



REVIEW ARTICLE

Air pollution tolerance index and anticipated performance index-based approach for selecting species for developing urban green space: A global synthesis

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Abstract

Urban trees play a crucial role in regulating the urban climate and improving air quality; however, they are adversely affected by urban air pollution. Pollutants such as NO_x, SO_x, CO_x, O₃ and PM_{2.5}/PM₁₀ alter the physiological and biochemical status of urban trees, thereby facilitating their ability to mitigate air pollution. As a result, phytoremediation has become increasingly popular as a method of reducing air pollution. A literature search was conducted using electronic resources such as PubMed, ScienceDirect, Web of Science and Scopus, as well as Google Scholar's advanced search feature. Articles published between 2018 and 2025, pertaining to air pollution tolerance index (APTI) and anticipated performance index (API) world widely, were selected. Nine distinct studies conducted under various environmental conditions were included and it was observed that several studies support the conclusion that plants such as *Ficus* spp., *Artocarpus heterophyllus* Lam., *Bauhinia purpurea* L., *Eucalyptus citriodora* Hook., *Terminalia catappa* L., *Polyalthia longifolia* (Sonn.) Benth. & Hook.f. ex Thwaites and *Mangifera indica* L. perform excellent in polluted areas-specifically in urban, industrial and roadside environments. While various plant species range from very good to good performers, some are moderate, while others range from poor to very poor; furthermore, certain plants-such as *Nerium odorum* Salisb., *Spathodea campanulata* P.Beauv., *Ligustrum obtusifolium* Siebold & Zucc., *Calendula officinalis* L. and *Euphorbia milli* Des Moul. are not recommended based on their API grades. Therefore, plants with a high APTI and API value are more tolerant and act as a 'sink' (absorber); whereas plants with a low APTI and API value are less tolerant and can be used to assess air quality. With the aid of the APTI method, decisions regarding the selection of plant species can be made when developing 'green belts' around polluted or urban areas.

Keywords: air pollution; air pollution tolerance index; anticipated performance index; environment; urban green space

Introduction

Worldwide, unpolluted air is crucial for the association among the environment and the well-being of society, but the degradation of the composition of air brought on by the release of polluting agents through several sources into the atmosphere has become an internationally recognised health concern for both human health and the climate. Air quality degradation in urban setups makes it a significant issue in both developed and developing countries. Transportation has been recognised as a chief contributor to urban air quality degradation, alongside other factors. Due to high pollution, air quality along roads is continuously deteriorating because of several factors, including heavy traffic, aging cars, poor fuel, declining conditions of the road and inadequate programs for inspection and maintenance (1). The chief air pollutants originating from vehicle emissions are particulate matter, sulphur oxides (SO_x), carbon monoxide (CO), nitrogen oxides (NO_x), heavy metals and polyaromatic hydrocarbons (PAHs) (2, 3). In the end, these harmful substances are discharged into the atmosphere, lowering the standard of the air we breathe.

Indoor and outdoor air quality degradation has been shown to pose a detrimental effect on people in low-income nations and to contribute to a variety of potentially fatal health issues. Furthermore, as per World Health Organization (WHO), polluted air is “the silent killer,” which causes an estimated 7 million deaths annually (4). Similarly, in 2016, it was estimated that more than 95 % of people on the planet were breathing in unhealthy air (5). This resulted in 6.1 million deaths from prolonged exposure to tainted air, with China and India jointly accounting for more than half of all PM_{2.5}-related deaths worldwide (5). Epidemiological studies indicate that air pollution may lead to various human health conditions, including lung, heart, chronic respiratory symptoms, vascular, nerve-related diseases and ailments among the elderly globally (6, 7). Furthermore, exposure to polluted air from various sources is connected to a steady rise in lung cancer, heart disease, respiratory conditions and mortality worldwide (8). Therefore, research relating to the assessment of air pollution via biological aids, addressing the science of restoration of urban ecosystems, is highly pertinent since pollutants spread and have an adverse impact on the environment once they are released into the atmosphere.

Furthermore, extensive research has emerged worldwide on how air pollution affects fauna communities, with a particular emphasis on the relationships between vegetation and its surrounding environments. Plants are often more sensitive to environmental changes compared to other organisms, making them effective pointers of air standard (9). The major concern of the government is primary reduction of pollutant emissions and then focus on mitigating the adverse consequences of polluted air. To achieve this, the first line of defence is to deploy devices that control pollution at its source. Trees and vegetation act as natural barriers against vehicular emissions by influencing airflow, altering dispersion patterns and aiding in the deposition of pollutants. They contribute to the cycling of gases and nutrients, specifically carbon dioxide (CO₂), making them essential for monitoring and maintaining ecological balance (10). Vegetation, characterised by its extensive leaf area, functions as a natural sink for air pollutants (11); therefore, it is a widely recognised approach to improving air quality in developed countries (12). This has led to increased attention to the importance of vegetation in reducing air pollution (13). Some plant species survive in polluted environments by altering their chlorophyll content (Chl), ascorbic acid levels, pH of leaf and relative water content (RWC) (14, 15). These four factors collectively form air pollution tolerance index (APTI), which evaluates the sensitivity of plants or the degree of tolerance to air born pollutants (16). APTI is a natural property of plants that allows them to endure pollution stress (17). Vegetation that has greater APTI values is highly resistant to air pollution, making it a good choice for sinking contaminants. Plants containing low APTI range are vulnerable to air born pollution and therefore serve as reliable biological markers (18, 19). Plants that show sensitivity to the increase in pollution level of atmosphere serve as bio-indicators and acts as indicating bodies of the quality of the air surrounding them. On the other hand, tolerant species act as pollutant deteriorate and are ideal for creating green belts in cities (14, 20).

Researchers have done a lot of research on both the APTI and anticipated performance index (API) of plants to reduce air pollution. Therefore, it is necessary to combine these two indices to understand the tolerance level of trees in a certain polluted environment and to develop sustainable green eco-management. However, only a few studies conducted in different settings report such combined analysis. This review assesses the APTI and API of common native plants to determine their tolerance levels for sustainable eco-management, aiming to identify plants that effectively mitigate air quality degradation across varying environments. The study promotes increasing the presence of native plants capable of pollutants absorption to enhance air quality through sustainable practices (21).

Air pollution and climate change in urban settlements: Global concern

Nowadays, rapidly growing cities are most threatened by air pollution and climate change. Sustainable development and climate action pose significant problems for developing nations like India, which are shifting from primarily rural to urban areas (22). The health of people and plants is already seriously threatened by the problem of air quality degradation. The major causes of air pollution in urban areas are particulate matter, gaseous pollutants, construction emissions, industrial emissions and vehicle emissions. In urban areas, indoor and outdoor pollution can be mainly due to primary or secondary air pollutants. Directly emitted primary air pollutants

include particulate matter {PM_{2.5}, PM₁₀, respirable particulate matter (RPM), suspended particulate matter (SPM)}, SO_x, CO, NO_x, (Table 1), dust particles and ammonia; however, the secondary air pollutants contain ozone, peroxyacyl nitrates (PANs), smog and more (22). Urbanisation contributes to climate change by reducing agricultural land, fallow land and vegetation areas. A prominent cause of change in climate is the emission of greenhouse gases (GHGs), which alter the concentrations of several gases in the atmosphere. Additionally, scientists are carefully examining how water vapor affects the climate (22, 23). Similarly, because black carbon has a strong ability to absorb incoming solar radiation, scientists are considering how it contributes to environmental change. The consequences of climate change on the temperature, rainfall patterns and solar radiation of plants are widely recognised. The link between air pollution, climate change and urbanization has been suggested because air pollutants such as aerosols have direct effects on Earth's climate through absorption and scattering, as well as indirect effects through changes in cloud properties and radiation transfer processes (22). Insufficient infrastructure and unplanned as well as mismanaged transportation, poorly organised industrial distribution and badly constructed roads are making it challenging for urban growth to keep up. Consequently, these factors have led to a rise in pollution levels (24–30).

Sources of air pollution in urban settlements

Emissions from industrial areas

Industry emits more greenhouse gases (GHGs) than other end-use sectors and these emissions are rising rapidly. About 47 % of energy-related carbon dioxide emissions come from the global industrial sector and large amounts of additional GHGs are released as industrial process gases (31). The energy consumption of the industries accounts for approximately one-third of carbon dioxide (CO₂) emissions worldwide. Energy-related emissions from the combustion of fossil fuel and process related emissions are the two main ways that industrial sources contribute to GHGs emissions. (a) CO₂ from the production of lime and cement (calcination process), steel (cock and pig iron production), aluminum (oxidation and electrodes), hydrogen (refineries and the chemical industry) and ammonia (fertilisers and chemicals), (b) halocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) utilised as solvents, coolants, aerosol propellants, refrigerants and foam expanders (29), (c) CH₄ from miscellaneous industrial processes (iron and steel, oil refining, ammonia and hydrogen) (32). (d) NO₂ from nitric acid and adipic acid (nylon) production (29) (e) carbon tetrafluoride or CFCs-14 (CF₄) and hexafluoroethylene or CFC-16 (C₂F₆), from aluminium production (electrolysis) (32).

Vehicular pollution

Automobile emissions, in particular, account for about two-thirds of air pollution in urban areas. The major pollutants released by automobiles such as lead (Pb), CO, NO_x, Sulphur oxides (SO), HC and suspended particulate matter (SPM) have damaging effects on environment and human health (33). The gases produced by gasoline engines are a mixture of unburned hydrocarbons (HC), nitrogen oxides (NO_x) and carbon monoxide (CO). Emissions from diesel vehicles are characterised by relatively low levels of CO and unburned hydrocarbons, which are compensated by higher levels of CO₂ and NO_x. Particulate matter (PM) emissions from diesel vehicles are 7.5 times greater than emissions from comparable gasoline vehicles.

Table 1. Region-wise acceptable limits for urban air pollution

Air quality standard	NO ₂ (Nitrogen dioxide)	CO (Carbon monoxide)	O ₃ ozone	SO ₂ (Sulphur dioxide)	PM _{2.5}	PM ₁₀	References
WHO	Annual average (40 µg-3) Number of exceedances of 1 hr average (200 µg-3)	Maximum daily 8 hr (10000 µg-3)	Maximum daily count over 8-hr average (100 µg m-3)	24-hr average number of exceedances (20 µg-3)	Average per year (10 µg-3) Number of exceedances from the 24 hr average (25 µg-3)	Annual average (20 µg-3) Total exceedances over 24 hr average (50 µg-3)	(25)
Europe	Yearly average (40 µg-3) the number of times the 1 hr average (200 µg-3) was exceeded	Maximum 8 hr per day (10000 µg-3)	The number of times the maximum daily 8 hr average (120 µg-3) was exceeded	The total count of exceedances of 24 hr average (125 µg-3)	Yearly average (25 µg-3)	Average per year (40 µg-3) 24 hr average exceedances number (50µg-3)	(25)
India	Mean per year (53 ppm) number of 1 hr average (100 ppb) exceedances	8 hr per day max (9 ppm)	Number of daily 8-hr mean exceedances (0.070 ppm)	Number of 1 h mean exceedances (75 ppb)	Average per year (9 µg-3) number of exceedances from the 24 h average (35 µg-3)	Total number of exceedances from the 24 average (150 µg-3)	(26)
Mexico	Yearly average (0.021 ppm) number of 1 hr mean exceedances (0.0106 ppm) total exceedances of the 24 hr average (0.040 ppm)	8 hr per day maximum (9 ppm)	Number of daily 8 h mean exceedances of the maximum (0.065 ppm)	Number of 1 hr mean exceedances (0.075 ppm) the number of exceedances from the 24 hr average (0.040 ppm)	Number of exceedances of the 24 h average (41 µg-3) annual mean (10 µg-3)	Average per year (36 µg-3) the number of exceedances from the 24 hr average (10 µg-3)	(27)
Japan	The count of exceedances of the 24 hr mean (60 ppb)	-	The number of 1 h mean exceedances (60ppb)	-	Average for the year (15 µg-3) the number of times the 24 h average (35 µg-3) was exceeded	24 h mean exceedances number (100 µg-3)	(28)
EU	Mean per year (53 ppm) number of 1 hr mean (100 ppb) exceedances	Maximum 8 hr per day (9ppm)	Number of daily 8 h mean exceedances (0.070 ppm)	Number of 1 h mean exceedances (75ppb)	Average per year (9 µg-3) numbers of exceedances from the 24 h average (35 µg-3)	The number of times the 24 hr average (150 µg-3) was exceeded	(29)
China	Yearly average (40 µg-3) count of exceedances from the 24 hr average (80 µg-3) 1 h mean exceedances number (200 µg-3)	Maximum of 8 hrs per day (4000 µg-3)	The number of times the daily 8 h mean (100 µg-3) is exceeded	Average for the year (20 µg-3) the number of times the 24 hr average (50 µg-3) was exceeded the number of exceedances from the 1 h mean (150 µg-3)	Average for the year (15 µg-3) the number of times the 24 hr average (35 µg-3) was exceeded	Annually (40 µg-3) the number of times the 24 h average (50 µg-3) was exceeded	(30)

Construction emission

The construction industry interacts with urbanisation by providing its materials (34). According to reports, the construction sector is the primary source of CO₂ emissions (34). Furthermore, increasing urbanisation will increase demand for infrastructure and buildings, which will increase CO₂ emission from the construction industry in the future (35, 36), construction related activities including the development of infrastructure, building and road in urban areas (36) often entail the use of equipment, materials and energy sources that produce GHGs and pollutants. The GHGs may be emitted during the energy-intensive production of materials, which are used for construction, such as cement, bricks and steel. Waste from construction is abundant and includes both construction debris and discarded materials. During the disposal of this waste, especially if it is burned in the open, pollutants may be emitted into the atmosphere.

Particulate matter and gaseous pollutants

Emissions from heavy vehicles usually contain PM, typically ranging between 1.9 µm and 10 µm in size. Diesel soot particles are released into the atmosphere as both liquid and solid particles (37) and the surfaces of these particles allow them to absorb many chemical substances. They are therefore more harmful to plants. Hydrophilic hydrocarbons are the main component of PM. Another component of ambient particulate matter is black carbon (38) that is made up of SO₄²⁻, NO₃⁻, NH₄⁺ (39). Additionally, aerosols from chemical reactions involving gases like SO₂, NO_x and VOC can form PM_{2.5} in the atmosphere (33).

Phytoremediation as a sustainable strategy for air pollution reduction

Research in air pollution science highlights the impact of air pollutants on the biochemical, physiological and morphological traits of plants. Recognised as the “lungs of cities”, plants act as natural bio-filters that help reduce air pollution, with urban trees serving as effective bio-monitors and bio-indicators of air quality (40). By absorbing gases and particles, plants contribute significantly to improving air quality, depending on the level of tolerance or sensitivity of the plant (41, 42). Phytoremediation is

currently being explored as an alternative environmentally friendly technology (43, 44). Some researchers have conducted studies on the distribution and elemental composition of dust particles absorbed on leaves and their tissues (43, 45, 46). Research on roadside deposition around the world has shown that large amounts of pollutants accumulate on plants in China (47) and India (46), highlighting high concentrations of PM, gaseous pollutants and heavy metals in plants. Several studies have suggested the treatment of air pollutants by various plant parts using various phytoremediation techniques as a new sustainable environmental health method (48, 49), as plants can absorb air pollutants without any harm. However, different behavioural patterns and tolerances affect how plants react to and tolerate air pollutants. The APTI is used globally to determine the sensitivity, response and tolerance of plants to air pollutants based on biochemical parameters only and to develop suitable environmental indicators and mitigation strategies (45, 50). Additionally, to reduce air pollution through greenbelt development in a given area, the anticipated performance index (API) should also be taken into consideration with the help of several socio-economic characteristics of the plants (51). When assessing the capacity of important species to eliminate pollutants from the atmosphere, API is a better metric than APTI.

Phytoremediation techniques

Environmental pollutants can be removed using the following method. Various phytoremediation methods, including rhizofiltration, phytodegradation, phytostimulation, phytovolatilisation, phytoextraction and phytostabilisation (42, 51–53) are depicted in Fig. 1.

- Process of Rhizofiltration: In brief, rhizofiltration is used to filter contaminated groundwater. Thus, contaminants (toxins or excess nutrients) from surface or groundwater are absorbed and stored by plant roots (54). Like the phytoextraction method, plants are harvested when the saturation limit of contaminants is reached (8). Implementing this treatment method further requires a deep comprehension of the interaction between plants and water that control the removal of a particular metal from contaminated water sources.

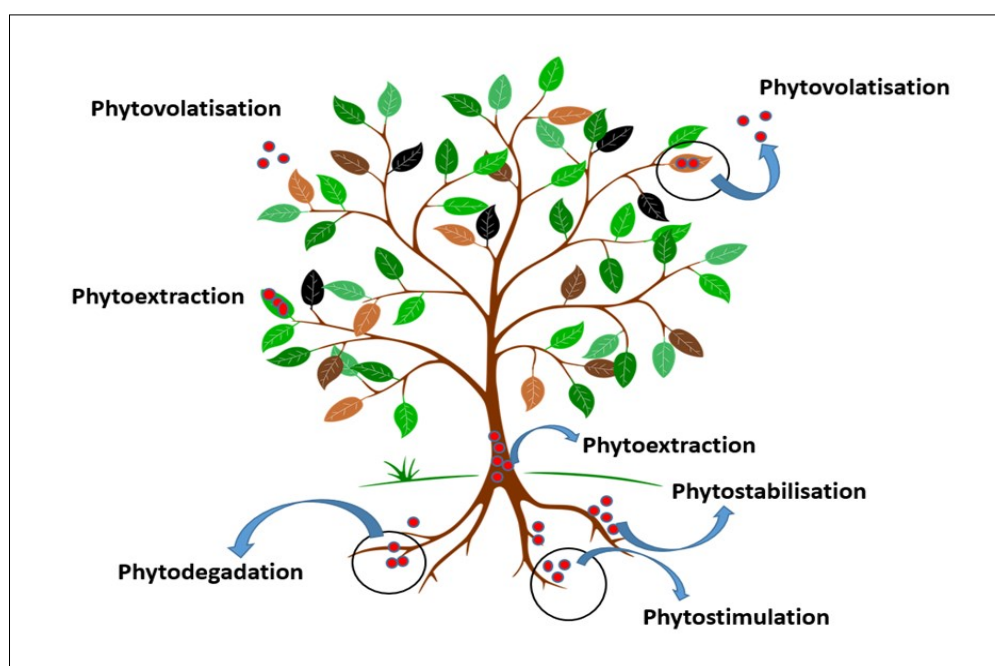


Fig. 1. Diagrammatic representation of phytoremediation methods.

- b. **Phytodegradation:** The process by which toxic pollutants are broken down in plant tissues using their enzymes after being absorbed and stored for some time is known as phytodegradation or phytotransformation (54, 55). Plants and associated rhizosphere microorganisms are used in remediation processes to eliminate, limit or transform harmful substances or surplus nutrients found in soil, sediment and groundwater, among other places (55). Plants can reduce the toxicity of air pollutants by converting organic pollutants into more water-soluble molecules. Endocytic bacteria help in this by colonising the internal tissues of plants without harming their host (plant) (42, 56). According to previous researchers, phytoremediation techniques can reduce persistent organic pollutants (POPs) (57).
- c. **Phytoextraction process:** When plants absorb water from the soil and surroundings, they accumulate or absorb pollutants, which then get stored in their leaves, roots and shoots but do not dissolve. Even at relatively low concentrations, this technique can be harmful to organisms and is often used on soils contaminated with metals (54). According to earlier reports, soil had high concentrations of lead (Pb) due to continuous exposure to air pollution from vehicle exhaust and the phytoextraction method was used to remove lead from contaminated soil (58).
- d. **Phytovolatilisation:** This process involves plants absorbing pollutants from the soil, converting them into volatile forms and releasing them into the atmosphere (54). It indicates that pollutants present in water absorbed by the plant either pass through the plant or undergo transformation before being released into the atmosphere as vapour or evaporation. In the case of air pollution, phytovolatilisation occurs when pollutants are diffused into the phyllosphere of plants, where they may become less toxic before being converted into volatile elements in the atmosphere (59).
- e. The use of plants to stimulate rhizodegradation, another name for phytostimulation, is the process by which plants release specific chemicals into groundwater or soil through their roots. These substances enhance the ability of microorganisms to rapidly decompose and remove pollutants (60). This process is essential to rhizoremediation technology, which effectively removes organic pollutants from soil by combining phytoremediation and bioaugmentation (42).
- f. **Phytostabilisation** is the process by which pollutants present in soil are immobilised in the root zone of a plant through precipitation, absorption by roots, or accumulation and absorption by roots. This process is used to treat sludge, sediments and soils (60). Plants absorb particulate matter and CO₂ through their leaves and shoots, which accumulate in the phyllosphere prior to phytostabilisation and immobilisation in the plant's wax layers (42, 53).

Leaf biochemical and physiological factors, which are mainly affected by air pollution, form the basis for air pollution tolerance index estimation

The capacity of different plants to withstand stress is mostly determined by their morphology and physiological traits. Temperature, humidity, salinity, pH, oxygen levels and soil chemistry are just a few of the many biotic, abiotic and physical

factors that affect plant growth. It is believed that plants high in ascorbic acid are resilient to air pollution. Plants with higher chlorophyll levels may be more resilient to pollutants since chlorophyll is an essential stress chemical. Because plant features change based on the range of environmental situations, various species exhibit varied levels of endurance in different regions.

Ascorbic acid

The bio-antioxidant and strong reductant agent ascorbic acid (AsA) makes a substantial contribution to the improvement of plant resistance to air pollution. Due to scavenging reactive oxygen species (ROS) oxidising agents as hydroperoxide, superoxide anion and hydroxyl free radical, it shields chloroplasts from oxidative stress brought on by sulphur dioxide, protecting chlorophyll and the enzymes that are involved in the carbon dioxide fixation cycle (61). The AsA strengthens plants' antioxidant defence system by stabilising cell membranes during pollution stress, influencing enzyme performance and encouraging α -tocopherol rejuvenation "vitamin E" (62). Numerous physiological or biochemical cellular functions depend on it (63). Elevated levels of ascorbic acid in plant leaves are correlated with enhanced tolerance to air pollution, as ascorbic acid alleviates the detrimental effects of oxidative stress induced by pollutants (64). Reduced leaf ascorbic acid concentration can result from environmental variables such as mineral inadequacies, air pollution and soil contamination, which boost the buildup of ROS (65, 66). On the other hand, higher levels of AsA make the plant more resistant to unfavourable conditions outside, which makes it a crucial biochemical indicator for determining a tree species' tolerance to air pollution (67).

Relative water content

The water status of plants is indicated by the relative water content (RWC). It serves as a tool for determining the water content of leaves and tissues in relation to their full turgidity. It is a crucial sign of a plant's capacity to hold onto water, particularly under stressful situations where water loss rates are usually high, like when exposed to air pollution, by sustaining vital functions like transpiration, photosynthesis, stomatal conductance, growth, respiration and leaf turgor, maintain a high RWC acids plants in maintain their physiological balance (68). Since leaf water status has a direct impact on this physiological process, RWC is commonly used to assess how plants respond to environmental stressors like air pollution. High RWC indicates greater water-retention capacity, which helps plants maintain optimal physiological function and more effectively manage pollution-induced stress.

pH of leaf extract

The pH of the leaf extract has a major impact on a plant's capacity to endure air quality degradation. In general, plants that have lower leaf pH are more vulnerable to pollution stress, whereas plants with a pH of about 7 show better resistance (69). Increases in hexose sugar conversion efficiency to ascorbic acid are linked to higher leaf pH, which reinforces the plant's antioxidant defensive mechanism (70). However, a lower pH in leaves is associated with a greater vulnerability to air pollutants, which may have an adverse effect on photosynthesis efficiency. Taken together, maintaining suitable pH is important to promote plant growth and survival of plants in contaminated environments due to the strong dependence on photosynthesis on leaves pH (19).

Total chlorophyll content

Since photosynthetic pigment promotes the pace at which biomass grows, it serves as a crucial indication of photosynthetic activity and plant production. The concentration of chlorophyll in plants is affected by many biotic and abiotic factors such as species, ages of leaves, pollution, etc. (71). Some pollutants can increase the total chlorophyll concentration, while others can decrease depending on the trees' response to environmental stressors (72). This is often linked to a greater amount of total chlorophyll, which enables certain photosynthetic processes to remain effective in a contaminated environment. High chlorophyll content has favoured resistance to air pollution and many plant species from diverse geographical origins have illustrated this tolerance level (73). It is thought that species with greater concentrations of chlorophyll have developed antioxidants to fight oxidative damage brought on by pollution. However ROS are produced by chloroplast in response to environmental stressors such as pollution and water deficit which decrease the content of chlorophyll (71). Soil, water and air all had an impact on changes in leaf biomass pigments, including ascorbic acid and chlorophyll. Measuring chlorophyll, the main photoreceptor in photosynthesis, can help assess the extent to which air pollution affects plant metabolism. Concentration of chlorophyll has a direct effect on plant development, As the chlorophyll content decreases it adversely impacts the plant growth, this fact reaffirms chlorophyll is a crucial scientific metric for evaluating pollution resistance and environmental stress.

Indices of air pollution

Air pollution tolerance index

Landscape professionals use the APTI index to identify plant species that are resistant to air pollution and to measure their tolerance to air pollutants. The RWC, total chlorophyll content (TChl), AsA content and leaf pH are the most important biochemical factors that determine a plant species' tolerance to air pollutants. Previous researchers suggested that plant species having higher APTI values are more tolerant to pollution (74). The following formula was used to calculate the APTI value (Table 2 and 3).

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

Where A = ascorbic acid (mg/g),

T = Total chlorophyll (mg/g)

P = pH of leaf extract

R = Relative water content (%)

Anticipated performance index

The APTI value is used to calculate the API, which considers both socio-economic and biological factors (Table 4). These include the tree's habitat, its size, the structure of tree canopy (irregularly rounded, open, semi-dense or spreading dense), plant type (deciduous or evergreen), leaf layer (size, texture, stiffness), use and socio-economic value. This makes it easier to select species for

afforestation, reforestation and establishment of green belts, keeping aesthetic and recreational considerations in mind (84, 85). Apart from the API, the Air quality impact index, is a newly proposed index, which considers additional factors such as pollen allergen effect, aerodynamic characteristics, structure of the foliage, absorption capacity of pollutant, tolerance level of pollution, ozone and aerosol precursors or emissions, etc. Compared to the API, this index provides a more in-depth assessment of how urban trees affect air quality (84). The AQII is a comparatively new indices that suggests a more in-depth approach than the API for making decisions about tree planting in urban areas. The API analysis was performed using the standards that were established by previous researchers (86) (Table 5).

Analysis of air pollution tolerance index and anticipated performance index

In this article 9 studies from different climatic zones like industrial area, urban area and roadside areas had been studied to evaluate the air pollution tolerance level of studied plant species in that study. The APTI values of any plants based on four biochemical parameters pH, relative water content, ascorbic acid and chlorophyll content. In polluted area the value of ascorbic acid is higher than unpolluted area where as the value of relative water content is low. The value of pH is low that is acidic due to this the value of chlorophyll content also get low. According to values of these four parameters APTI values are decided of any plant which conforms its tolerance level in a particular settings. APTI values of plants are higher in polluted areas like roadside and industrial than in less polluted like urban areas (87).

Table 3 presents the APTI values from nine different studies conducted under various climatic conditions. In earlier reports, 12 plant species in an industrial setting and reported APTI values ranging from 18.65 (*Ficus benghalensis* L.) to 8.65 (*Nerium odorum* Salisb.). Based on the API, *F. benghalensis* received an API grade of 6 and demonstrated excellent performance (Table 6) (75). Conversely, 17 plant species were examined in an industrial zone, where APTI values were recorded ranging from a maximum of 9.8 (*Hibiscus rosa-sinensis* L.) to a minimum of 6.6 (*Duranta repens* L.); thus, all the studied plants could be utilised as 'bioindicators' (76). In another study, 11 plant species were planted in an urban environment; it was found that the highest APTI value was 8.80 (*Caesalpinia pulcherrima* (L.) Sw.) and the lowest was 2.71 (*Nerium indicum* Mill.). All the plants studied were found to be sensitive and serve as bioindicators (77). In an urban area, 11 species were examined and the maximum APTI value was identified as 9.52 (*Pinus densiflora* Siebold & Zucc.) while the minimum was 7.11 (*Cuscuta chinensis* Lam.); notably, *P. densiflora* received an API grade of 4 and was selected as a good performer (78). Similarly, in a study conducted in an industrial setting, APTI values for 17 plant species were recorded ranging from 19.04 (*Cassia fistula* L.) to 13.69 (*Terminalia catappa* L.). In this study, *Ficus benghalensis* L. attained an API grade of 7 and demonstrated the best performance, while *Artocarpus heterophyllus* Lam., *Bauhinia purpurea* L., *Eucalyptus citriodora* Hook., *T. catappa* and *Polyalthia longifolia* (Sonn.) Thwaites. also achieved the second-highest API grade (6), indicating excellent performance; other plants exhibited performance ranging from good to moderate (79). In another study, APTI values were calculated for 9 plant species in an urban area; the highest recorded APTI value was 29.34 (*Ficus religiosa* L.), classified as tolerant, while the lowest value was

Table 2. The tolerance level of plants for APTI (74)

Range of APTI	Level of tolerance
>24	Tolerance
20-24	Intermediate
15-19	Sensitive
≤14	Very sensitive

Table 3. APTI differences among various plant species in different climatic zones

Sl. No.	Plant name	APTI values	Study area	References
1	<i>Polyalthia longifolia</i> Sonn.Thwaites	15.68	Industrial area	(75)
2	<i>Ficus benghalensis</i> L.	18.65	Industrial area	(75)
3	<i>Adina cordifolia</i> Hook.f.	12.05	Industrial area	(75)
4	<i>Alstonia scholaris</i> (L.) R.Br.	9.01	Industrial area	(75)
5	<i>Michelia champaca</i> L.	13.26	Industrial area	(75)
6	<i>Azadirachta indica</i> A.Juss.	12.98	Industrial area	(75)
7	<i>Cassia fistula</i> L.	13.65	Industrial area	(75)
8	<i>Cassia siamea</i> Lamk.	12.05	Industrial area	(75)
9	<i>Cascabela thevetia</i> L.	9.54	Industrial area	(75)
10	<i>Ficus religiosa</i> L.	14.42	Industrial area	(75)
11	<i>Spathodea campanulata</i> P.Beauv.	11.46	Industrial area	(75)
12	<i>Nerium odorum</i> Salisb.	8.65	Industrial area	(75)
13	<i>Alstonia scholaris</i> (L.) R.Br.	9.4	Industrial area	(76)
14	<i>Bougainvillea spectabilis</i> Willd.	9.6	Industrial area	(76)
15	<i>Lagerstroemia indica</i> L.	8.6	Industrial area	(76)
16	<i>Cassia fistula</i> L.	8.3	Industrial area	(76)
17	<i>Delonix regia</i> (Bojer ex Hook.) Raf.	8.1	Industrial area	(76)
18	<i>Melia azedarach</i> L.	7.5	Industrial area	(76)
19	<i>Duranta repens</i> L.	6.6	Industrial area	(76)
20	<i>Ficus benjamina</i> L.	8.3	Industrial area	(76)
21	<i>Morus nigra</i> L.	9.5	Industrial area	(76)
22	<i>Ficus religiosa</i> L.	8.7	Industrial area	(76)
23	<i>Murraya exotica</i> L.	9.0	Industrial area	(76)
24	<i>Tecoma stans</i> (L.) Juss. ex Kunth	7.7	Industrial area	(76)
25	<i>Nerium oleander</i> L.	9.0	Industrial area	(76)
26	<i>Syzygium cumini</i> (L.) Skeels	8.6	Industrial area	(76)
27	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	8.1	Industrial area	(76)
28	<i>Hibiscus rosa-sinensis</i> L.	9.8	Industrial area	(76)
29	<i>Jatropha integerrima</i> Jacq.	8.9	Industrial area	(76)
30	<i>Polyalthia longifolia</i> (Sonn.) Benth. & Hook.f. ex Thwaites.	6.16	Urban area	(77)
31	<i>Nerium indicum</i> Mill.	2.71	Urban area	(77)
32	<i>Clerodendrum inerme</i> (L.) Gaertn.	5.23	Urban area	(77)
33	<i>Peltophorum pterocarpum</i> (DC.) Backer ex K.Heyne	3.09	Urban area	(77)
34	<i>Croton variegatum</i> L.	6.96	Urban area	(77)
35	<i>Caesalpinia pulcherrima</i> (L.) Sw.	8.80	Urban area	(77)
36	<i>Caryota urens</i> L.	5.47	Urban area	(77)
37	<i>Plumeria alba</i> L.	4.92	Urban area	(77)
38	<i>Eucalyptus lanceolatus</i> L.	5.67	Urban area	(77)
39	<i>Callistemon viminalis</i> (Sol. ex Gaertn.) G.Don	6.21	Urban area	(77)
40	<i>Azadirachta indica</i> A.Juss.	6.83	Urban area	(77)
41	<i>Juniperus chinensis</i> L.	7.72	Urban area	(78)
42	<i>Ligustrum obtusifolium</i> Siebold & Zucc.	7.70	Urban area	(78)
43	<i>Pinus parviflora</i> Siebold & Zucc.	8.77	Urban area	(78)
44	<i>Acer triflorum</i> Kom.	8.38	Urban area	(78)
45	<i>Pinus densiflora</i> Siebold & Zucc.	9.52	Urban area	(78)
46	<i>Calendula officinalis</i> L.	7.95	Urban area	(78)
47	<i>Abies holophylla</i> Maxim.	8.85	Urban area	(78)
48	<i>Cuscuta chinensis</i> Lam.	7.11	Urban area	(78)
49	<i>Picea abies</i> (L.) H.Karst.	8.09	Urban area	(78)
50	<i>Pinus strobus</i> L.	8.12	Urban area	(78)
51	<i>Aesculus turbinata</i> Blume	7.75	Urban area	(78)
52	<i>Terminalia catappa</i> L.	13.69	Industrial area	(79)
53	<i>Acacia auriculiformis</i> A.Cunn. ex Benth.	17.74	Industrial area	(79)
54	<i>Tamarindus indica</i> L.	14.96	Industrial area	(79)
55	<i>Albizia lebbbeck</i> (L.) Benth.	17.64	Industrial area	(79)

56	<i>Syzygium cumini</i> (L.) Skeels	17.48	Industrial area	(79)
57	<i>Artocarpus heterophyllus</i> Lam.	16.53	Industrial area	(79)
58	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	17.31	Industrial area	(79)
59	<i>Azadirachta indica</i> A.Juss.	17.24	Industrial area	(79)
60	<i>Pongamia pinnata</i> (L.) Pierre	17.29	Industrial area	(79)
61	<i>Bauhinia purpurea</i> L.	18.22	Industrial area	(79)
62	<i>Nerium oleander</i> L.	17.07	Industrial area	(79)
63	<i>Cassia fistula</i> L.	19.04	Industrial area	(79)
64	<i>Mimusops elengi</i> L.	15.48	Industrial area	(79)
65	<i>Delonix regia</i> (Bojer ex Hook.) Raf.	18.42	Industrial area	(79)
66	<i>Mangifera indica</i> L.	14.63	Industrial area	(79)
67	<i>Eucalyptus citriodora</i> Hook.	15.72	Industrial area	(79)
68	<i>Ficus benghalensis</i> L.	13.81	Industrial area	(79)
69	<i>Terminalia arjuna</i> (Roxb. ex DC.) Wight & Arn.	15.29	Urban area	(80)
70	<i>Azadirachta indica</i> A.Juss.	15.84	Urban area	(80)
71	<i>Tabernaemontana divaricata</i> (L.) R.Br. ex Roem. & Schult.	20.88	Urban area	(80)
72	<i>Bougainvillea spectabilis</i> Willd.	16.0	Urban area	(80)
73	<i>Saraca asoca</i> (Roxb.) Willd.	21.99	Urban area	(80)
74	<i>Ficus benghalensis</i> L.	26.40	Urban area	(80)
75	<i>Plumeria rubra</i> L.	25.4	Urban area	(80)
76	<i>Nerium indicum</i> Mill.	17.8	Urban area	(80)
77	<i>Ficus religiosa</i> L.	29.34	Urban area	(80)
78	<i>Swietenia macrophylla</i> King	5.62	Industrial area	(81)
79	<i>Mimusops elengi</i> L.	5.93	Industrial area	(81)
80	<i>Filicium decipiens</i> (Wight & Arn.) Thwaites	5.08	Industrial area	(81)
81	<i>Eucalyptus globulus</i> Labill.	7.854	Roadside	(82)
82	<i>Shorea robusta</i> C.F.Gaertn.	7.896	Roadside	(82)
83	<i>Mallotus philippensis</i> (Lam.) Müll.Arg.	7.811	Roadside	(82)
84	<i>Ficus roxburghii</i> Wall.	7.869	Roadside	(82)
85	<i>Syzygium cumini</i> L.	9.17	Roadside	(83)
86	<i>Alstonia scholaris</i> L.	10.60	Roadside	(83)
87	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	9.40	Roadside	(83)
88	<i>Azadirachta indica</i> A.Juss.	9.26	Roadside	(83)
89	<i>Morus alba</i> L.	9.78	Roadside	(83)
90	<i>Bougainvillea spectabilis</i> Willd.	7.25	Roadside	(83)
91	<i>Mimusops elengi</i> L.	10.27	Roadside	(83)
92	<i>Conocarpus erectus</i> L.	8.73	Roadside	(83)
93	<i>Mangifera indica</i> L.	17.88	Roadside	(83)
94	<i>Eucalyptus citriodora</i> Hook.	7.23	Roadside	(83)
95	<i>Hibiscus rosa-sinensis</i> L.	12.28	Roadside	(83)
96	<i>Euphorbia milii</i> Des Moul.	11.08	Roadside	(83)
97	<i>Ficus religiosa</i> L.	9.01	Roadside	(83)
98	<i>Ficus benghalensis</i> L.	13.15	Roadside	(83)
99	<i>Ficus benjamina</i> L.	9.23	Roadside	(83)

Table 4. The plant species are classified according to their biological characteristics, socio-economic importance and degree of tolerance as measured by the air pollution tolerance index (APTI)

Grading characters		Pattern assessment	Allotted Grade
(1) Tolerance	APTI	9.0–12.0	+
		12.1–15.0	++
		15.1–18.0	+++
		18.1–21.0	++++
		21.1–24.0	+++++
		24.1–27.0	++++++
	Plant habit	Small	-
Medium		+	
(2) biological and socioeconomic	Structure of canopy	Large	++
		Asymmetrical/Sparse/spherical	-
		Spreading Crown/open/semi-dense	+
		Spreading dense	++
	Plant type	Deciduous	-
		Evergreen	+
	Size	Small	-
		Medium	+
	(3) Laminar structure	Texture	Large
Smooth			-
Hardiness		Coriaceous	+
		Delicate	-
Economic importance		Hard	+
		Not more than 3 usages	-
		3–4 uses	+
	At least 5 or more	++	

(+) Sign represent the presence of character while (–) sign shows the absence of character. Maximum grades are 16.

Table 5. Evaluation and classification of plant species using the anticipated performance index

Grade	Score (%)	Assessment category
0	Up to 30	Not recommended
1	31-40	Very poor
2	41-50	Poor
3	51-60	Moderate
4	61-70	Good
5	71-80	Very good
6	81-90	Excellent
7	91-100	Best

Table 6. API evaluation of various plant species in different environmental conditions

S.N.	Name of Plant	APTI	TH	CS	TT	L	S	T	EI	H	TP	GA % scoring	API grade	References
1	<i>Cascabela thevetia</i> L.	+	-	+	+	+	+	+	+	+	7	41.17	2	
2	<i>Michelia champaca</i> L.	++	+	+	+	++	+	-	+	+	9	52.94	3	
3	<i>Alstonia scholaris</i> (L.) R.Br.	+	+	+	+	-	-	+	+	+	6	35.29	1	
4	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	++	+	+	+	++	+	+	+	+	10	58.82	3	
5	<i>Nerium odorum</i> Salisb.	+	+	+	-	+	+	-	-	-	5	29.41	0	
6	<i>Azadirachta indica</i> A. Juss	+	++	++	-	-	-	++	+	+	8	47.06	2	
7	<i>Cassia siamea</i> Lamk.	++	+	+	+	+	+	+	+	+	9	52.94	3	
8	<i>Ficus religiosa</i>	++	++	++	+	++	+	+	+	+	12	70.59	5	
9	<i>Adina cordifolia</i> Hook. f.	+	++	++	-	++	+	+	+	+	10	58.82	3	
10	<i>Ficus benghalensis</i>	++++	++	++	+	++	+	+	+	+	14	82.35	6	
11	<i>Spathodea campanulata</i> P.Beauv.	+	+	-	+	+	-	-	-	-	4	23.53	0	
12	<i>Cassia fistula</i> L.	++	+	+	-	+	-	+	+	+	7	41.18	2	(75)
13	<i>Ligustrum obtusifolium</i> Siebold & Zucc.	+	-	-	-	+	-	-	-	-	2	12.5	0	
14	<i>Juniperus chinensis</i> L.	+	++	+	+	-	+	+	+	+	8	50	2	
15	<i>Acer triflorum</i> Kom.	++	+	+	-	+	+	-	+	+	7	43.8	2	
16	<i>Pinus parviflora</i> Siebold & Zucc.	++	++	++	+	-	+	-	+	+	9	56.3	3	
17	<i>Calendula officinalis</i> L.	+	-	-	-	+	-	-	+	+	3	18.8	0	
18	<i>Pinus densiflora</i> Siebold & Zucc.	++	++	++	+	-	+	+	+	+	10	62.5	4	
19	<i>Cuscuta chinensis</i> Lam.	+	-	-	-	++	+	+	+	+	6	37.5	1	
20	<i>Abies holophylla</i> Maxim.	++	++	++	+	-	+	-	+	+	9	56.3	3	
21	<i>Aesculus turbinata</i> Blume	+	++	+	-	++	+	+	+	+	9	56.3	3	(78)
22	<i>Pinus strobus</i> L.	++	++	++	+	-	+	--	+	+	9	56.3	3	
23	<i>Picea abies</i> (L.) H.Karst.	++	++	++	+	-	+	-	+	+	9	56.3	3	
24	<i>Acacia auriculiformis</i> A.Cunn. ex Benth.	+++++	+	-	++	-	-	+	+	+	9	56.25	3	
25	<i>Albizia lebbek</i> (L.) Benth.	+++++	++	++	+	-	-	+	+	+	11	68.75	4	
26	<i>Artocarpus heterophyllus</i> Lam.	+++++	+	+	+	+	+	++	+	+	13	81.25	6	
27	<i>Azadirachta indica</i> A.Juss.	+++++	++	+	+	-	-	++	+	+	12	75	5	
28	<i>Bauhinia purpurea</i> L.	+++++	+	+	+	++	+	++	+	+	14	87.5	6	
29	<i>Cassia fistula</i> L.	+++++	+	+	+	+	-	-	-	-	9	56.25	3	
30	<i>Delonix regia</i> (Bojer ex Hook.) Raf.	+++++	+	+	+	-	-	-	+	+	9	56.25	3	
31	<i>Eucalyptus citriodora</i> Hook.	+++++	+	+	+	+	+	++	+	+	13	81.25	6	
32	<i>Ficus benghalensis</i> L.	+++++	++	++	+	++	+	++	+	+	15	93.75	7	
33	<i>Tamarindus indica</i> L.	+++++	+	++	+	-	-	++	+	+	12	75	5	
34	<i>Mimusops elengi</i> L.	+++++	-	+	+	+	+	-	-	-	8	50	3	
35	<i>Nerium oleander</i> L.	+++++	-	+	+	+	+	-	-	-	9	56.25	4	
36	<i>Terminalia catappa</i> L.	+++++	+	++	+	+	+	+	+	+	13	81.25	6	
37	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	+++++	+	+	+	+	-	+	+	+	11	68.75	6	
38	<i>Syzygium cumini</i> (L.) Skeels	+++++	+	++	+	+	+	++	+	+	14	87.5	5	
39	<i>Mangifera indica</i> L.	+++++	++	+	+	+	+	++	-	-	12	75	5	(79)
40	<i>Pongamia pinnata</i> (L.) Pierre	+++++	-	+	+	+	-	+	+	+	10	62.5	4	
41	<i>Ficus roxburghii</i> Wall.	+	-	+	+	++	+	+	+	+	8	50	2	
42	<i>Mallotus philippensis</i> (Lam.) Müll.Arg.	+	++	+	-	+	-	++	+	+	8	50	2	
43	<i>Shorea robusta</i> Gaertn.	+	++	++	-	++	+	++	+	+	11	69	4	
44	<i>Eucalyptus globulus</i> Labill.	+	++	-	+	++	-	++	+	+	9	56	3	(82)
45	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	++	+	+	+	+	-	++	+	+	9	56.25	3	
46	<i>Syzygium cumini</i> (L.) Skeels	++	++	+	+	+	-	++	+	+	10	62.50	4	
47	<i>Mangifera indica</i> L.	+	+	+	+	+	++	-	+	+	8	50	2	
48	<i>Pongamia pinnata</i> (L.) Pierre	+	+	+	+	+	+	+	-	-	6	37.50	1	
49	<i>Ficus roxburghii</i> Wall.	+	+	+	+	+	+	++	+	+	9	56.25	3	
50	<i>Mallotus philippensis</i> (Lam.) Müll.Arg.	++	-	-	+	-	-	-	+	+	4	25	0	
51	<i>Shorea robusta</i> Gaertn.	+++	++	++	+	++	+	+	+	+	13	81.25	6	
52	<i>Eucalyptus globulus</i> Labill.	++	++	++	+	+	-	-	+	+	9	56.25	3	
53	<i>Polyalthia longifolia</i> (Sonn.) Thwaites	+	++	++	+	++	+	+	+	+	11	68.75	4	
54	<i>Syzygium cumini</i> (L.) Skeels	+++	+	++	+	+	+	+	+	+	11	68.75	4	
55	<i>Mangifera indica</i> L.	+++++	+	+	+	++	+	++	+	+	14	87.50	6	
56	<i>Pongamia pinnata</i> (L.) Pierre	++	-	+	+	+	-	-	-	-	5	31.25	1	
57	<i>Ficus roxburghii</i> Wall.	++	+	++	-	+	+	++	+	+	10	62.50	4	
58	<i>Mallotus philippensis</i> (Lam.) Müll.Arg.	++	++	++	+	+	+	+	-	-	10	62.50	4	(83)
59	<i>Syzygium cumini</i> L.	+	+	+	+	+	+	++	+	+	9	56.25	3	

APTI: air pollution tolerance index; TH: habit of tree; CS: structure of canopy; TT: tree type; L: laminar; S: size; T: texture; EI: economic importance; H: hardiness; TP: total plus; GA: grade allotted; API: anticipated performance index.

15.29 (*Terminalia arjuna* (Roxb. ex DC.) Wight & Arn.), falling into the moderate-to-sensitive category (80). Juswardi and colleagues conducted a study on 3 plant species in an industrial zone, finding that the highest APTI value was 5.93 and the lowest was 5.08 (81). In a study involving 4 plant species growing along roadside where the highest APTI value recorded was 7.896 (*Shorea robusta* C.F.Gaertn.) and the lowest was 7.811 (*Mallotus philippensis* (Lam.) Müll.Arg.), *S. robusta* was identified as a high-performing species, receiving an API grade of 4 (82). Meanwhile, an evaluation of APTI values for 15 plant species determined that the highest value was 17.88 (*Mangifera indica* L.) and the lowest was 7.23 (*E. citriodora*); *F. benghalensis* and *M. indica* performed exceptionally well, securing an API grade of 6 (83), whereas the performance of other species across all studies ranged from good-to-moderate to poor-to-very poor, with some falling into the 'not recommended' category (Tables 3 and 6).

Throughout our study we found that *F. benghalensis* (Banyan) performed the best and had the highest API value compared to other plants. At the same time, the APTI value of the same plant or different plants varies depending on the level of air pollution at different places, weather, climate changes and other environmental factors like temperature and humidity (88).

Conclusion and future scope

Climate change has increased the frequency of natural disasters, accelerating species displacement, population declines and extinctions; As a result, ecosystem conservation has emerged as one of the most important concerns of our time. In urban environments, air pollution further complicates these challenges, as pollutants such as NO_x, SO_x and CO_x disrupt essential biogeochemical cycles, while particulate matter (PM_{2.5} and PM₁₀) accumulates on leaf surfaces, impairing the physiological functions of vegetation and rendering trees more susceptible to diseases and pest infestations.

Given that urban ecosystems are highly controlled and modified spaces, research on the dynamic interactions between different plant and tree species has become even more imperative. Understanding these interactions provides a basis for promoting the coexistence of both pollution-tolerant and pollution-sensitive organisms, thereby providing meaningful insights for sustainable urban planning and design. Throughout this process, the conservation of urban trees must remain a priority, as they act as important 'bio-filters' and 'carbon sinks'; Furthermore, all our actions must be in accordance with international environmental agreements.

Based on this research, it has become clear that it is extremely important to select plant species specifically suited to specific environmental conditions. Some species exhibit greater tolerance in areas with high vehicular pollution, while others are more suited to industrial environments. To provide guidance in this selection process, the air pollution tolerance index (APTI) and the anticipated performance index (API) have emerged as valuable frameworks for assessing a plant's biochemical and physiological responses to pollution. Several studies support the conclusion that *Ficus spp.*, *Artocarpus heterophyllus*, *Bauhinia purpurea*, *Eucalyptus citriodora*, *Terminalia catappa*, *Polyalthia longifolia* and *Mangifera indica* perform excellent in polluted areas-such as urban, industrial and roadside environments.

Therefore, urban planners are strongly advised to evaluate APTI values prior to undertaking tree-planting initiatives; in this process, particular emphasis should be placed on local (native) species, which naturally exhibit greater tolerance and adaptability to local environmental conditions.

Despite their widespread utility in greenbelt and urban forest planning, APTI and API have some inherent limitations that experts should not ignore. The narrow four-parameter biochemical basis of the APTI, as well as significant seasonal and location-specific variability, indicate that rankings derived from single-season or different location data may misrepresent a species' true tolerance capacity. The API's reliance on subjective binary scoring further limits inter-study comparability and reproducibility. Therefore, these indices are best utilized as preliminary screening tools, integrated with multi-seasonal local sampling, morphological assessments and comprehensive environmental monitoring frameworks to ensure ecologically sound and contextually appropriate planning outcomes.

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Authors' contributions

KN conceived the study idea, supervised the work and drafted the manuscript. AC performed data extraction and contributed to manuscript writing. LGM prepared the tables and figures. CK provided supervision and finalised the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

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