Health Status of Street Trees Along the Urban–Rural Gradient in the Garden City of Bengaluru, India

Baragur Neelappa Divakara
bndsira@gmail.com

Institute of Wood Science and Technology
CU Nikhitha
Institute of Wood Science and Technology
VP Tewari
Institute of Wood Science and Technology

Research Article

Keywords: Urban–Rural gradient, Tree Health, Air Pollution Tolerance Index (APTI), Tolerant species, Bengaluru

Posted Date: July 11th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6946956/v1

Additional Declarations: No competing interests reported.

Abstract

Urban forestry involves the strategic management of trees within urban landscapes to enhance ecosystem services, improve biodiversity, mitigate climate change, and reduce the urban heat island effect. In addition to their ecological value, urban trees contribute aesthetic, economic, and functional benefits—such as increasing property value and attracting tourism. This study aimed to assess the health of urban trees exposed to various anthropogenic pressures in Bengaluru city. A total of 48 one-hectare plots were established—23 in the northern and 25 in the southern transects of the city. Trees with a diameter at breast height (DBH) of ≥10 cm were selected for analysis. Based on the extent of tree cover and built-up area, plots were categorized into urban, transition, and rural zones. Common tree species from each zone were evaluated for their Air Pollution Tolerance Index (APTI) in both transects. Fresh leaf samples were collected and analyzed for four key biochemical parameters: leaf pH, ascorbic acid content, relative water content, and total chlorophyll content. The results revealed that some species exhibited greater tolerance to air pollution. In the northern transect, *Mangifera indica*, *Psidium guajava*, *Ficus glomerata*, and *Pongamia pinnata* demonstrated higher APTI values, indicating greater tolerance. In the southern transect, *Mangifera indica*, *Ficus tinctoria*, *Commiphora caudata*, and *Alangium salviifolium* were identified as more tolerant. This study underscores the adaptive capacity of specific tree species to varying pollution levels and offers valuable insights for urban greening initiatives, species selection, and sustainable city planning aimed at enhancing ecological resilience and air quality in metropolitan areas.

Introduction

Urbanization is a continuous phenomenon observed in both developing and developed nations [48]. It typically refers to the demographic shift from rural areas to urban centres, influenced by a combination of economic, political, and geographical factors. Bengaluru, a major South Indian metropolis also known as the "Silicon Valley of India," has undergone rapid urbanization characterized by unplanned and uncontrolled development, demographic expansion, heterogeneous land use, deforestation, and various anthropogenic activities [46, 29]. Originally a modest village in the 12th century, Bengaluru has evolved into one of India's fastest-growing cities by the 21st century, now ranking as the second-fastest-growing and fifth-largest metropolis in the country [35, 46]. However, this rapid transformation has adversely impacted the region's biodiversity and ecosystem services, particularly through the reduction of green spaces and vegetation cover required to support the growing population [34, 28].

Urban green spaces are critical for delivering a range of ecological, environmental, economic, and social benefits. These include filtering airborne pollutants and dust [24, 6], mitigating the urban heat island effect and climate change [13], acting as noise barriers, alleviating urban floods, and enhancing biodiversity and ecosystem functionality [11, 36]. Additionally, they contribute to the hydrological cycle by recharging groundwater aquifers and stabilizing the urban climate [31]. Despite increasing scientific evidence over the past two decades highlighting the importance of urban green spaces, city planners and managers often undervalue the role of trees in maintaining urban ecological integrity [26, 17]. Effective conservation of urban biodiversity necessitates detailed data on tree species composition, including the influence of urbanization on species nativity. Notably, an increase in urban land cover is often associated with a rise in non-native species richness [4, 5]. Urban trees in Bengaluru face a range of anthropogenic stresses such as drought, impermeable surfaces restricting root growth, pest infestations, urban heat, humidity, and mechanical damage due to infrastructure development [43]. A study revealed that only 42% of the trees are native species, with four out of five being exotic [27].

Historically, Bengaluru was celebrated for its lush greenery and was famously dubbed the “Garden City of India,” a legacy attributed to Krishnaraja Wodeyar IV, who commissioned the creation of iconic green spaces such as Lalbagh and Cubbon Park. The city once boasted around 705 parks [10] and 200 additional green spaces (e.g., roadside and avenue trees), many of which have been lost due to urban development pressures [18]. Compared to surrounding rural areas, Bengaluru exhibits high species richness and diversity, largely due to the prevalence of exotic species. These urban green spaces serve as the city's “lungs,” contributing to pollution control, biodiversity conservation, and improved ecosystem services [45]. However, infrastructure projects like road widening and encroachments have led to a significant decline in large, mature canopy trees, exacerbating the urban heat island effect [26].

Urban trees are also vulnerable to vehicular pollution. Between 2005 and 2011, air pollution levels in the city fluctuated between critical and high at various monitoring sites. The Air Pollution Tolerance Index (APTI) is a valuable tool for assessing a tree's tolerance to urban air pollutants, based on physiological and biochemical parameters such as chlorophyll content, stomatal conductance, and relative water content of leaves. APTI is especially useful in assessing tree resilience to pollutants like nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and particulate matter (PM). Major sources of SO_2, NO_2, RSPM, and PM_{10} include vehicular emissions from fossil fuel combustion and industrial activities [12]. Previous assessments have reported that the estimated tree crown cover in Bengaluru stood at approximately 19.9%, with a per capita green space availability of around 17 m² [7, 44].

Given these findings, vegetation cover is a vital component of urban landscapes, essential for maintaining ecological balance and supporting human well-being. This study aims to evaluate the health of street trees across various urban-to-rural zones in Bengaluru using APTI as a key metric. By analyzing APTI values across the urban-rural gradient, the study seeks to understand how different tree species respond to varying pollution levels and how air pollution affects their overall health. These insights can inform urban planning and green space management strategies to mitigate pollution impacts and improve the city's ecological health.

Methodology

Bengaluru, the principal administrative capital of Karnataka, is geographically located in the southeastern part of the Indian peninsula, at coordinates 77°37'19.54" E and 12°59'09.76" N. The Greater Bengaluru area spans approximately 741 km² and falls under the jurisdiction of the Bruhat Bengaluru Mahanagara Palike (BBMP), which governs 198 wards across 8 zones. The city's spatial extent has undergone substantial urban expansion—growing more than tenfold from 69 km² in 1949 to 741 km² in 2006. The geographical boundaries of Bengaluru extend from 12°49'5" N to 13°8'32" N and from 77°27'29" E to 77°47'2" E. Bengaluru's population within BBMP limits witnessed a remarkable decadal growth of 47.18%, increasing from 6.53 million in 2001 to approximately 9.62 million in 2011. Consequently, population density surged from 10,732 persons/km² in 2001 to 13,392 persons/km² in 2011 [35].

Topographically, Bengaluru is situated at altitudes ranging between 740 m and 960 m above mean sea level. The city experiences an average annual rainfall of about 880 mm, typically spread over approximately 60 rainy days. Summer temperatures often exceed 38°C, whereas winter temperatures average around 25°C, contributing to the city's overall pleasant climate year-round. Positioned on a ridge, Bengaluru is drained by three principal valley systems: Hebbal-Nagavara, Koramangala-Challaghatta (K&C), and Vrishabhavathi. These valley systems facilitate drainage into major rivers such as the east-flowing Arkavathi and Pinakini (Pennar), and the west-flowing Shimsha, a tributary of the Cauvery. Historically, embankments constructed along these valleys gave rise to a network of tanks and lakes, which served irrigation and water storage purposes. While the low-lying areas are dominated by water bodies of varying sizes, the middle, northern, and eastern regions feature undulating terrain with scrub-covered highlands. The southern part is characterized by rugged hills surrounded by forests and scrub jungles. Geologically, the Bengaluru region is predominantly underlain by granitic and gneissic formations, interspersed with dolerites, dykes, and schist rocks [40].

Sampling and Data collection

The study was conducted on trees located in the northern and southern parts of Bengaluru city. A total of 48 plots, each measuring 100 m × 100 m (1 ha), were established—23 in the north and 25 in the south—along transects defined by the Indo-German research consortium (Fig. 1 & 2). Plot selection was based on a stratified random sampling approach, with two strata: "built-up" and "others." The "built-up" stratum was characterized by areas with more than 50% impervious surface, as identified from WorldView-3 satellite imagery (Fig. 1 & 2). All selected plots are within the "built-up" stratum, as the primary focus of the study was on urbanized areas.

For the study, plots delineated along the transects were categorized into urban, transition, and rural zones based on the proportion of built-up pixels derived from WorldView-3 satellite imagery. Grids with more than 50% built-up pixels were classified as *urban*, those with 10–50% as *transition*, and those with 0–10% as *rural*. The distance of each plot from the city center was also considered as a supplementary criterion for classification.

A total of 23 plots along the northern transect and 25 plots along the southern transect were surveyed in 2017 and 2018, respectively. The transects extended toward Doddaballapura in the north and Kanakapura in the south of Bengaluru. Using the geographic coordinates of each location, one-hectare (100 m × 100 m) plots were identified in the field using GPS. Distinct natural and anthropogenic features—such as buildings, roads, and tree arrangements—were used as reference markers to verify whether individual trees fell within or outside the plot boundaries. All trees within the plots were manually numbered with enamel paint on their stems to enable future identification and monitoring.

To achieve the study objectives, air quality data were obtained from monitoring stations operated by the Karnataka State Pollution Control Board (KSPCB) and the Central Pollution Control Board (CPCB). Data on particulate matter (PM_{10} and $PM_{2.5}$), sulfur oxides (SO_x), and nitrogen oxides (NO_x) were regularly collected from stations located in proximity to the plots.

To assess pollution-induced stress on urban vegetation, the Air Pollution Tolerance Index (APTI) was calculated for tree species across different land-use categories. From the northern transect, 15 common tree species representing urban, transition, and rural plots were selected for APTI analysis. Similarly, 16 common tree species were selected from the southern transect.

The APTI procedure was standardized, and leaf samples were analyzed on a day-to-day basis. Samples were collected from trees consistently exposed to vehicular emissions and other anthropogenic influences. Only mature leaves were selected for analysis, using a tree pruner to randomly sample leaves from the canopy. Samples were immediately transported to the laboratory in iceboxes to preserve their physiological integrity prior to analysis. The detailed methodology for APTI estimation is as follows:

a) Measurement of Leaf Extract pH

One gram of fresh leaf material was homogenized in 10 ml of distilled water using a mortar and pestle. The homogenate was then filtered, and the filtrate was diluted in a 1:1 ratio with distilled water. The resulting solution was centrifuged at 2,500 rpm for 3 minutes to remove any suspended particles [42, 21]. The pH of the clear supernatant was measured using a calibrated digital pH meter. The pH meter was calibrated using standard buffer solutions of pH 4.0 and 9.0 prior to measurement.

b) Determination of Relative Water Content (RWC)

Fresh leaves were initially weighed to record the fresh weight (FW). They were then immersed in distilled water for 24 hours to attain full turgidity. After immersion, the leaves were gently blotted dry with tissue paper and weighed to obtain the turgid weight (TW). Subsequently, the leaves were oven-dried at 70°C overnight to a constant weight, and the dry weight (DW) was recorded [41]. Relative Water Content was calculated using the formula:

RWC (%) = [(FW − DW) / (TW − DW)] × 100

where, W = Fresh weight of leaf; TW = Turgid weight of leaf; DW = Dry weight of leaf

c) **Estimation of Total Chlorophyll Content (TCC)**

To determine the total chlorophyll content, one gram of fresh leaf tissue was homogenized in 5 ml of 80 % acetone using a mortar and pestle. The volume was then made up to 10 ml with 80 % acetone, and the mixture was left undisturbed for 15–20 minutes to ensure thorough pigment extraction. The liquid extract was decanted into a clean test tube and centrifuged at 2,500 rpm for 3 minutes. If required, centrifugation was extended for an additional 3–4 minutes to ensure clear separation. The supernatant was carefully collected, and absorbance was measured using a spectrophotometer at wavelengths of 645 nm and 663 nm [3, 1]. Total chlorophyll content was calculated using the following formula:

$$Chlorophyll\ a = \frac{12.7\ A_{663} - 2.69\ A_{645}\ x\ V}{1000\ W}\ mg/g$$

$$Chlorophyll\ b = \frac{22.9\ A_{645} - 4.68\ A_{663}\ x\ V}{1000\ W}\ mg/g$$

$$TCh\ = [Chlorophyll\ a\ + Chlorophyll\ b]\ mg/g$$

Where, A = Absorbance of the extract at the wavelength y nm; V = Total volume of the chlorophyll solution (ml); W = Weight of the tissue extracted (g).

d) **Estimation of Ascorbic Acid Content (AAC)**

Requirements:

1. 4% (w/v) Oxalic acid: 40 g of oxalic acid in 1000 ml of distilled water.

2. Dye solution: 84 mg of sodium bicarbonate and 104 mg of 2, 6- dichlorophenol indophenol in 400 ml of distilled water.

3. Ascorbic acid stock standard: (1mg/ml): 100 mg in 100 ml of 4 % oxalic acid.

4. Ascorbic acid working standard: (100µg/ml): 10 ml of the ascorbic acid stock standard diluted to 100 ml with 4% oxalic acid.

Ascorbic acid content was determined using the **indophenol (DCPIP) titration method** [38]. Approximately one gram of fresh leaf tissue was accurately weighed and ground in a mortar and pestle with 10 ml of 4% oxalic acid. The homogenate was further ground and then filtered through filter paper. A 5 ml aliquot of the filtrate was transferred into a standard flask and the volume was made up to 25 ml with 4% oxalic acid. For standardization, 5 ml of the ascorbic acid working standard solution (500 µg/5 ml) was mixed with 10 ml of 4% oxalic acid in a 100 ml conical flask. This solution was titrated against the standard DCPIP dye solution until a persistent pale pink color appeared; the volume of dye used was noted as $\mathbf{V_1}$. Similarly, 5 ml of the prepared test sample was titrated against the DCPIP solution, and the dye volume required was recorded as $\mathbf{V_2}$. Ascorbic acid content in the test sample was calculated as follows:

$$Ascorbic\ Acid\ Content\ (mg/1g)\ = \frac{0.5\ x\ V2\ x\ 25}{V1\ x\ 1\ x\ 5}$$

where, 500 = µg of standard ascorbic acid taken for titration = 0.5 mg; V1 = Volume of dye consumed by 500µg of standard ascorbic acid; V2 = Volume of dye consumed by 5 ml of test sample; 25 = Corresponds to total volume of the extract; 1 = Weight of sample taken for extraction; 5 = Volume of the test sample taken for titration.

The APTI was calculated by the formula below [42];

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

where, A = Ascorbic acid content; T = Total Chlorophyll Content; P = p^H of the leaf sample;   R = Relative Water Content.

The air pollution index [47] and the plant response to pollution is mentioned below: the index range of <10 shows sensitive response, besides the index range of 10 - 16 and >17 show intermediate and tolerant responses respectively.

Results and Discussion

Air pollution data collected from three KSPCB monitoring stations near the study plots indicated that the Air Quality Index (AQI) ranged from satisfactory levels of 51 to 100. Among the measured pollutants, particulate matter (PM_{10}) was the only parameter consistently exceeding permissible limits. Other pollutants, including sulfur oxides (SO_x) and nitrogen oxides (NO_x), remained within acceptable regulatory thresholds (Fig. 3).

The results of APTI are as follows:

3.1 NORTHERN TRANSECT

3.1.1 APTI analysis

The selection of plant or tree species is a critical consideration when planting along roadsides or in urban green spaces. The Air Pollution Tolerance Index (APTI) is a useful tool to identify species based on their tolerance to air pollution. This index involves measuring leaf relative water content, pH, ascorbic acid, and chlorophyll content of leaf extracts [20]. Among the 15 tree species studied, *Mangifera indica*, *Psidium guajava*, *Ficus glomerata*, and *Pongamia pinnata* were relatively more tolerant compared to the other species. Although most species were categorized under a sensitive response category based on their APTI values, only *Mangifera indica* exhibited an intermediate tolerance level across the pollution gradient.

Overall, species from urban and transition plots demonstrated higher tolerance to pollution compared to those from rural plots (Tables 1 and 2). The tolerance ranking of species in urban plots, from most to least tolerant, is as follows:

Mangifera indica > *Psidium guajava* > *Grevillea robusta* > *Ficus glomerata* > *Tectona grandis* > *Syzygium cumini* > *Moringa oleifera* > *Eucalyptus* hybrid > *Murraya koenigii* > *Pongamia pinnata* > *Muntingia calabura* > *Tecoma stans* > *Artocarpus heterophyllus* > *Azadirachta indica* > *Samanea saman*.

Similarly, the tolerance ranking in transition plots, from least to most tolerant, is: *Muntingia calabura* < *Murraya koenigii* < *Artocarpus heterophyllus* < *Samanea saman* < *Azadirachta indica* < *Eucalyptus* hybrid < *Moringa oleifera* < *Syzygium cumini* < *Pongamia pinnata* < *Tectona grandis* < *Grevillea robusta* < *Ficus glomerata* < *Psidium guajava* < *Tecoma stans* < *Mangifera indica*. In rural plots, species such as *Murraya koenigii*, *Moringa oleifera*, and *Muntingia calabura* exhibited the lowest tolerance indices among the studied species (Tables 1 and 2).

Table 1
Parameters of Air Pollution Tolerance Index (APTI) along the domains of northern transect

		Urban				Transition				Rural			
Sl. No.	List of species	p^H	RWC	Ascorbic Acid	Total Chlorophyll	p^H	RWC	Ascorbic Acid	Total Chlorophyll	p^H	RWC	Ascorbic Acid	Total Chlorophyll
1	Mangifera indica	5.32	88.81	2.50	0.68	5.37	92.78	2.32	0.74	5.08	90.48	2.05	0.68
2	Artocarpus heterophyllus	6.06	61.45	0.63	0.70	6.03	70.33	0.09	0.70	6.11	61.38	0.36	0.71
3	Pongamia pinnata	6.91	70.77	0.09	0.67	6.16	82.86	0.09	0.69	6.25	71.43	0.09	0.69
4	Murraya koenigii	5.95	70.59	0.18	0.56	6.12	65.00	0.27	0.69	5.98	62.03	0.09	0.68
5	Azadirachta indica	6.18	54.82	0.96	0.66	6.32	69.51	0.88	0.63	6.38	77.78	0.76	0.69
6	Tectona grandis	6.83	84.23	0.18	0.69	6.59	86.95	0.09	0.70	5.80	75.78	0.18	0.57
7	Grevillea robusta	5.78	89.66	0.76	0.57	5.98	83.33	0.80	0.65	5.53	84.21	0.45	0.68
8	Muntingia calabura	7.52	62.50	0.98	0.23	5.83	64.29	0.31	0.70	5.85	39.26	0.58	0.71
9	Syzygium cumini	7.07	82.99	0.18	0.48	6.57	77.45	0.32	0.53	4.55	71.50	0.58	0.68
10	Samanea saman	5.90	50.00	1.07	0.70	5.95	71.43	0.58	0.70	5.63	74.64	0.58	0.71
11	Ficus glomerata	6.69	84.09	0.22	0.68	7.78	91.89	0.18	0.69	7.51	87.50	0.09	0.69
12	Tecoma stans	7.34	66.85	0.18	0.67	6.08	96.59	0.27	0.66	5.57	83.33	0.18	0.69
13	Psidium guajava	4.85	91.67	0.89	0.66	5.16	93.18	0.89	0.66	5.98	91.78	0.18	0.49
14	Moringa oleifera	5.61	80.00	0.63	0.70	5.44	75.00	0.63	0.69	5.27	42.86	0.18	0.67
15	Eucalyptus hybrid	4.97	69.85	0.82	0.59	5.29	72.68	0.74	0.67	4.85	78.90	0.67	0.67

Table 2
APTI values of northern transect

Species	Urban	Transition	Rural
Mangifera indica	10.38	10.70	10.23
Artocarpus heterophyllus	6.57	7.09	6.38
Pongamia pinnata	7.14	8.35	7.20
Murraya koenigii	7.18	6.68	6.26
Azadirachta indica	6.14	7.57	8.31
Tectona grandis	8.56	8.76	7.69
Grevillea robusta	9.45	8.87	8.70
Muntingia calabura	7.01	6.63	4.31
Syzygium cumini	8.43	7.97	7.45
Samanea saman	5.71	7.53	7.83
Ficus glomerata	8.57	9.34	8.82
Tecoma stans	6.83	9.84	8.45
Psidium guajava	9.66	9.84	9.29
Moringa oleifera	8.39	7.88	4.39
Eucalyptus hybrid	7.44	7.71	8.26

3.2 SOUTHERN TRANSECT

3.2.1 APTI analysis

Among the 16 tree species evaluated, *Mangifera indica*, *Ficus tinctoria*, *Commiphora caudata*, and *Alangium salviifolium* demonstrated relatively higher tolerance to air pollution compared to the others. Based on the Air Pollution Tolerance Index (APTI), all species were categorized under a sensitive response, except for *Mangifera indica*, which exhibited an intermediate response in both transition and rural plots. Overall, tree species in urban and rural plots showed comparatively higher tolerance than those in transition zones.

The tolerance index in rural plots, arranged in decreasing order, is as follows: *Mangifera indica* > *Commiphora caudata* > *Ficus tinctoria* > *Psidium guajava* > *Azadirachta indica* > *Alangium salviifolium* > *Grevillea robusta* > *Pongamia pinnata* > *Morus alba* > *Muntingia calabura* > *Tectona grandis* > *Murraya koenigii* > *Moringa oleifera* > *Phyllanthus acidus* > *Artocarpus heterophyllus* > *Leucaena leucocephala*.

In contrast, the tolerance index in transition plots, presented in increasing order, is: *Artocarpus heterophyllus* < *Murraya koenigii* < *Muntingia calabura* < *Psidium guajava* < *Grevillea robusta* < *Leucaena leucocephala* < *Moringa oleifera* < *Tectona grandis* < *Phyllanthus acidus* < *Alangium salviifolium* < *Azadirachta indica* < *Morus alba* < *Commiphora caudata* < *Pongamia pinnata* < *Ficus tinctoria* < *Mangifera indica*. Species such as *Phyllanthus acidus*, *Leucaena leucocephala*, *Artocarpus heterophyllus*, and *Moringa oleifera* recorded the lowest tolerance indices among all.

Global climate change is expected to intensify pollutant emissions and greenhouse gas release in tropical urban environments. Therefore, the selection of suitable tree species is crucial for urban greening initiatives, especially along roadsides and in green spaces. Based on this study, species categorized as sensitive can also serve as effective bio-indicators for environmental monitoring. These findings are consistent with earlier research [16, 14], which also reported similar physiological responses in tree species under polluted conditions. Notably, a shift toward acidic pH in urban plots and reductions in total chlorophyll content and relative water content suggest physiological stress in trees due to pollution [14].

Table 3
Parameters of Air Pollution Tolerance Index (APTI) along the domains of southern transect

		Urban				Transition				Rural			
Sl. No.	List of species	P^H	RWC	Ascorbic Acid	Total Chlorophyll	P^H	RWC	Ascorbic Acid	Total Chlorophyll	P^H	RWC	Ascorbic Acid	Total Chlorophyll
1	Mangifera indica	4.88	85.71	1.38	0.65	5.11	92.59	1.63	0.69	5.91	88.98	1.88	0.73
2	Artocarpus heterophyllus	5.75	65.66	0.25	0.64	5.89	56.23	0.50	0.67	6.40	60.70	0.13	0.73
3	Pongamia pinnata	6.12	82.50	0.13	0.51	6.60	84.88	0.13	0.68	6.51	79.59	0.13	0.70
4	Murraya koenigii	5.66	70.00	0.25	0.64	6.07	57.89	0.25	0.57	5.87	71.43	0.13	0.60
5	Azadirachta indica	6.03	71.43	0.13	0.64	6.70	76.92	0.75	0.68	6.47	82.61	0.81	0.72
6	Tectona grandis	6.86	77.56	0.25	0.64	6.32	77.96	0.13	0.68	6.26	73.45	0.13	0.69
7	Alangium salviifolium	5.50	85.19	1.25	0.64	6.23	78.95	0.38	0.66	6.36	80.95	0.50	0.47
8	Grevillea robusta	5.61	80.00	0.13	0.66	5.73	64.00	0.13	0.74	6.23	78.95	0.25	0.71
9	Muntingia calabura	5.38	73.68	0.13	0.61	6.27	60.00	0.25	0.66	5.97	75.86	0.69	0.68
10	Phyllanthus acidus	5.78	69.23	0.25	0.58	5.98	80.00	0.13	0.58	6.32	66.67	0.13	0.73
11	Psidium guajava	5.17	85.37	0.13	0.51	5.96	62.50	0.25	0.54	5.96	86.36	0.50	0.51
12	Moringa oleifera	5.48	60.00	0.38	0.58	5.43	75.00	0.38	0.69	5.73	66.67	0.50	0.55
13	Morus alba	6.21	71.67	0.25	0.65	6.24	82.43	0.25	0.66	6.82	79.55	0.13	0.67
14	Leucaena leucocephala	6.16	66.67	0.13	0.61	6.43	66.67	0.50	0.68	6.44	50.00	0.13	0.72
15	Ficus tinctoria	5.68	86.03	0.25	0.62	6.19	89.07	0.13	0.65	5.82	87.67	0.38	0.65
16	Commiphora caudata	4.49	80.00	0.13	0.58	4.78	84.00	0.13	0.57	5.52	90.48	0.13	0.56

Table 4
APTI values of southern transect

Species	Urban	Transition	Rural
Mangifera indica	9.33	10.20	10.14
Artocarpus heterophyllus	6.73	5.95	6.16
Pongamia pinnata	8.33	8.58	8.05
Murraya koenigii	7.16	5.96	7.22
Azadirachta indica	7.23	8.25	8.85
Tectona grandis	7.94	7.88	7.43
Alangium salviifolium	9.29	8.15	8.44
Grevillea robusta	8.08	6.48	8.07
Muntingia calabura	7.44	6.17	8.04
Phyllanthus acidus	7.08	8.08	6.75
Psidium guajava	8.61	6.41	8.96
Moringa oleifera	6.23	7.73	6.98
Morus alba	7.34	8.42	8.05
Leucaena leucocephala	6.75	7.02	5.09
Ficus tinctoria	8.76	8.99	9.01
Commiphora caudata	8.06	8.47	9.12

The Air Pollution Tolerance Index (APTI) has been widely employed across different geographic regions to evaluate the tolerance of plant species to atmospheric pollutants. Several studies across industrial and urban landscapes have yielded insightful comparisons of plant species in relation to their pollution response mechanisms.

In Beijing, China, a study near a steel industry identified *Broussonetia papyrifera*, *Robinia pseudoacacia*, and *Ailanthus altissima* as species with moderate to high tolerance to industrial emissions [22]. Similarly, in Delta State, Nigeria, species such as *Emilia samtfolia*, *Manihot esculenta*, and *Elaeis guineensis* exhibited higher APTI values near the Otorogun Gas Plant, indicating their resilience in a polluted environment [1]. At the Erhoike-Kokori oil drilling site in the same region, *Mangifera indica* and *Chromolaena odorata* topped the tolerance rankings, while *Psidium guajava* and *Elaeis guineensis* showed lower tolerance [2].

In Enugu, Nigeria, APTI analysis in both urban and industrial zones revealed that tree species generally outperformed ornamental shrubs in pollution tolerance. *Anacardium occidentale*, *Pinus spp.*, and *Catalpa bungei* recorded higher APTI values than shrubs, suggesting their suitability for urban landscaping to combat heat island effects [15]. Furthermore, in the Ama industrial area of Enugu, *Delonix regia* (APTI: 5.308 ± 0.090) showed significantly higher tolerance compared to *Anacardium occidentale* (APTI: 3.470 ± 0.001) [32].

In Pulau Pinang, Malaysia, comparative evaluation between *Ficus sp.* and *Bougainvillea sp.* along major roads showed that *Ficus* exhibited greater APTI values, indicating higher tolerance, while *Bougainvillea* was more sensitive and suitable as a biological indicator [25].

In Côte d'Ivoire, *Ficus benjamina* recorded the highest APTI among ornamental plants (up to 17.15), followed by *Jatropha integerrima* and *Barleria prionitis*. *Cassia surattensis* was the most sensitive species based on APTI scores [47]. Studies from Ahvaz, Iran, showed notable spatial variation in APTI values across polluted and non-polluted sites. *Myrtus* exhibited the highest tolerance in both areas, while *Prosopis* showed vulnerability to pollution, with its APTI dropping from 4.97 (unpolluted) to 4.57 (polluted) [16].

In the Babylon region of Mesopotamia, *Conocarpus lancifolius* was found tolerant, while *Dodonaea viscosa* was more sensitive, as influenced by prevailing wind directions and proximity to pollution sources [39].

A notable observation from several studies is the positive correlation between higher ascorbic acid content and SO_2 tolerance, supporting the use of physiological parameters in APTI computation [49]. In Indian studies, *Mangifera indica*, *Alstonia scholaris*, and *Eupatorium odoratum* emerged as effective biomonitors of vehicular pollution [19].

In Bangalore, India, field comparisons showed that *Bougainvillea spectabilis* and *Ageratum conyzoides* had significant drops in APTI values from control to polluted sites, indicating high sensitivity, whereas *Peltophorum pterocarpum* and *Portulaca oleraceae* retained relatively stable scores, marking them as pollution-tolerant species [14].

A broader study assessing APTI and Anticipated Performance Index (API) for 29 species showed that *Ficus benghalensis*, *Cassia fistula*, and *Ficus religiosa* had the highest tolerance scores, while *Mangifera indica* showed lower tolerance in comparison. In marble industrial zones of Potwar, species such as *Polyalthia longifolia*, *Ficus glomerata*, and *Ailanthus indicus* were noted for their resilience [33].

In Navsari, India, *Cassia fistula* outperformed other species like *Saraca asoca* and *Syzygium cumini* in terms of APTI, affirming its tolerance in urban polluted environments. In contrast, *Tectona grandis* and *Terminalia catappa* showed moderate sensitivity [30]. Lastly, in Dehradun, *Eucalyptus globulus* exhibited the highest APTI values, followed by *Ficus religiosa* and *Mangifera indica*, while lower APTI was observed in species like *Lantana camara* [23].

Conclusion

The APTI values indicated that several tree species found along the northern and southern transects exhibit relatively higher tolerance to air pollution. In the northern transect, species such as *Mangifera indica*, *Psidium guajava*, *Ficus glomerata*, and *Pongamia pinnata* were identified as pollution-tolerant. Similarly, in the southern transect, *Mangifera indica*, *Ficus tinctoria*, *Commiphora caudata*, and *Alangium salviifolium* demonstrated higher tolerance levels. These findings underscore the importance of selecting tree species based on the local air quality index (AQI). In urban environments—where pollution levels are often elevated—prioritizing species with high APTI values is critical for the success and sustainability of urban forestry and landscape planning initiatives. Pollution-tolerant species not only have a higher likelihood of survival in degraded environments, but also contribute significantly to mitigating air pollution, reducing urban heat island effects, and enhancing biodiversity. Therefore, incorporating APTI as a guiding criterion in species selection can improve the resilience and ecological performance of urban green spaces. This approach ensures that planted trees are better adapted to prevailing environmental stresses, thereby maximizing the long-term benefits of urban forests. In turn, this supports the development of healthier, greener, and more sustainable cities.

Declarations

Acknowledgements: The authors express their sincere gratitude to the Director, Institute of Wood Science and Technology (IWST), for providing the necessary facilities and institutional support to carry out this study. The research was funded by the Department of Biotechnology (DBT), Government of India, under the Indo-German collaborative program, which is gratefully acknowledged. The authors also extend their appreciation to the German collaborators, Dr. Christoph Kleinn and Dr. Nils Nölke from Georg-August-University, Göttingen, Germany, for their valuable contributions to the Indo-German research consortium. Their support in providing WorldView-3 satellite imagery was instrumental in the layout and selection of plots along the urban–rural gradient across the northern and southern transects of Bengaluru.

Funding: The study was funded by the **Department of Biotechnology (DBT), Government of India, New Delhi**, under the **Indo-German collaborative research programme.**

Author contributions: All authors have approved the final version of the manuscript.

B.N.D. conceptualized, planned, and executed the fieldwork, and led the drafting of the manuscript.
C.U.N. assisted in data collection, compilation, and contributed to the manuscript drafting.
V.P.T. supported the execution of the study, reviewed the manuscript, and provided valuable suggestions for its improvement.

Competing interests: The authors declare that they have received no financial support for the preparation of this manuscript and have no competing interests to disclose.

Ethics approval and Consent to participate: The collection of leaf samples in this study was carried out in accordance with applicable local and national guidelines. All samples were obtained from cultivated plants, and no endangered or protected species were involved.

Data availability: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Consent to Publish: All authors have read and approved the final manuscript and consent to its publication.

Clinical trial number: Not Applicable

References

1. Agbaire PO, Esiefarienrhe E. Air Pollution Tolerance Indices (APTI) of some plants around Otorogun Gas Plant in Delta State, Nigeria. J Appl Sci Environ Manage. 2009;13(1):11–4.
2. Agbaire PO. Air pollution tolerance indices (APTI) of some plants around Erhoike-Kokori oil exploration site of Delta State, Nigeria. Int J Phys Sci. 2009;4(6):366–8.
3. Arnon DI. Copper Enzymes in Isolated Chloroplasts Polyphenol Oxidase in Beta vulgaris. Plant physiol. 1949;24:1–15.
4. Aronson MF, La Sorte FA, Nilon CH, Katti M, Goddard MA, Lepczyk CA, Warren PS, Williams NS, Cilliers S, Clarkson B, Dobbs C, Dolan R, Hedblom M, Klotz S, Kooijmans JL, Kühn I, Macgregor-Fors I, McDonnell M, Mörtberg U, Pysek P, Siebert S, Sushinsky J, Werner P, Winter M. 2014. A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. Proceedings of The Royal Society, B: Biological Sciences, 281:20133330. 10.1098/rspb.2013.3330
5. Aronson MFJ, Handel SN, La Puma IP, Clemants SE. Urbanization promotes non-native woody species and diverse plant assemblages in the New York metropolitan region. Urban Ecosyst. 2015;18(1):31–45.

6. Beckett KP, Smith PF, Taylor G. The capture of particulate pollution by trees at five contrasting UK urban sites. Arboricultural J. 2000;24:2–3. 10.1080/03071375.2000.9747273.
7. Behera G, Nageshwara R, Dutt PP, Manikiam B, Balakrishna P, Krishnamurthy J, Jagadeesh KM, Ganesha RK, Diwakar PG, Padmavathy AS, Parvathy R. 1985. Growth of Bangalore city since 1980 based on maps and satellite imagery, Technical Report, ISRO-EOS-TR-55-85, Indian Space Research Organization, Bangalore, India.
8. Census of India. 2001. https://www.census2011.co.in/census/district/242-bangalore.html
9. Census of India. 2011. https://www.census2011.co.in/census/city/448-bangalore.html
10. Chaudhry P, Bagra K, Singh B. Urban Greenery Status of Some Indian Cities: A Short Communication. Int J Environ Sci Dev. 2011;2(2):98–101.
11. Chaudhry P, Tewari VP. Urban forestry in India: development and research scenario. Interdisciplinary Environ Rev. 2011;12(1):80–93. 10.1504/IER.2011.038881.
12. Chinnaswamy AK, Naguib RNG, Nguyen QT, Olayanju LO, Trodd N, Marshall IM, Yaacob N, Santos GN, Vallar EA, Galvez MC, Shaker MH, Ton TN. 2014. Air Pollution in Bangalore, India: A Six-Year Trend and Health Implication Analysis. Proc. IEEE Int. Conf. on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management at Manila, Philippines. https://www.researchgate.net/publication/257816315
13. Chow WTL, Roth M. Temporal dynamics of the urban heat island of Singapore. Int J Climatol. 2006;26:2243–60.
14. Deepalakshmi AP, Ramakrishnaiah H, Ramachandra YL, Radhika RN. Roadside Plants as Bio-indicators of Urban Air Pollution. J Environ Sci Toxicol Food Technol. 2013;3(3):10–4.
15. Enete IC, Chukwudeluzu VU, Okolie AO. Evaluation of Air Pollution Tolerance Index of Plants and Ornamental Shrubs in Enugu City: Implications for Urban Heat Island Effect. World Environ. 2013;3(3):108–15. 10.5923/j.env.20130303.06.
16. Gholami A, Mojiri A, Amini H. Investigation of the air pollution tolerance index (APTI) using some plant species in Ahvaz Region. J Anim Plant Sci. 2016;26(2):475–80.
17. Gopal D, Nagendra H. Vegetation in Bangalore’s slums: Boosting livelihoods, well-being and social capital. Sustainability. 2014;6:2459–573. 10.3390/su6052459.
18. Gowda K, Sridhara MV, Rajan S. Planning and management of parks and green areas: The case of Bangalore metropolitan area. Manage Environ Qual. 2007;19(3):270–82.
19. Jyothi SJ, Jaya DS. Evaluation of air pollution tolerance index of selected plant species along roadsides in Thiruvananthapuram, Kerala. J Environ Biol. 2010;31(3):379–86.
20. Kaur M, Nagpal AK. Evaluation of air pollution tolerance index and anticipated performance index of plants and their application in development of green space along the urban areas. Environ Sci Pollut Res. 2017;24:18881–95. 10.1007/s11356-017-9500-9.
21. Kumari J, Deswal S. Assessment of Air Pollution Tolerance Index of Selected Plants Unveil to Traffic Roads of Noida, Uttar Pradesh. Int J Emerg Technol. 2017;8(1):179–84.
22. Liu Y, Ding H. Variation in air pollution tolerance index of plants near a steel factory: Implications for landscape-plant species selection for industrial areas. WSEAS Trans Environ Dev. 2008;1(4):24–32.
23. Lohe RN, Tyagi B, Singh V, Tyagi PK, Khanna DR, Bhutiani R. A comparative study for air pollution tolerance index of some terrestrial plant species. Global J Environ Sci Manage. 2015;1(4):315–24. 10.7508/gjesm.2015.04.006.
24. McPherson EG, Nowak D, Heisler G, Grimmond S, Souch C, Grant R, Rowntree P. Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. Urban Ecosyst. 1997;1:49–61.
25. MohdSabri SNA, Ahmad MI, Yusup Y. Assessment of Air Pollution Tolerance Index of Selected Plant Species Commonly Found along Roadsides in Pulau Pinang, Malaysia. Int J Sci Res. 2015;4(11):1914–8. Paper ID: NOV151452.
26. Nagendra H, Gopal D. Street trees in Bangalore – Density, diversity, composition and distribution. Urban forestry Urban Green. 2010;9:129–37.
27. Nagendra H, Gopal D. Tree diversity, distribution, history and change in urban parks: studies in Bangalore, India. Urban Ecosyst. 2011;14:211–23.
28. Nagendra H, Sudhira HS, Katti M, Schewenius M. 2013. In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment (eds Elmqvist, T. 65–74 (Springer Netherlands, Dordrecht, 2013) 10.1007/978-94-007-7088-1_33
29. Narayana MR. Globalization and Urban Economic Growth: Evidence for Bangalore, India. Int J Urban Reg Res. 2011;35:1284–301.
30. Nayak D, Patel DP, Thakare HS, Satashiya K, Shrivastava PK. Evaluation of air pollution tolerance index of trees. Res Environ Life Sci. 2015;8(1):7–10.
31. Nidzgorski DA, Hobbie SE. Urban trees reduce nutrient leaching to groundwater. Ecol Appl. 2016;26:1566–80.
32. Nwadinigwe AO. Air pollution tolerance indices of some plants around Ama industrial complex in Enugu State, Nigeria. Afr J Biotechnol. 2013;13(11):1231–6. 10.5897/AJB2014.13616.
33. Pandey AK, Pandey M, Mishra A, Tiwary SM, Tripathi BD. Air pollution tolerance index and anticipated performance index of some plant species for development of urban forest. Urban Forestry Urban Green. 2015;14:866–71. http://dx.doi.org/10.1016/j.ufug.2015.08.001.
34. Paul S, Nagendra H. Vegetation change and fragmentation in the mega city of Delhi: Mapping 25 years of change. Appl Geogr. 2015;58:153–66. 10.1016/j.apgeog.2015.02.001.
35. Ramachandra TV, Aithal BH, Durgappa DS. Insights to urban dynamics through landscape spatial pattern analysis. Int J Appl Earth Obs Geoinf. 2012;18:329–43.
36. Ramachandra TV, Aithal BH, Kulkarni G, Vinay S. Green spaces in Bengaluru: Quantification through geospatial techniques. Indian forester. 2017;143(4):307–20.

37. Roth M. Review of urban climate research in (sub)tropical regions. Int J Climatol. 2007;27:1859–73. 10.1002/joc.1591.
38. Sadasivam S, Manickam A. 1991. Biochemical methods, New Age International Publishers.
39. Salaa MM, Al-Kawaz LS. Assessment of Air Pollution Using Air Pollution Tolerance Index (APTI) by two species plant (Conocarpus lancifolius and Dodonaea viscosa) in Bbylon provinus plant. Mesopotemia Environ J. 2017;3(2):11–7.
40. Sekhar M, Mohan Kumar MS. 2009. Geo-hydrological studies along the metro rail alignment in Bangalore. Technical report, Department of Civil Engineering, Indian Institute of Science, Bangalore, India. http://bmrc.co.in/pdf/news/iisc-report.pdf
41. Singh A. Practical Plant physiology. New Delhi: Kalyari; 1977.
42. Singh SK, Rao DN. 1983. Evaluation of plants for their tolerance to air pollution. In Proc. Symp. on Air pollution control, IIT, Delhi, pp 218–224.
43. Stagoll K, Lindenmayer DB, Knight E, Fischer J, Manning AD. Large trees are keystone structures in urban parks. Conserv Lett. 2012;5:115–22.
44. Sudha P, Ravindranath NH. A study of Bangalore urban forest. Landsc Urban Plann. 2000;47(1–2):47–63.
45. Sudhira HS, Nagendra H. Local Assessment of Bangalore: Graying and Greening in Bangalore - Impacts of Urbanization on Ecosystems, Ecosystem Services and Biodiversity. In: Elmqvist T, et al. editors. Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Dordrecht: Springer; 2013. pp. 75–91. https://doi.org/10.1007/978-94-007-7088-1_7.
46. Sudhira HS, Ramachandra TV, Subrahmanya MHB. City profile Bangalore Cities. 2007;24:379–90.
47. Tra Bi ZF, Angaman DM, Barima YSS, Dongui BK. Evaluation of air pollution tolerance indices of four ornamental plants arranged along roadsides in Abidjan (Côte d'Ivoire). Int J Environ Monit Anal. 2015;3(1):22–7. 10.11648/j.ijema.20150301.14.
48. United Nations. Urbanization and Development - Emerging Futures (World Cities report) [United. Nations Human Settlements Programme (UN-Habitat)]; 2016.
49. Varshney SRK, Varshney CK. Effects of SO2 on ascorbic acid in crop plants. Environ Pollution Ser Ecol Biol. 1984;35(4):285–90.

Figures

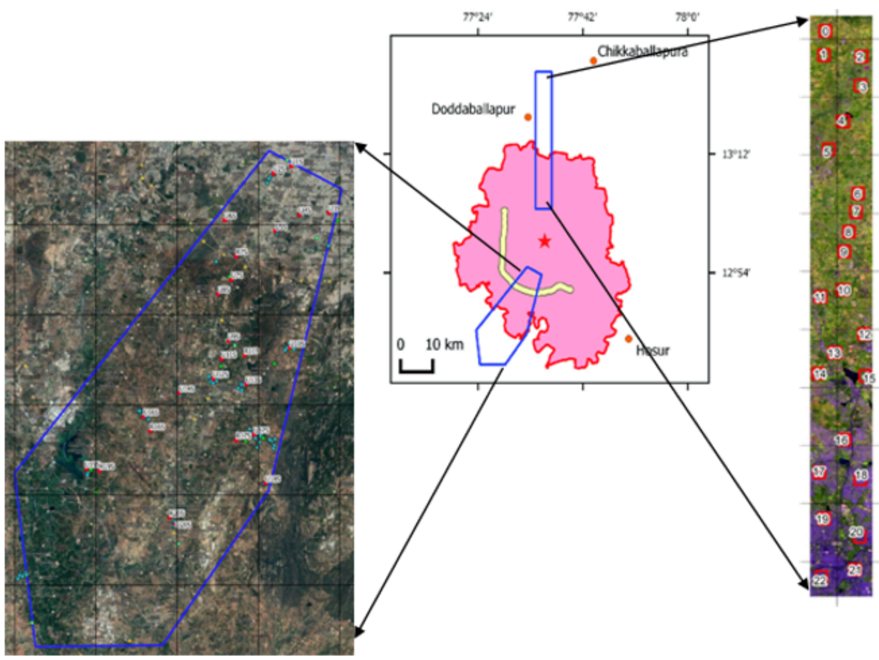

Figure 1

Location of the study area in the northern and southern part of Bengaluru

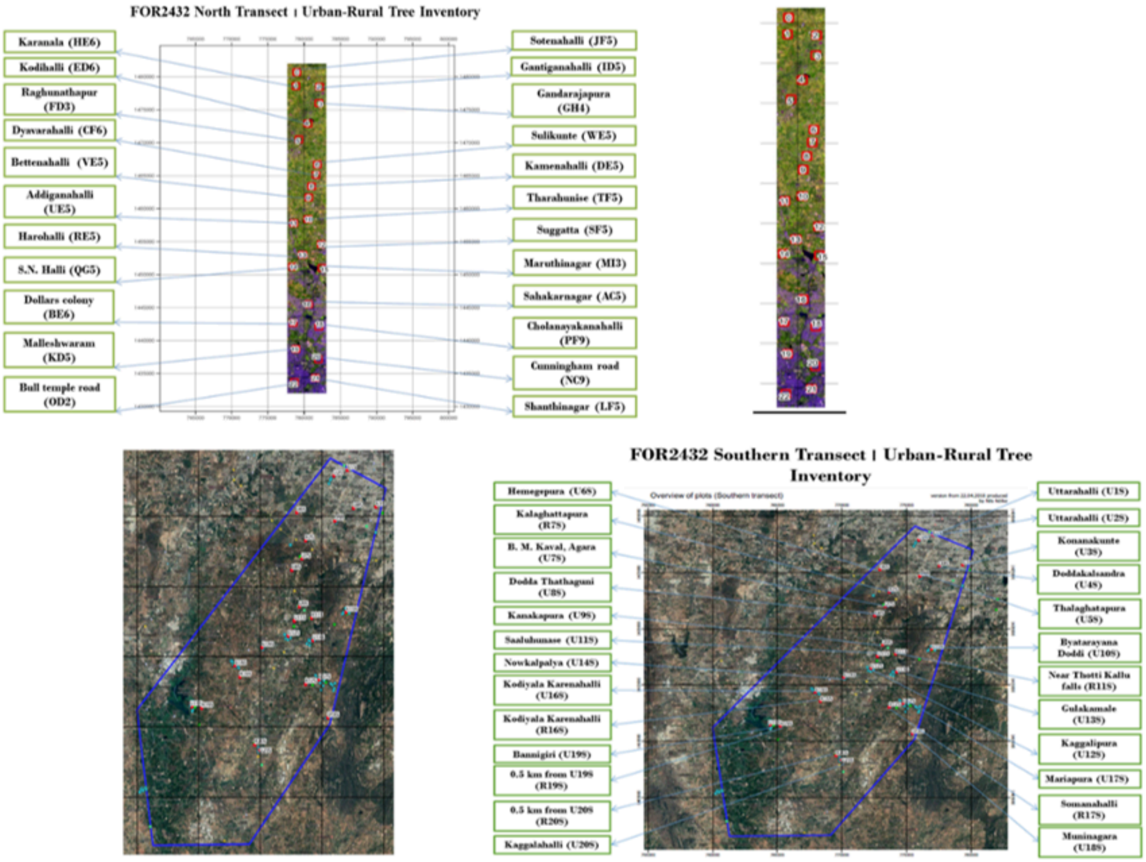

Figure 2

Study plots identified along the northern and southern part of Bengaluru

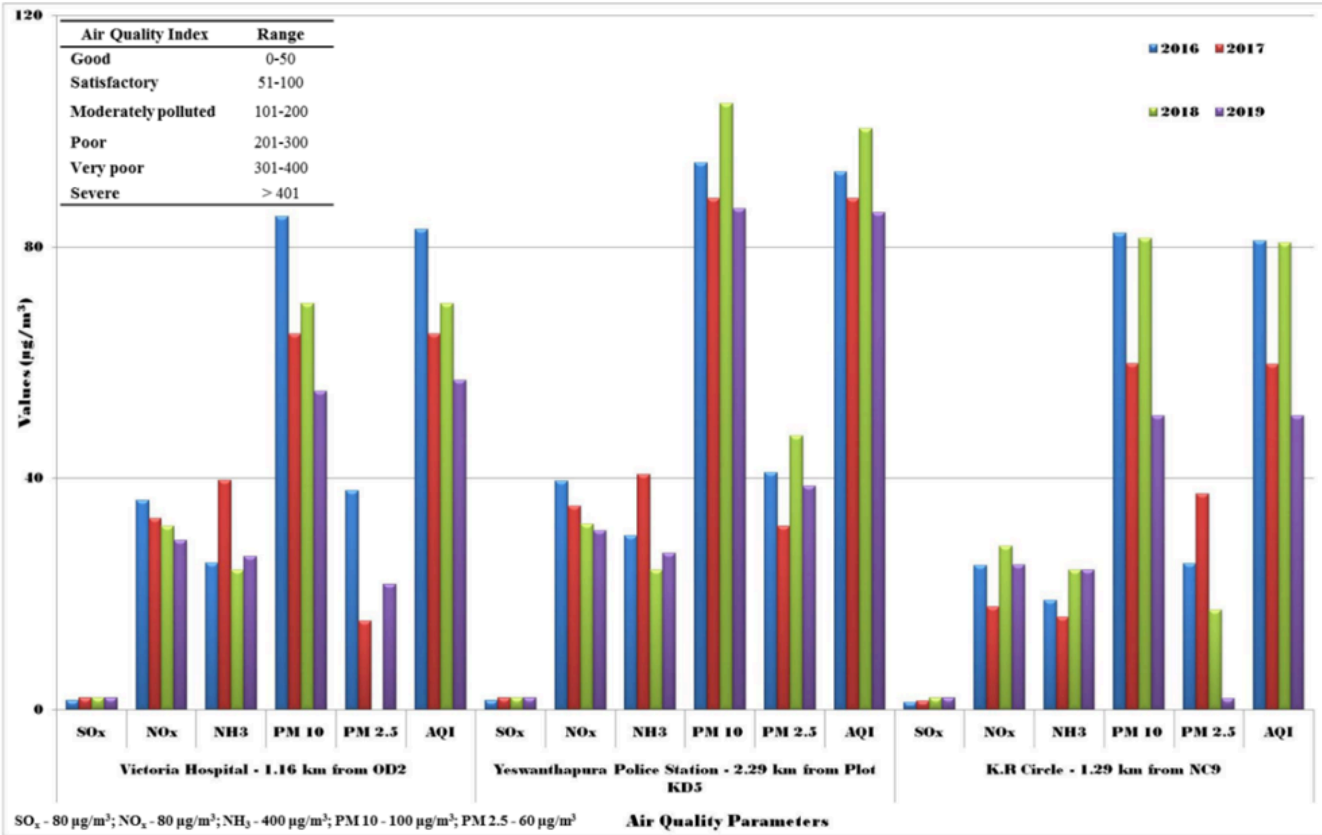

Figure 3

Air quality parameters from the Karnataka State Pollution Control Board (KSPCB) monitoring stations