera indica* exhibited the highest APTI at the polluted site, while *Eucalyptus* showed the lowest among the tested species. *Nerium* also demonstrated relatively high tolerance. These findings demonstrate that APTI can help identify tolerant species, but APTI should not be interpreted as a direct measurement of actual pollutant-removal capacity.

VII. PHYSIOLOGICAL RESPONSES OF ROADSIDE PLANTS TO VEHICULAR POLLUTION

Roadside plants are simultaneously pollution mitigators and biological receptors of pollution. Their physiological responses provide evidence of the stress imposed by traffic emissions. Singh et al. (2020) investigated *Grevillea robusta* and *Mangifera indica* under roadside vehicular exposure in Dehradun. Roadside plants showed changes in CO₂ assimilation, transpiration, stomatal conductance, water-use efficiency, APTI, proline, copper accumulation, leaf thickness, cooling effects and dust-removal efficiency. CO₂ assimilation was reduced relative to the less polluted comparison site, while several adaptive traits increased. This demonstrates an important paradox: a plant can contribute to pollution mitigation while simultaneously experiencing pollution stress. Particles deposited on leaves may interfere with stomatal functioning and photosynthesis, while gaseous pollutants can cause oxidative stress. Research on *Lagerstroemia speciosa* under heavy roadside traffic similarly documented reductions in carbon assimilation, transpiration and stomatal conductance, accompanied by changes in leaf thickness, water-use efficiency, lead concentration and proline content (Singh et al., 2017). In Lucknow, investigations of *Sida cordifolia* and *Catharanthus roseus* exposed to automobile pollution demonstrated alterations in photosynthetic pigments and relative water content, together with increases in antioxidant enzymes such as catalase and peroxidase (Sharma et al., 2016). These physiological responses are relevant to species selection because long-term mitigation requires plants that can survive and continue functioning under chronic pollution exposure.

VIII. HEAVY-METAL ACCUMULATION BY ROADSIDE VEGETATION

Traffic pollution can also involve heavy metals originating from fuel combustion, lubricants, brake wear, tyre wear and resuspended contaminated road dust. Plant leaves can accumulate these elements externally as deposited particles or internally following uptake. A Delhi study examining 16 common plant species across control, residential, commercial and industrial environments investigated Pb, Cd, Cu and Zn. The authors found differences among species and sites and identified *Ficus religiosa*, *Terminalia arjuna*, *Morus alba*, *Prosopis juliflora* and *Milletia pinnata* as useful biomonitors or bioaccumulators under the study conditions (Patel et al., 2023). A 2024 study conducted in Delhi further examined 26 elements associated with airborne suspended particulate matter and plant tissues across commercial, traffic-prone, residential,

educational, greenbelt and industrial locations. The study emphasized that plants can accumulate elements associated with traffic, road dust and other anthropogenic sources (Tripathi & Nema, 2024).

Such findings support the use of roadside vegetation as a biomonitoring system. Nevertheless, pollutant accumulation does not automatically mean that a plant has removed pollutants permanently from the environment. Leaves may eventually fall, and deposited material can return to soil. Therefore, leaf litter management becomes important where heavy-metal accumulation is substantial. A major research gap in India is the lack of standardized comparative measurements of PM_{2.5} and PM₁₀ interception by common roadside shrubs. Many studies focus on APTI rather than actual atmospheric concentration changes. Future research should therefore combine biochemical tolerance indices with direct measurements of pollutant removal.

IX. INFLUENCE OF ROAD GEOMETRY AND URBAN FORM

Roadside vegetation cannot be evaluated independently of the physical structure of a city. In open roads, vegetation barriers can intercept pollutants and encourage deposition. In narrow street canyons, however, dense tree canopies can interfere with vertical pollutant dispersion. Abhijith et al. (2017) found that the effects of vegetation differed markedly between open-road and street-canyon environments. Vegetation design should therefore consider, road width, building height, traffic volume, prevailing wind direction, pedestrian pathways, distance between road and receptor, vegetation height, barrier thickness, vegetation porosity, leaf area density; and maintenance condition. Barwise and Kumar (2020) emphasized that vegetation barriers require careful species and configuration selection because their effectiveness depends on both pollutant deposition and aerodynamic effects.

X. SPECIES SELECTION CRITERIA FOR INDIAN ROADS

Species selection should integrate pollution tolerance, pollutant-interception characteristics, growth form, climatic adaptability, infrastructure compatibility, ecological value, and maintenance requirements. Leaf traits are particularly important because the physical structure of foliage directly affects particle deposition. Rough, waxy, hairy, ridged, and complex surfaces can increase opportunities for particulate retention (Barwise and Kumar, 2020).

Climatic suitability is equally important in India because roadside environments experience large differences in temperature, precipitation, soil moisture, and seasonal stress. Plants used in dry and semi-arid

cities must tolerate water limitation and high temperatures, whereas species planted in humid or coastal environments must tolerate different combinations of rainfall, humidity, and soil conditions. Native and well-adapted species can therefore provide important advantages, although native status should not be treated as the sole criterion for selection.

Mature plant size and root characteristics must also be considered. Trees with large crowns and aggressive roots can damage pavements or underground infrastructure if planted in restricted spaces. Branches may interfere with electrical lines, streetlights, traffic signs, or sight lines. Species with inappropriate growth forms can consequently create safety and maintenance problems despite possessing otherwise desirable pollution-related characteristics.

Maintenance requirements should be incorporated at the planning stage. Roadside plants experience dust accumulation, soil compaction, water limitation, physical damage, pruning pressure, and exposure to vehicle-generated turbulence. Species capable of maintaining healthy foliage under relatively low-input conditions may therefore be more appropriate for extensive road networks. Nevertheless, maintenance remains essential because damaged vegetation and heavily contaminated leaf surfaces may reduce functional performance.

Seasonal foliage characteristics should also be considered. Evergreen species can provide more continuous interception, whereas deciduous species may provide stronger seasonal ecosystem services but lose much of their leaf surface during periods of leaf fall. A combination of species with complementary phenology may provide more consistent vegetation structure throughout the year. Such considerations are especially relevant in northern Indian cities, where winter pollution episodes can coincide with stagnant atmospheric conditions.

XI. VEGETATION CONFIGURATION FOR TRAFFIC-POLLUTION MITIGATION

Roadside planting should be designed as a three-dimensional system rather than as isolated trees. A multilayer structure consisting of trees, shrubs and ground vegetation can increase the effective interception area. Trees can intercept pollutants at upper levels, while shrubs can intercept particles closer to pedestrian height. Ground vegetation can reduce soil erosion and resuspension. For open roads, a sufficiently continuous vegetation barrier between the road and receptor can increase pollutant interception. However, gaps should be minimized where a barrier function is intended. At the same time, the barrier must be designed with appropriate porosity so that airflow is not unnecessarily obstructed. The 2018 study of roadside vegetation characteristics demonstrated that vegetation density and structure

strongly influence pollutant dispersion. Modeling indicated that a leaf-area density around $3 \text{ m}^2 \text{ m}^{-3}$ or greater was associated with downwind PM reductions under the studied conditions, while the study emphasized that vegetation barriers should maintain appropriate height, thickness and ground-to-canopy coverage.

XII. ROADSIDE VEGETATION AND URBAN SUSTAINABILITY

The role of roadside vegetation extends beyond direct air-pollution mitigation. Urban trees contribute to thermal regulation by providing shade and through evapotranspiration. They can store carbon, provide habitat for birds and insects, intercept rainfall, reduce surface temperatures, and improve the visual quality of transportation corridors. These combined services make roadside vegetation an important component of climate-resilient urban planning.

Large-canopy trees can be particularly valuable for shading pedestrians and reducing heat exposure, whereas shrubs and hedges can contribute to ground-level screening and habitat complexity. The combination of different vegetation forms may therefore provide multiple ecosystem services simultaneously. However, species should be selected with awareness of potential negative characteristics, including high pollen production, excessive biogenic VOC emissions, invasive behaviour, thorniness, unstable branches, or fruit and litter production. Barwise and Kumar (2020) emphasized that species selection should account for both beneficial and potentially disadvantageous effects of vegetation on urban air quality.

XIII. RECOMMENDED ROADSIDE PLANTING STRATEGY FOR INDIAN URBAN ENVIRONMENTS

Indian roadside plantation should be based on functional zoning rather than uniform planting along entire road corridors. Broad roads and highways with sufficient land availability can accommodate larger canopy trees combined with shrubs or hedges. Urban avenues with limited horizontal space may require species with narrower crowns and carefully managed root systems. Highly built-up street canyons require particular attention to vegetation density and airflow, while areas containing schools, hospitals, and residential buildings require vegetation configurations designed specifically around sensitive receptors.

Species such as *Ficus religiosa*, *Terminalia arjuna*, *Mangifera indica*, *Millettia pinnata*, *Grevillea robusta*, *Morus alba*, *Lagerstroemia speciosa*, *Azadirachta indica*, and *Saraca asoca* may be considered among candidate species depending on regional climate and site conditions. These species should not, however, be regarded as universally superior.

Indian studies demonstrate differences in pollution tolerance, physiological response, and pollutant accumulation among species, emphasizing the need for site-specific evaluation (Prajapati and Tripathi, 2008; Singh et al., 2017; Singh et al., 2020; Bhadauria et al., 2022; Patel et al., 2023). The most effective strategy is therefore likely to involve combinations of species and vegetation layers selected according to local conditions. Such diversity can also improve ecological resilience and reduce dependence on a single species. Where space permits, integrating roadside trees with shrub layers, bioswales, green strips, and other forms of urban green infrastructure may produce additional environmental benefits.

XIV. CONCLUSION

Roadside vegetation represents an important nature-based component of traffic-pollution management in India. Its principal functions include interception of particulate matter, uptake of selected gaseous pollutants, modification of pollutant dispersion, reduction of resuspended dust and provision of wider urban ecosystem services. Indian studies conducted in cities and roadside environments have demonstrated considerable differences among plant species in pollution tolerance, physiological response, particulate accumulation and heavy-metal uptake. Species such as *Ficus benghalensis*, *Ficus religiosa*, *Mangifera indica*, *Delonix regia*, *Polyalthia longifolia*, *Azadirachta indica*, *Saraca asoca*, *Grevillea robusta*, *Terminalia arjuna*, *Millettia pinnata* and others have demonstrated useful characteristics in individual Indian studies. However, the evidence does not support a universal ranking of species. Performance is strongly dependent on local environmental conditions, pollution composition, plant age, leaf characteristics, season and vegetation configuration. APTI and API provide useful screening tools, but they should not be treated as direct measures of atmospheric pollutant removal. Future roadside-plantation programmes should combine physiological tolerance with direct measurements of PM deposition and ambient concentration reduction.

The greatest opportunity lies in integrating species selection, leaf traits, vegetation density, road geometry, urban morphology and pollutant characteristics into city-specific green-infrastructure planning. Dense vegetation barriers may be beneficial along open roads, while different configurations may be required in street canyons. Low-level vegetation can be particularly useful where pedestrian exposure is important. Importantly, roadside plants should complement rather than replace emission-control measures. Vehicle standards, cleaner fuels and technologies, public transportation, traffic management, road-dust control and urban planning remain essential. Vegetation provides an additional biological layer of protection that can simultaneously deliver shade,

cooling, carbon storage, biodiversity and landscape benefits. For India, the next generation of roadside vegetation research should move from simply identifying "pollution-tolerant" species toward quantifying species-specific pollutant removal under realistic Indian traffic conditions. Standardized measurements, long-term experiments, computational modeling and interdisciplinary collaboration among botanists, atmospheric scientists, transport planners and urban designers will be essential for developing scientifically optimized roadside green infrastructure.

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