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A Review on the Role of Urban Trees in Air Pollution Reduction

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ABSTRACT: Urban air pollution due to rapid urbanization and industrialization, is a serious threat to ecological stability and public health. The paper reviews studies across the world on the role of urban trees in accumulating particulate matter (PM) and reducing gaseous pollutants including sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) through stomatal absorption. The fact that the effectiveness of this mitigation varies significantly by species demonstrates the importance of selecting suitable trees using the Air Pollution Tolerance Index (APTI). Ascorbic acid content, total chlorophyll, leaf extract pH, and relative water content are only a few of the biochemical indicators that make up this composite metric. Low-APTI species are bio-indicators, whereas high-APTI species are pollution "sinks." APTI-based selection is incorporated with ecological services (such as carbon sequestration and thermal regulation), morphological adaptations (such as canopy density and leaf texture), and urban barriers (such as allergenicity and infrastructure compatibility) in optimal urban forestry. Pollution abatement is further maximized through strategic planting patterns, spatial buffering close to sources of pollution, and maintenance techniques including pruning and improving soil health. This review suggests that species-specific green infrastructure is essential in order to improve urban air quality and human well-being.

Keywords: Air Pollution Reduction; Air Pollution Tolerance Index; Gaseous Pollutants; Green Infrastructure; Particulate Matter; Urban Trees

INTRODUCTION

Urban air pollution is a major global issue that has significant effects on climate systems, environmental integrity, and human health. The impact of air pollutants from transportation, industry, and the burning of fossil fuels continue to increase as urbanization increases speed, especially in developing nations (Taiwo et al., 2015; Upreti et al., 2024). Because of their dense populations and high energy requirements, megacities in particular serve as centers of pollution (Gurjar et al., 2016).

By 2050, around 70% of the world's population will live in cities (United Nations, 2018), which is predicted to worsen air quality issues. According to the Global Burden of Disease study (Global Burden of Disease Risk Factors Collaborators, 2020), exposure to fine particulate matter ($PM_{2.5}$), ozone (O_3), and nitrogen dioxide (NO_2) was the main cause of 4.14 million premature deaths worldwide in 2019. Neurological, cardiovascular, and respiratory disorders are associated with these contaminants (Echendu et al., 2022). In addition to its detrimental impacts on human health, air pollution exacerbates climate change through greenhouse gas (GHG) emissions and further contributes to ecosystem degradation through acidification and eutrophication.

As a result, urban vegetation especially trees has grown increasingly recognized as a sustainable and multifunctional approach to reduce air pollution. Two main methods are used by urban trees to reduce pollution: (1) stomatal absorption of gaseous pollutants such as NO_2 and SO_2, and (2) particulate matter interception and retention on leaf surfaces (Nowak et al., 2014). However, species, leaf structure, climate, and pollutant concentration all have a significant impact on how well pollutants are removed.

Thus, selecting trees effectively is important. A diagnostic method for determining tolerant and sensitive species is the Air Pollution Tolerance Index (APTI), which assesses physiological characteristics such as chlorophyll concentration, ascorbic acid content, relative water content, and pH of leaf extract (Sahu et al., 2020; Edeigba et al., 2024). While sensitive species (low APTI) may act as early-warning bio-indicators, tolerant species (high APTI) can be planted in highly contaminated areas (Fig. 1).

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Furthermore, the integration of APTI with morphological and ecological factors such as leaf surface roughness, canopy structure, evapotranspiration capacity, and allergenic potential improves the efficacy of green infrastructure (Aslanoğlu et al., 2025). This review's objectives are to: (1) investigate global evidence of urban trees' ability to reduce air pollution; (2) evaluate the importance of APTI for species selection; and (3) suggest practical recommendations for urban forestry planning that enhance ecosystem services while reducing trade-offs with ecology and public health.

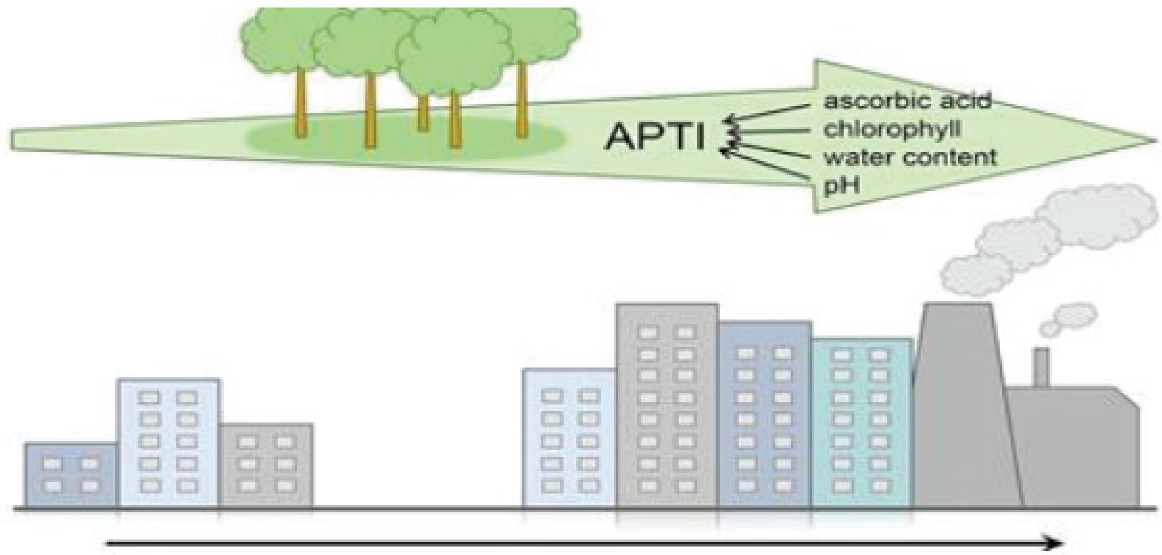

Figure 1: The Use of Air Pollution Tolerance Index in Urban Trees Resilience to Air Pollution (Tesfaye, 2022)

URBAN AIR POLLUTION: SOURCES AND IMPERATIVES FOR MITIGATION

Rapid industrialization and population increase have made urban air pollution a pressing global concern for environment and public health. The primary sources are transportation, which contributes 40–70% of urban NO_x and PM emissions from vehicle exhaust; industrial emissions (heavy metals, sulphur oxides and VOCs); and open waste burning, which remains a significant source of PM in developing nations (Atubi, 2015; Okedere *et al*., 2019; Kumar et al., 2024). Consequently, more than 90% of cities worldwide fail to meet World Health Organization's (WHO) recommended limits for pollutants such as $PM_{2.5}$, NO_2, and O_3 (WHO, 2025).

Vulnerable populations such as children, the elderly, and low socioeconomic groups are disproportionately affected by air pollution. Globally, 4.14 million premature deaths in 2019 were directly associated with ambient air pollution, primarily from cardiovascular and respiratory conditions (Global Burden of Disease Risk Factors Collaborators, 2020). Beyond this public health crisis, air pollution exacerbates climate change through carbon dioxide and methane emissions and contributes to ecosystem degradation including acid rain and biodiversity loss (Echendu et al., 2022).

These threats are becoming more severe due to rapid urbanization. By 2050, 70% of the world's population is projected to live in urban areas, and megacities like Delhi, Lagos, and Manila are expected to face $PM_{2.5}$ concentrations exceeding WHO recommendations by 10–25 times (United Nations, 2018; Kundu et al., 2024). However, implementing conventional mitigation strategies such as stricter pollution regulations and transitioning to clean energy are challenging to implement in emerging economies due to limited budgets, inadequate infrastructure, and governance challenges.

The present challenges demonstrate how urgently nature-based, scalable, and low-cost solutions are needed. A promising synergistic approach is the strategic use of urban trees which includes co-benefits like carbon sequestration, hydrological regulation, urban cooling, and enhanced urban biodiversity in addition to reducing pollutant loads (Nowak et al., 2014; Gong et al., 2023). However, the efficacy of this approach depends on species selection based on their adaptability to urban constraints and local pollution profiles.

TREES AND AIR POLLUTION MITIGATION

Mechanisms of Air Pollution Removal by Trees

Urban trees reduce air pollution through a variety of biophysical mechanisms. Particulate matter is intercepted and captured by tree bark and leaf surfaces, whereas gaseous pollutants like NO_2 and SO_2 enter the leaf through stomatal openings (Diana Grecia et al., 2025). Following absorption, these gases can dissolve in aqueous films in the intercellular spaces or undergo reactions within the apoplast to form acidic chemicals that are subsequently neutralized or metabolized by the leaf (Nowak et al., 2006).

The efficiency of these biophysical systems is influenced by tree height, leaf shape, and canopy structure. Particulate matter deposition occurs through diffusion, impaction, interception, and sedimentation (Song et al., 2015). The capture of fine particles ($PM_{2.5}$) is influenced by leaf texture and turbulent airflow (De Jalon et al., 2019). Brownian motion facilitates the diffusion of ultrafine particles onto the surfaces of damp leaves. Larger, rougher leaves can be removed more effectively since they frequently have higher deposition velocities (Xue et al., 2025).

The length of foliar activity, climate conditions, and species-specific traits all affect the removal of pollutants. For example, Chicago's urban trees, which make up 11% of the city's land cover, remove over 234 tons of $PM_{2.5}$ every year (Popek et al., 2022; Nersisyan et al., 2024).

APTI and Its Application in Urban Tree Selection

A widely used composite indicator for assessing how plants react to air pollution stress is the APTI (Shrestha et al., 2020). Four leaf biochemical parameters are used to calculate it:

Ascorbic acid content (A): functions as an antioxidant that mitigates oxidative stress.

Total chlorophyll (T): reflects photosynthetic capacity, often reduced under pollution.

Leaf extract pH (P): indicates metabolic activity and buffering capacity.

Relative water content (RWC, R): maintains cell turgidity and metabolic function.

The formula for calculating APTI is:

$$\text{APTI} = \frac{A(T+P)+R}{10} \ldots\ldots\ldots\ldots\ldots (1)$$

Greater tolerance to air pollution is suggested by higher APTI values, whereas vulnerability is shown by lower values. To find tolerant plants for roadside planting, afforestation, and pollution buffers, numerous studies have utilized APTI in urban and industrial environments (Anake et al., 2018; Bharti et al., 2018; Enitan et al., 2022).

APTI is useful for more than selecting trees. Additionally, it is a tool for monitoring ambient air quality and urban ecological planning, guiding the placement of sensitive species as bio-indicators in regions under ecological assessment and tolerant plants in polluted zones (Sapkota and Shrestha, 2024).

AIR POLLUTION TOLERANCE OF TREE SPECIES IN GLOBAL URBAN CONTEXTS

Overview of International Research On Urban Tree Species Tolerance

The resistance of urban tree species to air pollution varies greatly, depending on their physiological and biochemical characteristics. A standardized method for categorizing species along a sensitivity–tolerance spectrum is the APTI (Singh et al., 2020). Planners can optimize tree selections for site-specific pollution mitigation by having a global understanding of these variances (Table 1). For high-pollution corridors, species with high APTI values (>30) are advised. Due to characteristics like thick cuticles and high antioxidant content, *Ficus rumphii* (45.10) and *Artocarpus heterophyllu*s (46.74) showed strong tolerance in India (Gupta et al., 2020; Patil *et al*., 2022). *Mangifera indica* (38.07) and *Gmelina arborea* (47.46) were also proven to be successful in Metro Manila in Southeast Asia (Sia Su et al., 2018). Notably, *Polyalthia longifolia* continuously shows great tolerance in a variety of locations, including Lahore (78.9) (Nawaz et al., 2023) and Dombivli (58.01) (Satpute and Bhalerao, 2017), demonstrating its wide applicability in global green infrastructure.

Species in the intermediate APTI range (15–30) are suitable for moderately polluted areas. For instance, *Azadirachta indica* displayed location-dependent tolerance-sensitive in Haridwar (15.51) (Anjali et al., 2018), but more resilient in Sambalpur (17.94) (Sahu et al., 2020). In sub-Saharan Africa, *Terminalia catappa* (30.22) (Ekene et al., 2019) has shown adaptability to tropical urban stressors. In Europe, though fewer studies are available, *Acer saccharinum* (23.50) (Simon et al., 2021) has been identified as moderately tolerant in temperate settings.

Sensitive species (APTI < 15) are often located in rapidly urbanizing regions with high pollution loads. Examples include *Grevillea robusta* (10.45) in Ethiopia (Tesfaye, 2022) and *Ficus elastica* (8.25) in Kathmandu (Ter et al., 2020). These species may be better suited as bio-indicators rather than for pollution abatement.

In Bangladesh, several peer-reviewed studies have looked at the APTI of common roadside tree species. Shahrukh et al. (2023) examined four evergreen tree species in Dhaka, reporting APTI values between 10.31 and 12.51, with *Mangifera indica* exhibiting the greatest tolerance among the species evaluated. Azam et al. (2023) examined *Polyalthia longifolia* and *Swietenia mahagoni* in Dhaka, determining APTI values of 12.54 and 12.27, respectively, thereby validating their sensitivity (APTI <15) in conditions of elevated pollution load. Sadia et al. (2019) specifically assessed the APTI of *Mangifera indica* in the greater Dhaka region, reporting an APTI of 12.51, thereby confirming the species' sensitivity in urban Bangladeshi environments. These findings collectively address a geographical deficiency in the APTI literature and provide practical data for urban forestry in the Ganges-Brahmaputra delta region.

Table 1: Air Pollution Tolerance Index (APTI) of Some Tree Species Across Diverse Polluted Urban Environments in Some Countries

Tree species	Location	APTI Value	Tolerance category	References
Tolerant Species (APTI >30)				
Polyalthia longifolia	Lahore, Pakistan	78.9	Tolerant	Nawaz *et al*., 2023
Polyalthia longifolia	Dombivli, India	58.01	Tolerant	Satpute and Bhalerao, 2017
Gmelina arborea	Metro Manila, Philippines	47.46	Tolerant	Sia Su *et al*., 2018
Artocarpus heterophyllus	Ratnagiri, India	46.74	Tolerant	Patil *et al*., 2022
Ficus rumphii	Moradabad, India	45.10	Tolerant	Gupta *et al*., 2020
Mangifera indica	Metro Manila, Philippines	38.07	Tolerant	Sia Su *et al*., 2018
Intermediate Tolerance Species (APTI 15-30)				
Terminalia catappa,	Abakaliki, Nigeria	30.22	Intermediate	Ekene *et al*., 2019
Acer saccharinum	Debrecen, Hungary	23.50	Intermediate	Simon *et al*., 2021
Azadirachta indica	Sambalpur, India	17.94	Intermediate	Sahu *et al*., 2020
Azadirachta indica	Haridwar, India	15.51	Intermediate	Anjali *et al*., 2018
Sensitive Species (APTI < 15)				
Ficus benghalensis	Bathinda, India	13.54	Sensitive	Yadav and Pandey, 2020
Ficus elastic	Kathmandu, Nepal	8.25 ± 0.82	Sensitive	Ter *et al*., 2020
Grevillea robusta	Bahir Dar, Ethiopia	10.450±0.087	Sensitive	Tesfaye, 2022
Grevillea robusta	Himachal Pradesh, India	12.89	Sensitive	Sharma *et al*., 2019
Mangifera indica	Dhaka, Bangladesh	12.51	Sensitive	Shahrukh *et al*., 2023;
Polyalthia longifolia	Dhaka, Bangladesh	12.54	Sensitive	Sadia *et al*.,2019
Swietenia mahagoni	Dhaka, Bangladesh	12.27	Sensitive	Azam *et al*., 2023
				Azam *et al*., 2023

Factors Influencing the Tolerance of Urban Trees to Air Pollution

Differences in plant reactions to air pollution are mostly determined by morphological and physiological adaptations, especially in leaf features (Bui et al., 2023). This variation in species sensitivity is essential for pollution biomonitoring and the application of remediation strategies (Pandey et al., 2015).

Four key physiological parameters (leaf pH, relative water content (RWC), chlorophyll content, and ascorbic acid) form the biochemical foundation for the APTI (Molnár et al., 2020). Higher APTI values of plants demonstrate a stronger tolerance and mitigation potential to air pollutants (Kamble et al., 2021). RWC plays a role in maintaining physiological balance, as pollution-induced reduction in RWC has been demonstrated to reduce stomatal conductance and disrupt CO_2 absorption (Najib et al., 2022). In general, plants with higher RWC are more resilient to air pollution (Tak and Kakde, 2017).

Leaf micromorphology significantly influences PM accumulation. Compared to rough, hairy, or waxy foliar surfaces, smooth leaves hold less PM (Zhang et al., 2018; Corada et al., 2021). Leaf size and shape also influence deposition efficiency; smaller or needle-shaped leaves characterized by a high perimeter-to-surface area ratio facilitate PM capture via impaction and interception (Weerakkody et al., 2018; Chiam et al., 2019).

The efficacy of pollutant removal by trees is influenced by canopy structure, with dense, healthy foliage and greater tree heights increasing deposition potential and pollutant interception, thereby enhancing ecosystem services (Rodríguez-Santamaría et al., 2022; Liang and Huang, 2023). Another important factor is bark texture: rough bark acts as a long-term sink for particulate matter more than smooth bark (Ismail et al., 2016).

Removal efficiency is also influenced by species type. Evergreen and coniferous trees characterized by year-round foliage and finely divided leaves enable them to absorb more PM and NO_2 than deciduous trees (Kwak et al., 2019; Arnold, 2024).

SELECTING AND MANAGING TREES FOR AIR POLLUTION MITIGATION

Selection Standards for Tree Species with High Air Pollution Tolerance

Selecting tree species for pollution mitigation involves a multi-criteria analysis of physiological, ecological, and morphological characteristics that enhance pollutant removal and stress tolerance. APTI remains a crucial indicator for measuring biochemical resilience, where a higher value indicates greater tolerance. Platanus orientalis (APTI: 23.08) in Tehran showed excellent gaseous pollutant absorption (Rabiee et al., 2024), while *Mangifera indica* in Ethiopia (APTI: 16.44) captures $PM_{2.5}$ efficiently due to its high ascorbic acid content (Tesfaye, 2020). Generally, species with APTI >16 are suitable for greenbelt development, while species with APTI <11 are considered sensitive and serve as bio-indicators (Bui et al., 2022).

Morphological traits are equally important as selection standards. Textured leaf surfaces such as rough, hairy, or waxy improve PM deposition through interception and impaction mechanisms. For example, *Pinus densiflora*, which has needle-like foliage and epicuticular wax, accumulates 1.5–2.3 times more $PM_{2.5}$ than comparable broadleaf trees (Chen et al., 2017; Li et al., 2023). Canopy structure is another factor: *Pinus nigra* provides perennial filtration in temperate regions, while the dense and multi-layered canopy of *Ficus benghalensis* promotes PM_{10} deposition (Nowak et al., 2013; Arnold, 2024).

Evaluation of ecosystem services provides additional support for species selection. Trees like *Albizia saman* and other plants with high transpiration rates mitigate ozone production by reducing surrounding temperatures by 2–4°C (Yarnvudhi et al., 2022). High-biomass plants like *Azadirachta indica* can store up to 215 kilotons of CO_2 annually in American communities (Nowak et al., 2013). Although they remove pollutants quickly, fast-growing species like *Populus spp*. require greater maintenance than long-term, slower-growing species like *Quercus robur* (Boisvert-Marsh et al., 2020). The use of native tree species is strongly recommended for sustainable ecological adaptation and biodiversity protection.

Best Practices for Managing Urban Trees to Reduce Pollution

Effective tree management requires site-specific, flexible techniques that balance ecological performance and practical limitations. Pruning plays an essential role in maintaining the canopy's health and its efficiency to filter pollutants. Research shows that strategic selective pruning of less than 30% of live branches sustains photosynthetic capacity (Muscas et al., 2024). Excessive pruning, on the other hand, impairs tree health and decreases carbon sequestration by 15–20% (Ramirez et al., 2018).

Strategic spatial arrangement is a necessary factor in designing effective vegetative buffers. Particulate matter removal in mixed-species plantings is enhanced by vertical layering. Trees taller than 4 m with canopies wider than 10 m can reduce $PM_{2.5}$ levels near roadsides by up to 24% (Baldauf, 2017). Similarly, polycultures such as *Acer buergerianum* combined with understory shrubs boosted NO_2 removal in Seoul by 18% compared to monocultures (Brantley et al., 2014). While trees grown within 50 m of highways can intercept up to 60% of NO_x emissions, they require careful placement to avoid creating stagnant air zones (Baldauf, 2017). This highlights the critical importance of proximity to sources of pollution.

Soil health and irrigation have significant impact on tree viability and pollution uptake capacity. In arid areas, drought-tolerant species like *Terminalia catappa* reduce irrigation costs by 30% (Uka et al., 2019). Urban soils are often compacted and nutrient-deficient, requiring remediation through annual aeration and organic amendments like biochar to improve structure and pollution degradation capacity (Speak et al., 2020). Maintaining optimal soil pH (6.0–7.5) in industrial settings is a key strategy, as it increases microbial activity and accelerates the decomposition of contaminants such as benzene (Hanisch et al., 2020).

Tree rotation is recommended in high-pollution areas because prolonged exposure to particulate matter can reduce chlorophyll content by 20–40% (Li et al., 2023). Secondly, root systems cause damage to 12% of urban pavement annually; this requires the use of permeable pavement or root barriers as solutions (Hanisch et al., 2020). Precision forestry leveraging emerging technologies such as IoT-enabled canopy sensors provides real-time data on tree health and pollutant retention efficiency (Nersisyan et al., 2024).

CONCLUSION

Urban trees are essential nature-based solutions for reducing air pollution, a growing hazard to public health and ecological threats posed by urbanization and industrialization. Trees function as biological filters by depositing particulate matter on their leaves and bark and assimilating gaseous pollutants through their stomata. They also provide critical co-benefits, such as carbon sequestration, support for urban wildlife, and micro-climate cooling.

Strategic tree species selection is essential since the pollution removal effectiveness varies by species and environmental context. APTI, which is based on biochemical indicators (leaf pH, chlorophyll, ascorbic acid, and relative water content), provides a strong framework for identifying tolerant species. *Polyalthia longifolia*, *Gmelina arborea*, *Mangifera indica*, and *Azadirachta indica* (APTI >16) have been shown to be effective pollution sinks in megacities while, *Grevillea robusta* and certain *Ficus species* (APTI <11) serve more effective as bio-indicators. Recent research from Bangladesh indicates that prevalent roadside species such as *Mangifera indica*, *Polyalthia longifolia*, and *Swietenia mahagoni* are classified as sensitive (APTI <15), providing essential baseline data for urban forestry planning in South Asian cities.

Morphological traits, like rough or hairy leaf surfaces and dense canopies improve tree's potential pollution capture. To maximize benefits urban forestry programs must integrate APTI with local pollutant profiles, urban morphology, climate concerns, and biodiversity objectives while minimizing adverse effects such as allergenicity or airflow obstruction.

To maximize impact, a strategic urban forestry framework should include deploying high-APTI species in identified pollution hotspots, developing multi-layered green buffers near to emission sources, implementing adaptive management including precision pruning, soil health interventions, and integrating urban greening into wider environmental policy and sustainability planning.

Future studies should focus on:

- The long-term resilience of high-APTI species under climate stressors like heatwaves and drought;
- Developing optimization models that balance pollutant removal efficiency with cost and biodiversity outcomes;
- Investigating species-specific responses to complex urban pollutant mixtures, beyond isolated contaminants. Bottom of Form

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Author Contributions (CRediT Statement)

Alexander Terdoo Akighirga: Conceptualisation, original draft writing, project administration, visualisation, review and editing (final manuscript refinement and submission preparation). Adewale Matthew Taiwo: Writing, editing, and validation (proofreading and critical revision).

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The authors declare that they have no conflicting interests.

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