Research Article

Evaluating Urban Foliage for Bioindicator Potential through Pollution Tolerance Traits and Particulate Matter Accumulation

Mohan Marumudi and Keerthi Katam*
Department of Civil Engineering, École Centrale School of Engineering, Mahindra University, Hyderabad, India

Debdip Das and Pararth Mishra
Department of Electronics and Computer Engineering, École Centrale School of Engineering, Mahindra University, Hyderabad, India

* Corresponding author. E-mail: keerthi.katam@mahindrauniversity.edu.in DOI: 10.14416/j.asep.2026.02.007
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Abstract
In this study, ten different plant leaves were collected from different urban microenvironments in the Hyderabad metropolitan area to assess their potential as bioindicators of air pollution. The collected leaf samples were analysed for surface PM accumulation, total chlorophyll concentration, carotenoid content, ascorbic acid, leaf extract pH, relative water content, and air pollution tolerance index (APTI). Out of ten plants, *Ficus religiosa,* which is located near the roadside, showed the highest PM accumulation with 54 µg/cm^2. *Tecoma stans* showed the highest APTI value of 7.45 and ascorbic acid content of 10 mg/g, exhibiting greater tolerance to pollution, as well as potential for urban greening and air quality enhancement. *Senegalia caesia* with low APTI showed excellent carotenoid concentration of 19.42 mg/g, indicating that the plant is pollutant-sensitive, but activates antioxidant defence in response to oxidative stress. Hierarchical clustering analysis revealed a decent grouping of plant species based on biochemical profiles, validating stress tolerance patterns and PM deposition. The study highlights how pollutant deposition is linked to plant health and suggests that plants with adaptive leaf traits are more capable of tolerating polluted conditions. The findings of the study suggest that sensitive plants like *Senegalia caesia, Lantana camara* L., can serve as effective bioindicators and passive monitors of pollution levels and urban greening initiatives, and tolerant plants like *Wodyetia bifurcata* and *Tecoma stans* may contribute to a sustainable solution for mitigating urban air quality and supporting long-term environmental planning in polluted urban ecosystems.

Keywords: Air Pollution Tolerance Index (APTI), Anticipated Performance Index (API), Bioindicators, Hierarchical Clustering Analysis (HCA), Particulate Matter Accumulation, Urban Ecology

1 Introduction

Urban air pollution has become an imminent environmental and public health challenge in rapidly growing cities worldwide. The increase in population, industrial activity, traffic intensity, and construction has all contributed to a mix of pollutants entering the air, especially particulate matter and toxic gases such as nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), and volatile organic compounds (VOCs) [1], [2]. Among these air pollutants, particulate matter (PM), which are solid and liquid particles that remain suspended in the air, is of great concern. These particles may come from primary sources such as construction dust, diesel exhaust, and industrial emissions, or they may come from secondary processes in which gaseous precursors undergo chemical reactions. In addition, these particles are categorized according to their size (e.g., PM100, PM10, PM2.5, or ultrafines) based on their physical characteristics, persistence in the atmosphere, and biological effects. Larger particles (PM100) are often generated through mechanical activities similar to soil erosion or dust resuspension on roadways, construction, and demolition. However, smaller particles (≤ PM2.5) are primarily from combustion or chemical reactions in the atmosphere. These small particles can penetrate deeply into the respiratory tract and enter the bloodstream, where they are associated with respiratory and cardiovascular diseases [3], [4]. Particularly for sensitive groups like children, women, the elderly, and patients. It was reported that every year, one in six deaths is related to diseases caused by air pollution [5]. Larger particles, such as PM100, are typically regarded as less relevant because of their short residence duration in metropolitan environments. Nonetheless, it may cause health hazards by collecting in the upper respiratory tract and complicating attempts to purify the air.

The conventional approaches to monitoring urban air quality typically rely upon the use of reference–grade instruments, including gravimetric samplers, beta–attenuation monitors, gas analysers, and high-tech remote sensing networks [6], [7]. These instruments, while providing relative temporal resolution and specificity for pollutants, represent large financial, technical, and logistical burdens, leading to their placement only at single fixed stations and often only in high–resource locations. The cost of a reference station, for example, can exceed thousands of USD per year for a single site, which limits the ability to provide continuous spatially dense coverage for either larger, high–resource urban areas that are limited by financial resources [8], [9]. In mobile monitoring, reference–grade instruments are equipped on vehicles to track hourly readings of pollutants, which is more effective yet costly and resource–intensive. Low–cost sensor (LCS) networks of micro–sensors sampling with spatial resolutions as fine as 100–300 meters are increasingly used to fill these gaps, delivering continuous, real–time atmospheric data at operational costs up to two orders of magnitude lower than reference–grade sites. Although high–density LCS networks have improved, their accuracy for particulate matter (especially coarse PM) depends on sensor technology and environmental calibration. Light–scattering sensors underestimate larger PM fractions, while counters capture larger sizes but require frequent validation. Due to device constraints and data handling costs, hyperlocal LCS deployment requires extensive calibration and data correction, and is seldom practicable for broad pollutant coverage [10], [11].

In contrast, the use of biomonitoring methods, most notably the application of urban plants as bioindicators, provides scientifically sound and economical alternatives that integrate both spatiotemporal exposure to numerous pollutants within a living system [12]. Trees and shrubs are fundamentally sessile and exposed to the ambient environment, and thus will accumulate particulate matter and absorb gaseous compounds across leaf surfaces and tissues, which serve as an integral record of pollutant burden within the ecosystem over greater durations of time. They play a vital role as bioindicators, contributing valuable insights into environmental health by reflecting deviations in soil, air, and water quality, particularly effective due to their sessile nature, which requires them to interact with environmental pollutants and adapt to varying conditions directly. The change in physiologic and biochemical responses, such as chlorosis, necrosis, chlorophyll, ascorbic acid, and relative water content (RWC), has been positively correlated with ambient pollution. In addition to being a bioindicator, plantations have been a solution for air pollution and climate change for a long time. They are installed as green walls on the roadside for capturing the PM through adsorption on their leaf surface, settled on leaf wax and stomata [13]–[18]. Leaf surface morphology may affect the ability to accumulate PM [19] along with environmental factors like PM concentration, precipitation patterns, and wind behaviour [20]. Small and medium-sized plants such as *Allium cepa*, *Vicia faba*, and *Zea* mays have been used to evaluate and forecast pollution levels and other environmental fluctuations, serving as significant indicators of urban ecosystem health [21].

In a polluted environment, plant leaves exhibit adaptive responses to the pollution stress, as the accumulated PM reduces the ability to photosynthesize, which affects their metabolic activity. This may lead to variations in the leaf shape, yellowing, a decrease in their growth, and ultimately the death of the plant species. Various studies show that long–term exposure to PM tends to decrease leaf RWC and reduce their tolerance towards air pollution stress [22], [23]. In addition, acidic pollution caused by the gaseous pollutants (NOx and SOx) can damage the plant and may alter the leaf pH and reduce the ability to convert the sugar to ascorbic acid [24]. Therefore, it is important to evaluate the physiological stress caused by PM accumulation on urban foliage and to identify the tolerant species with the help of comprehensive tools such as the anticipated performance index (API) value and air pollution tolerance index (APTI) [14], [25]–[27]. The biochemical monitoring of plant species can help identify those suitable for urban greening and for managing air pollution within urban ecosystems.

The APTI quantitatively integrates key biochemical components (total chlorophyll, ascorbic acid, relative water content, and leaf pH) that serve to evaluate plant tolerance and sensitivity to urban pollution. This aids in the assessment of species that serve as candidates for phytoremediation and green infrastructure (i.e., tolerant taxa) vs. species sensitive to pollution that could serve as biomonitoring species (sensitive taxa). Typically, APTI values above 17 indicate tolerant taxa, while values below 12 indicate sensitive taxa [28]. Quantitative research in multiple cities across Asia and Europe indicates strong relationships between leaf accumulation of PM and proximity to traffic or industrial sources of pollution, supporting the decision to use biomonitoring as a representation of exposure assessment and a demonstration of reliability [29], [30]. Similarly, the use of naturally–persistent combinations of physical characteristics, including but not limited to high leaf roughness, dense trichomes, and thick cuticular wax, has been quantitatively linked to higher rates of PM capture and reported differences of up to 2 to 4 times the amount of PM accumulation among species when subjected to the same environmental conditions [31], [32]. This study aims to assess particulate matter deposition and associated leaf biochemical traits to identify plant species with potential for air pollution monitoring and for improving urban ecosystems. The research investigates surface PM accumulation on the urban foliage of the ten different plant species at various locations. The observations from the study are used to identify the efficient plant species that could help in reducing the air pollution, especially the PM deposition in urban areas, through parameters such as the surface PM accumulation, ascorbic acid content, leaf extract pH, RWC percentage, total chlorophyll concentration, carotenoid content, and hierarchical clustering analysis (HCA). In addition to biochemical and physiological assessment, X–ray Diffraction (XRD) analysis was conducted to characterize the effect of pollution on foliage, providing complementary insights into pollutant material composition and its functional role in influencing pollution stress tolerance in the plant species.

2 Materials & Methods

2.1 *Geographical Location of the Area and Leaf Sampling*

The leaf samples are collected from ten different locations, named as L1–L10 in Gandimaissama, Hyderabad (17.3850° N, 78.4867° E), located in Telangana (Figure 1).

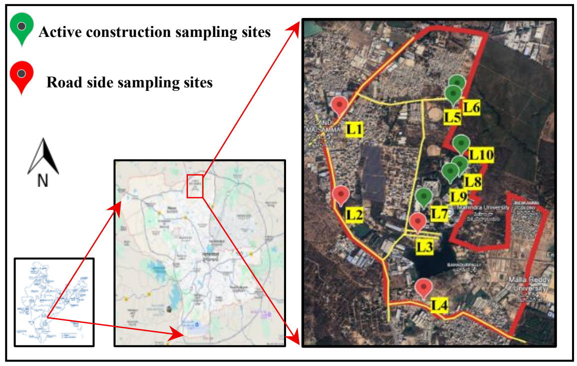

Figure 1: Geographical location of the study area and leaf sampling sites.

Hyderabad is one of India's fastest–growing metropolitan cities, spreading over an area of approximately 650 km² with a population exceeding 80 lakhs. It is a major hub for pharmaceuticals, information technology, and manufacturing industries. The city lies on the Deccan Plateau at an elevation of approximately 500 meters above sea level and experiences a tropical wet and dry climate, with hot summers, moderate monsoons, and mild winters [33]. In recent years, Hyderabad has observed a steady rise in air pollution levels due to swift urbanization, amplified vehicular traffic, and industrial emissions. The average PM2.5 concentration in the city often exceeds 50 μg/m³ during winter months, more than the WHO guideline of 15 μg/m³. In January 2025, AQI levels frequently ranged between 120–150, signifying unhealthy conditions for sensitive groups like elderly people, children, and patients [34]. Gandimaisamma, a suburban locality in the northwestern periphery of Hyderabad, is part of the Hyderabad Urban Development Area (HUDA) and has the average PM10 and PM2.5 concentrations of 82 μg/m³ and 32 μg/m³, respectively, as per the Central Pollution Control Board (CPCB) [35]. It is characterized by mixed land use, including residential zones, educational institutions, and proximity to industrial clusters. Hyderabad's summer season (March–June) is characterized by intense heat, strong solar radiation, and dry atmospheric conditions. Daytime temperatures often ascend above 40 °C, especially in May, which is typically the hottest month [36].

To assess the interrelationship between vegetation and air pollutants, stress tolerance indices such as APTI and API values are applied to evaluate the resilience of urban flora [37]. For the present investigation, ten sampling sites were selected within a 5 km radius (peri–urban/industrial fringe), with ten different plant species leaves that are healthy and in good condition were collected from the corresponding locations (Figure 2). Namely, Honey Locust (*Gleditsia triacanthos*), Jackfruit (*Artocarpus heterophyllus*), White Acacia (*Senegalia caesia*), Indian Milkweed Calotropis (*Calotropis gigantea*), Oleander (*Nerium oleander*), Peepal Tree (*Ficus religiosa*), White Datura (*Datura metel* [white-flowered variety]), Lantana (*Lantana camara* L.), Foxtail Palm (*Wodyetia bifurcate*), and Yellow Trumpet (*Tecoma stans*). The details of the plant species collected from different locations are presented in Table 1.

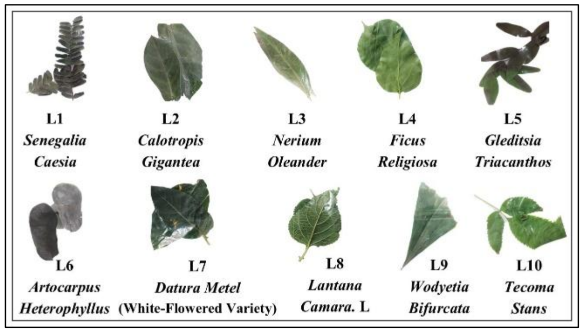

Figure 2: Pictures of plant leaf samples with their location names.

All the samples were collected on the same day. Leaves were collected by cutting them with sterilized scissors and using nitrile gloves to prevent contamination. Samples were placed into labelled polyethene bags without delay and transported to the laboratory within 4 hours after sampling.

Table 1: Plant species with scientific names analyzed in this study and their sampling locations.

Location	Plant/Tree Common Name	Plant/Tree Scientific Name	Latitude	Longitude
L1	White Acacia	*Senegalia caesia*	17°34'36.1" N	78°25'28.5" E
L2	Indian Milkweed Calotropis	*Calotropis gigantea*	17°34'06.4" N	78°25'32.4" E
L3	Oleander	*Nerium oleander*	17°33'57.2" N	78°25'59.2" E
L4	Peepal Tree	*Ficus religiosa*	17°33'38.1" N	78°26'03.4" E
L5	Jackfruit	*Artocarpus heterophyllus*	17°34'43.7" N	78°26'06.1" E
L6	Honey Locust	*Gleditsia triacanthos*	17°34'47.3" N	78°26'07.0" E
L7	White Datura	*Datura metel (White-Flowered Variety)*	17°34'08.4" N	78°26'00.1" E
L8	Lantana	*Lantana camara* L.	17°34'20.3" N	78°26'10.8" E
L9	Foxtail Palm	*Wodyetia bifurcata*	17°34'17.7" N	78°26'08.0" E
L10	Yellow Trumpet	*Tecoma stans*	17°34'27.4" N	78°26'10.6" E

2.2 *Surface PM accumulation analysis*

The surface PM accumulation on leaf samples was quantified using a washing protocol as described by Dzierzanowski [13]. Collected leaf samples were cut into 1 cm x 1 cm and washed with 10 mL of deionized (DI) water to collect PM on the leaf surface. The leaf samples were soaked in DI water for approximately 1 minute and stirred. To ensure uniformity across leaf surface texture, the beakers were held on an ultrasonic cleaner (Make: Bio-Technics India) for 6 minutes to check that all particles were cleaned off the leaf surface. Pre-weighed filter paper of 10 µm (Whatman Filter Paper Grade No. 1) was used to filter the collected water solution, and then the filter paper was dried at 60 °C for 24 h. The difference in weight of the filter paper was used to quantify the amount of PM accumulated on the leaf surface. Each leaf sample area was measured using the graph paper tracing method.

2.3 *Biochemical analysis*

2.3.1 *Leaf extract pH*

The leaf extract pH was determined by homogenizing 0.1 g of fresh leaf samples in 10 mL of DI water. Subsequently, the resulting samples were centrifuged for 3 minutes at 2700 rpm. The pH of the homogenate was then determined using a calibrated pH meter (Make: Systronics, model LT_150), following the method of Singh *et al*. [37].

2.3.2 Relative Water Content (RWC)

RWC is measured by first recording the fresh weight (FW) of the leaf samples immediately after collection. The leaves are then soaked for 24 hours in DI water at 4 °C to attain full turgidity, and the samples are weighed once more after removing the excess water to ascertain their turgid weight (TW). Following this, the samples were dried for 24 hours at 80°C in an oven to obtain the dry weight (DW) of the leaves. The following equation (1) was used to determine the RWC [38].

$$RWC(\%) = \frac{(FW-DW)}{(TW-DW)} \times 100 \quad (1)$$

2.3.3 Chlorophyll contents and carotenoids

The chlorophyll and carotenoids in the collected samples are analyzed using the method reported by Lichtenthaler [39]. The leaves, weighing around 0.1 g, were crushed in 10 mL of 100% acetone. The resultant solution was then centrifuged at 2700 rpm for 10 minutes, using a centrifuge (Remi CR 24 Plus). The absorbance of the supernatant was measured at 616.6 nm and 644.8 nm for estimating chlorophyll and at 470 nm, 616.6 nm and 644.8 nm for carotenoids using a spectrophotometer (Systronics UV–Vis Spectrophotometer 2202 TS). The determined absorbance values were then used to calculate the total chlorophyll and carotenoid contents using the following Equations (2) and (3).

$$Total\ Chlorophyll = (7.05 \times A_{616.6}) + (18.09 \times A_{644.8}) \quad (2)$$

$$Carotenoids = (1000 \times A_{470}) - \frac{(260.68\ X\ A_{644.8} - 1249.64\ X\ A_{616.6})}{214} \quad (3)$$

Where $A_{616.6}$, $A_{644.8}$, and A_{470} are corresponding absorbance wavelength values

2.3.4 Ascorbic Acid Content (AAC)

AAC in the collected leaf samples was determined using a modified colorimetric 2,6–dichlorophenol–indophenol titration method [40]. The leaf samples were oven–dried at 40 °C for 96 hours and then made into a fine powder. Approximately 0.5 g (w) of the leaf powder was mixed with 10 mL of 4% oxalic acid. The mixture was stirred and strained through muslin cloth, and the volume was adjusted to 25 mL using 4% oxalic acid. Standard ascorbic acid of 100 mg is added to 100 mL of 4% oxalic acid, labeled as a stock solution. The prepared stock solution was diluted ten times using 4% oxalic acid to prepare a working solution with a concentration of 100 µg/mL, and it was titrated against the dye solution (V_1) until a light pink endpoint persisted for about 15 seconds. Similarly, the leaf extracted sample is titrated against the dye solution (V_2). The following Equation (4) was used to determine the amount of ascorbic acid.

$$Ascorbic\ acid\ content(mg/100g) = \frac{500\ x\ V_2\ x\ 25\ x\ 100}{V_1\ x\ 5\ x\ w} \quad (4)$$

Where: 500 = Micrograms of standard ascorbic acid used during titration; 5 = Volume (in mL) of the sample extract used in the titration; 25= Total volume (in mL) of the prepared extract; 100 = Conversion factor to express ascorbic acid content per 100 grams of sample.

2.3.5 Air Pollution Tolerance Index (APTI)

The APTI of a plant species was determined by using the equation developed by Singh & Rao [41]. The determined values of ascorbic acid content (A), total chlorophyll (T), leaf extract pH (P), and relative water content percentage (R) were then used to calculate the APTI using the following Equation (5).

$$APTI = \frac{[A(T+P)]+R}{10} \quad (5)$$

Plants with APTI values of ≤ 11 are considered sensitive, between 12 and 16 as intermediately tolerant or sensitive, and ≥ 17 as tolerant of air pollution [28].

2.3.6 Anticipated Performance Index (API)

Evaluation of the API was carried out according to the method given by Prajapati *et al.* [42]. Parameters such as APTI, plant habitat, canopy structure, type of plant, size, texture, hardiness, and economic value of the plants were considered to calculate the grade per plant species. Plants with an API score of 0 to 7 are considered to have low performance potential and are not recommended as the best choices. The detailed calculations were shown in supporting information Tables S1–S3. The following equation in Equation (6) was used to determine percentage scoring.

$$\% \, Scoring = \frac{Grades \ obtained \ by \ plant \ species}{Max. \ possible \ grades \ for \ any \ plant \ species} \times 100 \quad (6)$$

2.4 *X–Ray diffraction (XRD) analysis*

The XRD analysis was performed for the dried and powdered leaf samples. The 2θ scan was performed from 20° to 90°, and the XRD data were captured at intervals of 0.01° with a rate of 3°/min. The effect of PM deposited on the leaf samples was quantitatively assessed using XRD Rietveld analysis (Rigaku X–ray Diffractometers with Smart Lab Studio II software). The analysis focused on identifying the elements of silica (Si), calcium (Ca), sodium (Na), potassium (P), magnesium (Mg), sulfur (S), carbon (C), aluminum (Al), iron (Fe), lead (Pb), Mercury (Hg), cadmium (Cd), chromium (Cr), and nickel (Ni) from the collected plant leaf samples.

2.5 *Statistical analysis*

Analysis of variance (ANOVA) and paired comparison analyses were conducted to assess the significance of the leaf traits, while the hierarchical clustering analysis (HCA) was used to group the plant species according to the surface PM accumulation and biochemical characteristics, using Origin Pro 2025 software [43].

3 Results and Discussion

3.1 *Surface PM accumulation*

In the current study, a significant difference in surface PM accumulation on leaves was observed among the plant species, as shown in Figure 3. The earlier studies reported that the PM accumulation depends on the leaf surface morphology [44]–[48]. Additionally, the structural features of leaves, like petiole length and shape, influence the movement of the plant with respect to the natural conditions like wind flow, precipitation, and sunlight availability, which in turn affect the PM accumulation on the leaf surface [49]. Among the ten plant species, *Ficus religiosa* exhibits the peak PM accumulation, with 54 µg/cm^2 at location L4, which is a busy roadside area. *Ficus religiosa* is a well–known species with large, rough, or hairy leaves that act as effective biofilters for atmospheric particulates [50], [51]. The PM accumulation of 24.6 µg/cm^2 was observed on *Datura metel* and 22 µg/cm^2 on *Lantana camara* L. at locations L7 and L8, respectively, reflecting their morphological traits such as dense trichomes and sticky surfaces that enhance deposition. *Calotropis gigantea* and *Wodyetia bifurcata* show the moderate values, indicating the lower surface PM accumulation capacity compared to the *Ficus religiosa, Datura metel,* and *Lantana camara* L. In contrast, *Nerium oleander* and *Gleditsia triacanthos* accumulated the least due to the inadequate surface microstructure and glossy texture. However, for road safety and space constraints, planting the tall trees may not be feasible; therefore, herbaceous species may serve as an alternative option. In the current study, we observed that *Datura metel*, which is similar to other herbaceous plants, was quite effective in accumulating the PM and phytochemical resilience [52]. These observations underline the active role of the plant species in bio-filtration, where some species act as a sink for surface PM accumulation, thereby improving the roadside air quality. However, the PM accumulation on the leaf surface may adversely affect the plant health by impairing the photosynthetic efficiency and metabolic activity of the plant species, potentially leading to plant mortality.

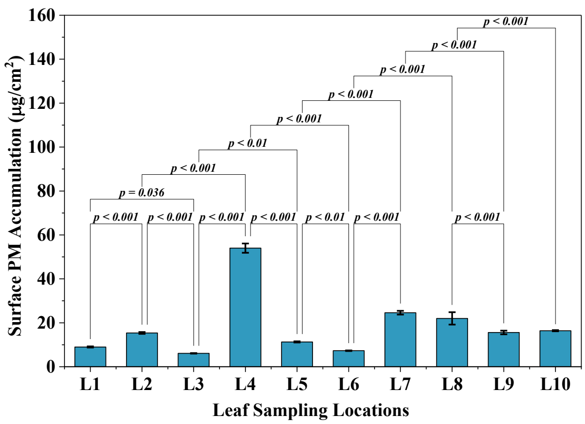

Figure 3: Surface PM accumulation concentration on the surface of the plant leaves.

The stress physiology markers are coupled with PM accumulation data, could enhance the species selection model for green barriers. Plant species exhibiting high surface PM accumulation may serve as primary pollutant buffers, while those with lower accumulation plant species may be helpful in bio–monitoring or aesthetic contributions. These results show that morphological features of leaves, like broad lamina, dense trichomes, and leathery rough surface texture, play an important role in surface PM accumulation.

3.2 *Biochemical composition*

3.2.1 Leaf extract pH

The leaf extract pH values of plant species are given in Table 2. pH is one of the important biochemical parameters that helps to understand the plant's performance under the pollution–associated stress. The detoxification mechanism is associated with leaf alkalinity, which is essential for tolerance. Plant species with near–neutral or slightly alkaline pH are more resilient [41]. *Calotropis gigantea, Datura metel*, and *Artocarpus heterophyllus,* with leaf extract pH values greater than 6, suggest they have a stronger internal buffering system and potential tolerance to air pollutants. It was reported in earlier studies that plants having a pH around 7 in a polluted environment have tolerance against air pollutants [53], [54]. Plants with a pH less than 6 have less tolerance compared to the other plant species due to the presence of gaseous pollutants like SOx or NOx, making the leaves to acidic in nature through stomatal exchange [41]. The average concentrations of the NO_2 and SO_2 in the study area are 10.6 $\mu g/m^3$ and 10.8 $\mu g/m^{3,}$ as per CPCB [35], which is less than the standard limit of 80 $\mu g/m^3$.

3.2.2 Relative Water Content (RWC)

RWC reflects the ability to retain the water content under turgor pressure, which helps in enzymatic activity and metabolic functions of the plant species. RWC is a dynamic physiological parameter of a plant's hydration status and its tolerance to drought or pollution stress. The higher the RWC percentage, the greater the tolerance towards the air pollutants under the stress condition [54], [55]. In our study, *Nerium oleander* at location L3 had an RWC of 32.64% and *Calotropis gigantea* at location L2 had an RWC of 33.94%, exhibiting the highest percentage shown in Table 2. The higher RWC indicates that these plant species are likely to perform better even under exposure to air pollutants and dry conditions. These species display xerophytic adaptations, with thick cuticles and internal water storage, which allow for water retention even under vehicular pollution stress [56]. The plants that have less RWC, like *Senegalia caesia* with 4.92%, show the potential vulnerability to pollutant exposure. Soil compaction and mechanical root damage are common at construction sites and likely also led to impairment of water uptake. Dust on leaf surfaces may have also reduced stomatal function and increased water stress.

3.2.3 Total chlorophyll

The total chlorophyll concentration of the plant species varied significantly from 0.03 to 0.17 mg/g, as shown in Table 2. Among these ten plant species, *Ficus religiosa* and *Senegalia caesia* have 0.11 mg/g and 0.17 mg/g at location L4 and L1, respectively. Similarly, *Calotropis gigantea* and *Datura metel* have moderate concentrations of 0.08 mg/g and 0.09 mg/g at location L2 and L7, respectively. In contrast, *Nerium oleander* and *Lantana camara* L. have the lowest concentration of 0.03 mg/g at locations L3 and L8. In the green plant metabolic activities, the chlorophyll present in chloroplasts performs a vital function in photosynthesis [23]. Reduction in the chlorophyll concentration directly affects the plant growth; analyzing the chlorophyll concentration will help to measure the effect of air pollution on vegetation [57]. Other studies have shown that PM accumulation limits the light absorption and reduces plant chlorophyll content [27], [58]. Stomatal blockage caused by PM accumulation contributes to a reduction in the chlorophyll concentration [59]. Additionally, chlorophyll content may be reduced by exposure to gaseous pollutants like SO_2 and NO_2, as well as by environmental factors like high temperature, intense daylight, salinity, and stress due to drought [41]. Making total chlorophyll a vital biochemical marker in the selection of plants in landscape development to overcome air pollution in urban ecosystems.

3.2.4 Carotenoid

Carotenoid pigments act as a sensitive biomarker of plant stress, aiding chlorophyll in light absorption for photosynthesis and protecting from photooxidative damage [59]. However, carotenoids may be affected by the poor air quality caused by PM accumulation and oxidative pollutants. In our study, the values ranged from 2.76 to 19.42 mg/g, as shown in Table 2. *Senegalia caesia* showed the highest carotenoid concentration of 19.42 mg/g at location L1, followed by *Calotropis gigantea* and *Artocarpus heterophyllus* with 8.53 mg/g and 9.96 mg/g at location L2 and L5, respectively. Plant species of *Lantana camara* L. and *Nerium oleander* showed the lowest carotenoid concentration of 4.32 mg/g at location L8 and 2.76 mg/g at L3. Increased carotenoid concentration supports the robust defence mechanism against the antioxidative stress induced by the pollutant exposure, and decreasing the concentration of the carotenoid leads to yellowing of the plant leaves, which is consistent with pollution stress [13], [60], [61].

Table 2: Parametric analysis of ten plant leaf samples with their location

Location	Plant Species	Leaf extract pH	RWC (%)	Total Chlorophyll (mg/g)	Carotenoid (mg/g)	AAC (mg/g)
L1	*Senegalia caesia*	6.25 ± 0.21	4.92 ± 0.42	0.17 ± 0.04	19.42 ± 6.72	0.25 ± 0.10
L2	*Calotropis gigantea*	6.4 ± 0.21	33.94 ± 0.44	0.08 ± 0.03	8.53 ± 2.54	2.00 ± 0.20
L3	*Nerium oleander*	6.08 ± 0.74	32.64 ± 0.40	0.03 ± 0.01	2.76 ± 0.82	0.10 ± 0.00
L4	*Ficus religiosa*	6.08 ± 0.29	24.63 ± 0.44	0.10 ± 0.00	7.23 ± 0.32	1.00 ± 0.00
L5	*Artocarpus heterophyllus*	6.34 ± 0.33	26.73 ± 0.27	0.05 ± 0.01	9.96 ± 1.48	0.27 ± 0.00
L6	*Gleditsia triacanthos*	5.47 ± 0.07	15.00 ± 1.37	0.11 ± 0.01	7.22 ± 1.03	0.46 ± 0.20
L7	*Datura metel*	6.64 ± 0.17	17.42 ± 0.42	0.09 ± 0.01	6.92 ± 0.01	0.47 ± 0.00
L8	*Lantana camara L.*	5.96 ± 0.05	15.61 ± 0.41	0.03 ± 0.01	4.32 ± 0.93	0.31 ± 0.00
L9	*Wodyetia bifurcate*	6.04 ± 0.04	25.47 ± 0.17	0.06 ± 0.00	4.78 ± 0.06	6.00 ± 0.20
L10	*Tecoma stans*	5.74 ± 0.02	14.16 ± 0.84	0.06 ± 0.03	6.60 ± 3.24	10.00 ± 1.00

3.2.5 Ascorbic Acid Content (AAC)

The variations of ascorbic acid content (AAC) among the ten plant species at ten different locations ranged from as low as 0.1 mg/g in *Nerium oleander* to 10 mg/g in *Tecoma stans* (Table 2). The highest values of *Tecoma stans* with 10 mg/g at location L10 and *Wodyetia bifurcata* (6 mg/g) at location L9 indicate a better antioxidant defence system to balance the reactive oxygen species (ROS) caused by the PM accumulation. *Gleditsia triacanthos* and *Senegalia caesia* with less than 0.5 mg/g values indicate that these plants have limited physiological adaptability under stress [62]. Ascorbic acid plays a major role and enhances the stability and enzymatic activity under pollution conditions [59]. It serves not only as a biochemical marker but also as a predictive indicator of plant species that are suitable for urban green initiatives and air quality management.

3.2.6 Air Pollution Tolerance Index (APTI)

Air Pollution Tolerance Index (APTI) values, which indicate the comprehensive measurement of the physiological resilience to the exposed air pollution of plant species, are shown in Figure 4. APTI integrates the four significant parameters, mainly total chlorophyll, AAC, leaf extract pH, and RWC. All these parameters collectively represent the ability of a plant species to tolerate oxidative stress and maintain photosynthetic efficiency under exposure to air pollution. *Tecoma stans* and *Wodyetia bifurcata* showed the highest APTI values of 7.22 and 6.21, respectively.

Similar results were observed in previous studies. Bui *et al.*, studied six different plant species in Cheongju city, South Korea, reporting APTI values ranging from 6.6 to 8.96 [63]. Similarly, Agbaire *et al.*, observed APTI values ranging between 4.81 and 8.41 in Delta State, Nigeria [64]. Saif Shahrukh *et. al.*, have studied four different sites in Dhaka city, Bangladesh, where APTI values ranged from 10.64 to 12.51 [65], while Chandan *et. al.*, reported a wide range of 8.88 to 31.63 in Sambalpur town, India [26]. APTI with high ascorbic acid concentration and stable total chlorophyll, which indicates the strong antioxidant defence and good photosynthetic activity [15], [18], [66].

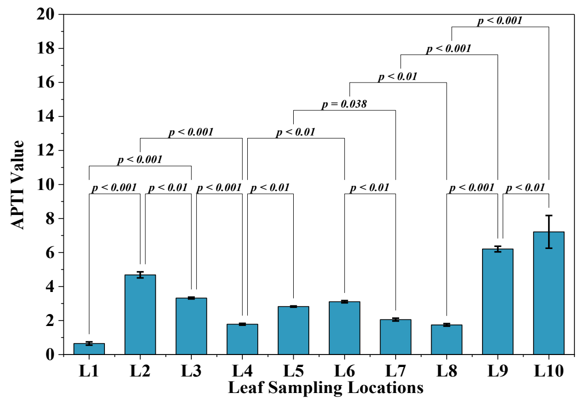

Figure 4: APTI value of the plant species at the construction area and the busy roadside junction**.**

3.2.7 Anticipated Performance Index (API)

The API values of the ten plant species are shown in Figure 5, which gives a wider outlook on their suitability for urban greening in air pollution tolerance. The maximum grade that can be allotted per plant is 16. Plant species were graded in accordance with the percentage-based scoring shown in supporting information Table S4 [42], [67]. Unlike APTI, it focuses on additional criteria such as plant height, canopy structure, economic value, and aesthetic appeal, along with biochemical resilience, making it a more comprehensive tool for species selection in urban landscape planning. Among the ten plant species, *Artocarpus heterophyllus* and *Senegalia* *caesia* recorded the highest API value of 4, representing their strong overall performance across both physiological and morphological characters. These species likely combine moderate pollution tolerance with favourable growth habits and visual appeal, making them ideal species for urban plantations.

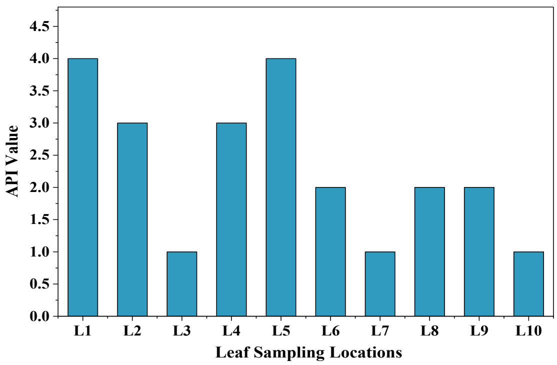

Figure 5: API value of the plant species at the construction area and the busy roadside junction.

Followed by *Calotropis gigantea*, *Ficus religiosa*, and *Wodyetia bifurcata,* with a moderate API value of 3, suggesting balanced performance. These species may not top every individual trait, but offer a reliable combination of pollutant capture, resilience, and landscape value. *Nerium oleander*, *Datura metel*, *Lantana camara* L., and *Tecoma Stans* have low API values < 2. This variance tells the importance of considering practical deployment factors such as invasiveness, maintenance needs, or growth form, and the sustainability when selecting species for urban greening to mitigate air pollution in urban settings. The influence of all these constraints on the recital of a plant species selection was stated in the earlier studies [65], [68].

The biochemical data in Table 2 show that the leaf pH has a comparable trend to RWC, with lower pH values corresponding to a reduced RWC of the leaf samples, suggesting a possible physiological relation between hydration and leaf acidity. AAC indicating the stress–induced antioxidant accumulation, and the single–factor ANOVA across the measured values of PM accumulation and biochemical parameters yielded a statistically significant difference between groups ($F = 15.31$, p-value < 0.001), see in supporting information Table S5 and S6, indicating that the observed variations in PM accumulation and biochemical parameters show species–specific influence.

3.3 *X–Ray Diffraction (XRD) Analysis*

Figure 6 shows the XRD results of the plant species, exhibiting the substantial variation in crystalline composition across plant leaf samples.

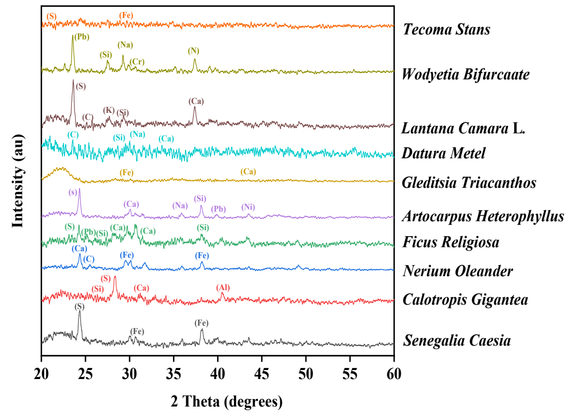

Figure 6: XRD analysis of the leaf samples.

The graph plots intensity (au) against diffraction angle (2θ), with each curve representing an individual plant species. The presence of mineral phases demonstrated by peaks at specific angles is typically allied with atmospheric particulates like calcite, quartz, alumina, and probably the trace heavy metal oxides. The leaf surfaces of *Senegalia caesia, Calotropis gigantea, Ficus religiosa, Artocarpus heterophyllus*, and *Gleditsia triacanthos, Lantana camara* L.*,* and *Wodyetia bifurcata* collected from L1, L2, L3, L4, L5, L6, L8, and L9 locations, respectively, show noticeable peak intensities in the 20°–40° region. These peaks indicate the presence of Ca, Si, C, K, Na, S, Al, Pb, Fe, Ni, Hg, Cr, and Cd. Among them, Si, Ca, Fe, and S were the most abundant in the majority of the leaf samples. The XRD analysis shows the differences in peak intensity and sharpness, suggesting a variable degree of crystallinity and availability of functional groups such as hydroxyl, carboxyl, and amines, which facilitate the interaction of hydrogen boning and enhance the adsorption efficiency of the plant leaves [69], [70]. All these integrated data analyses are helpful in the plant species selection process to enhance the ability of pollution tolerance. Additional research is needed to accurately determine the concentrations of accumulated elements on plant leaves, using advanced quantitative analytical methods such as X–ray fluorescence (XRF) or inductively coupled plasma mass spectrometry (ICP–MS).

3.4 *Hierarchical Clustering Analysis (HCA)*

The dendrogram of HCA is shown in Figure 7, representing the grouping of the ten plant species based on the PM accumulation, along with the APTI and API values, which show the three primary clusters.

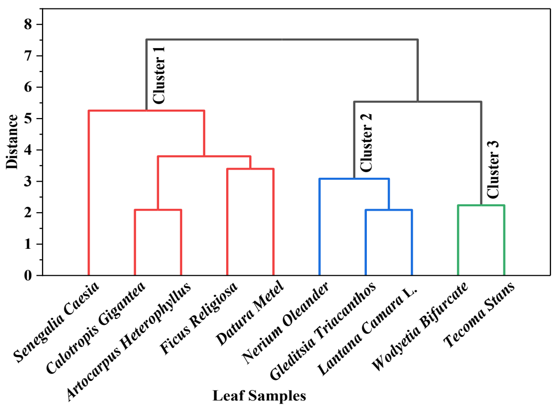

Figure 7: Hierarchical Clustering Analysis (HCA) of the leaf samples.

This cluster grouping helps urban planners in the plant species selection framework to have sustainable air pollution management. *Senegalia caesia, Caltropis ginganatea*, *Artocarpus heterophyllus*, *Ficus religiosa,* and *Datura metel* are clustered by high to moderate API value, and biochemical traits such as ascorbic acid content, total chlorophyll concentration, and carotenoids, signifying that these species exhibit resilience to air pollution, making them tolerant species. *Nerium oleander*, *Gladitsia triacanthos*, and *Lantana camara* L. are clustered, characterised by low PM accumulation, RWC, total chlorophyll, carotenoids, and moderate API value, suggesting that these are sensitive plant species as bioindicators. *Tecoma stans* and *Wodyetia bifurcate* form a distinct cluster characterised by PM accumulation, ascorbic acid content, RWC, and total chlorophyll concentrations, signifying that the species are maintaining a balance between pollutant capture and biochemical resilience. Making them partially tolerant and effective in PM capture may be suitable for use as buffer vegetation in urban greening.

4 Conclusions

In this study, the surface particulate matter (PM) accumulation and pollution-associated stress response of ten plant species from different locations of a peri-urban area surrounding pharmaceutical, manufacturing, and educational institutions in Hyderabad city were examined. The analysed results show that plant species like *Ficus religiosa* and *Datura metel* are quite effective for the surface PM accumulation due to their leaf surface morphology. However, the PM accumulation alone does not accurately reflect pollution tolerance. Plant species like *Tecoma stans* and *Wodyetia bifuecata* exhibit high APTI values, suggesting their high antioxidant content and cellular stability. The HCA successfully grouped the species among the ten-plant species, resembling the trend observed in the APTI and API values. Carotenoid and total chlorophyll, besides leaf extract pH and RWC, provide an effective resilience mechanism that enables plant species to withstand the pollution-associated stress. The summarized results of this study emphasize that cultivating and promoting such plant species in urban areas could mitigate the toxic gas emissions and support urban sustainability and climate resilience, and also highlight the importance of multicriteria decision-making for the assortment of plant species in urban greening to maintain the urban air quality and ecosystem. The limitation of this study is the lack of a control site for comparing pollution-associated stress, representing a critical gap that needs to be addressed.

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Author Contributions

M.M.: Writing – Original draft, Investigation, Data curation; D.D.: Investigation, Data curation; P.M.: Investigation, Data curation; K.K.: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the Grammarly tool to enhance the language and readability of the manuscript.

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Supporting Information

Table S1: Gradation of plant species on the basis of the air pollution tolerance index (APTI) and other biological and socioeconomic characters for determination of the anticipated performance index (API) of plants under this study.

Grading character			Pattern of Assessment	Grade Allotted *
Tolerance	APTI		9.0 – 12.0	+
			12.1 – 15.0	++
			15.1 – 18.0	+++
			18.1 – 21.0	++++
			21.1 – 24.0	+++++
Biological and socio-economic characters	Plant height		Small	-
			Medium	+
			Large	++
	Canopy structure		Sparse/irregular/globular	-
			Spreading crown/open/semi-dense	+
			Spreading dense	++
	Type of plant		Deciduous	-
			Evergreen	+
	Laminar structure	Size	Small	-
			Medium	+
			Large	++
		Texture	Smooth	-
			Coriaceous	+
		Hardiness	Delineate	-
			Hardy	+
	Economic value		Less than three uses	-
			Three or four uses	+
			Five or more uses	++

*Total maximum allotted grades per an individual plant is 16

Table S2: Evaluation criteria for assigning anticipated performance index (API) values and categories of plants on the basis of percentage score.

Grade	Scores (%)	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 S3: Evaluation of plant species based on their APTI values and some biological and socioeconomic characters.

Location	Plant Species	APTI	Plant Habitat	Canopy Structure	Type of Plant	Size	Texture	Hardiness	Economic Value	Total Plus (+)	% scoring
1	*Senegalia caesia*	+	+	++	+	++	+	+	+	10	62.5
2	*Calotropis gigantea*	+	+	++	-	++	+	-	+	9	56.25
3	*Nerium oleander*	+	+	+	+	-	-	+	-	5	31.25
4	*Ficus religiosa*	+	++	++	-	+	+	+	+	9	56.25
5	*Artocarpus heterophyllus*	+	++	++	+	++	+	+	+	11	68.75
6	*Gleditsia triacanthos*	+	++	++	+	-	-	+	+	8	50

Table S3: (Continued)

Location	Plant Species	APTI	Plant Habitat	Canopy Structure	Type of Plant	Size	Texture	Hardiness	Economic Value	Total Plus (+)	% scoring
7	*Datura metel* (White-Flowered Variety)	+	-	+	+	++	+	-	+	7	43.75
8	*Lantana camara*	+	+	++	+	+	+	-	+	8	50
9	*Wodyetia bifurcata*	+	++	+	+	+	+	+	-	8	50
10	*Tecoma stans*	+	+	+	+	+	-	-	-	5	31.25

Table S4: Anticipated performance index (API) of different tree species in Hyderabad City.

Location	Plant Species	Grade		API Value	Assessment
		Total plus	% Score		
1	*Senegalia caesia*	10	62.5	4	Good
2	*Calotropis gigantea*	9	56.25	3	Moderate
3	*Nerium oleander*	5	31.25	1	Very poor
4	*Ficus religiosa*	9	56.25	3	Moderate
5	*Artocarpus heterophyllus*	11	68.75	4	Good
6	*Gleditsia triacanthos*	8	50	2	Poor
7	*Datura metel* (White-Flowered Variety)	7	43.75	1	Very poor
8	*Lantana camara*	8	50	2	Poor
9	*Wodyetia bifurcata*	8	50	2	Poor
10	*Tecoma stans*	5	31.25	1	Very poor