

Evaluating the pollution tolerance potential of commonly grown tree species in the urban megacity of Dhaka, Bangladesh

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ABSTRACT

Rapid urbanization and traffic-related emissions pose important challenges for vegetation in tropical megacities. This study evaluated variation in leaf-surface dust accumulation and selected physiological and biochemical traits of ten commonly grown tree species sampled from a reference site and a traffic-exposed urban site in Dhaka, Bangladesh. Leaf dust deposition, leaf extract pH, total chlorophyll, ascorbic acid content (AAC), relative water content (RWC), and the Air Pollution Tolerance Index (APTI) were quantified and compared using two-way analysis of variance, principal component analysis, and correlation analysis. Two-way ANOVA revealed that dust deposition was significantly higher at polluted sites, with *Ficus benghalensis* exhibiting exceptionally more dust accumulation, indicating high surface dust retention capacity. Most species showed significant reductions in chlorophyll content and leaf pH under polluted conditions, reflecting impaired photosynthetic integrity and tissue acidification. In contrast, tolerant species maintained higher AAC and RWC, suggesting effective antioxidative defense and water regulation under pollution stress. APTI values revealed pronounced interspecific variability, identifying *Polyalthia longifolia* and *Mimusops elengi* as highly tolerant, while *Terminalia catappa* and *Swietenia mahagoni* were the most sensitive species. Principal component and correlation analyses demonstrated a pollution-induced reorganization of trait relationships, with tolerance at polluted sites governed primarily by antioxidative capacity and water status. Overall, the findings demonstrate substantial species-specific variation in leaf traits and APTI under contrasting urban exposure conditions. The results provide a basis for further evaluation of tree species for urban planting and biomonitoring, while direct measurements of ambient pollutants and replicated sites are needed to establish pollutant-specific responses and broader ecological applicability.

KEYWORDS: Urban vegetation; Biochemical parameters; Leaf dust; Tolerance index; Pollution stress

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1. INTRODUCTION

Rapid urbanization and industrial expansion in developing countries have intensified environmental degradation, with air pollution emerging as a major threat to urban sustainability [1]. Elevated concentrations of particulate matter, nitrogen oxides, sulfur dioxide, carbon monoxide, and ground-level ozone are now common features of many megacities, posing serious risks to public health, ecosystem stability, and climate regulation [2-4]. Among these, Dhaka, the capital of Bangladesh, frequently ranks among the most polluted cities worldwide, driven by dense traffic congestion, rapid infrastructure development, and limited emission control measures [5-6].

Urban vegetation, particularly roadside and peri-urban trees, plays a critical role in mitigating air pollution by intercepting particulate matter, absorbing gaseous pollutants, and regulating microclimatic conditions [7-

9]. However, continuous exposure to high pollution loads can compromise plant physiological performance. Dust deposition on leaf surfaces may obstruct stomatal apertures, reduce photosynthetic efficiency, and impair gas exchange, while gaseous pollutants penetrating leaf tissues can induce oxidative stress through excessive production of reactive oxygen species (ROS) [2,10]. If not adequately neutralized by antioxidative defense mechanisms, ROS can damage cellular membranes, pigments, and metabolic processes, ultimately reducing plant growth and survival in polluted urban environments [11-12].

Plants exhibit species-specific physiological and biochemical adjustments in response to pollution stress, including alterations in chlorophyll concentration, leaf extract pH, relative water content, and antioxidant metabolites such as ascorbic acid [13-14]. These traits collectively determine a plant's tolerance or sensitivity to air pollution. The Air Pollution Tolerance Index (APTI), which integrates these parameters, has been widely applied as a reliable indicator for assessing plant resilience under polluted conditions [9,15-16]. Species with higher APTI values are considered pollution-tolerant and suitable for urban greening, whereas species with lower values are regarded as sensitive and useful as bioindicators of environmental stress [14,17-18].

Despite its broad application, APTI-based multi-species assessment in Dhaka remains limited, particularly under realistic urban conditions where plants experience simultaneous exposure to ambient air pollutants and heavy particulate deposition on leaf surfaces. Moreover, most previous studies have evaluated pollution stress in isolation, without adequately capturing the combined influence of atmospheric pollution intensity [5] and surface-bound particulates that characterize megacity environments [19]. This gap constrains effective species selection for urban forestry and limits the integration of plant functional traits into pollution-mitigation planning.

In this context, The present study therefore compared ten common tree species growing at a reference site and a traffic-exposed urban site in Dhaka. The study quantified leaf-surface dust deposition, leaf extract pH, total chlorophyll, AAC, RWC, and APTI and examined patterns of variation among species and sites. We hypothesized that (i) leaf-surface dust deposition and selected physiological and biochemical traits would differ between the two contrasting urban locations; (ii) species would differ in the magnitude and direction of their responses to the contrasting site conditions; and (iii) APTI would differ among species and between sites, providing a comparative screening of species based on the traits incorporated into the index. By explicitly accounting for both ambient pollution and leaf surface dust accumulation, this study provides a more realistic and functionally relevant assessment of urban tree performance and provides a scientific basis for selecting resilient species for urban greening and air quality mitigation in highly polluted tropical cities.

2. MATERIALS AND METHODS

2.1. STUDY AREA

The study was conducted at two contrasting sites in Dhaka, Bangladesh: The National Botanical Garden (control site) and the Motijheel-Sayedabad area (polluted site) (Fig. 1). The National Botanical Garden, located in Mirpur (23.81660° N, 90.34875° E) and covering approximately 204 acres, is characterized by high vegetation cover, rich plant diversity, and comparatively low vehicular activity, making it suitable as a reference site [6,8,20]. In contrast, the Motijheel–Sayedabad area is a major urban pollution hotspot due to persistent heavy traffic, dominated by vehicles, and busy roads, leading to elevated particulate matter emissions [5-6,8]. These contrasting conditions enabled an effective assessment of the impacts of urban air pollution on vegetation.

2.2. STUDY SPECIES AND SAMPLING DESIGN

Based on their prevalence and distribution across the study locations, ten common tree species were selected: *Swietenia mahagoni*, *Polyalthia longifolia*, *Ficus benghalensis*, *Mangifera indica*, *Syzygium cumini*, *Terminalia catappa*, *Artocarpus heterophyllus*, *Terminalia arjuna*, *Mimusops elengi*, and *Ficus religiosa*.

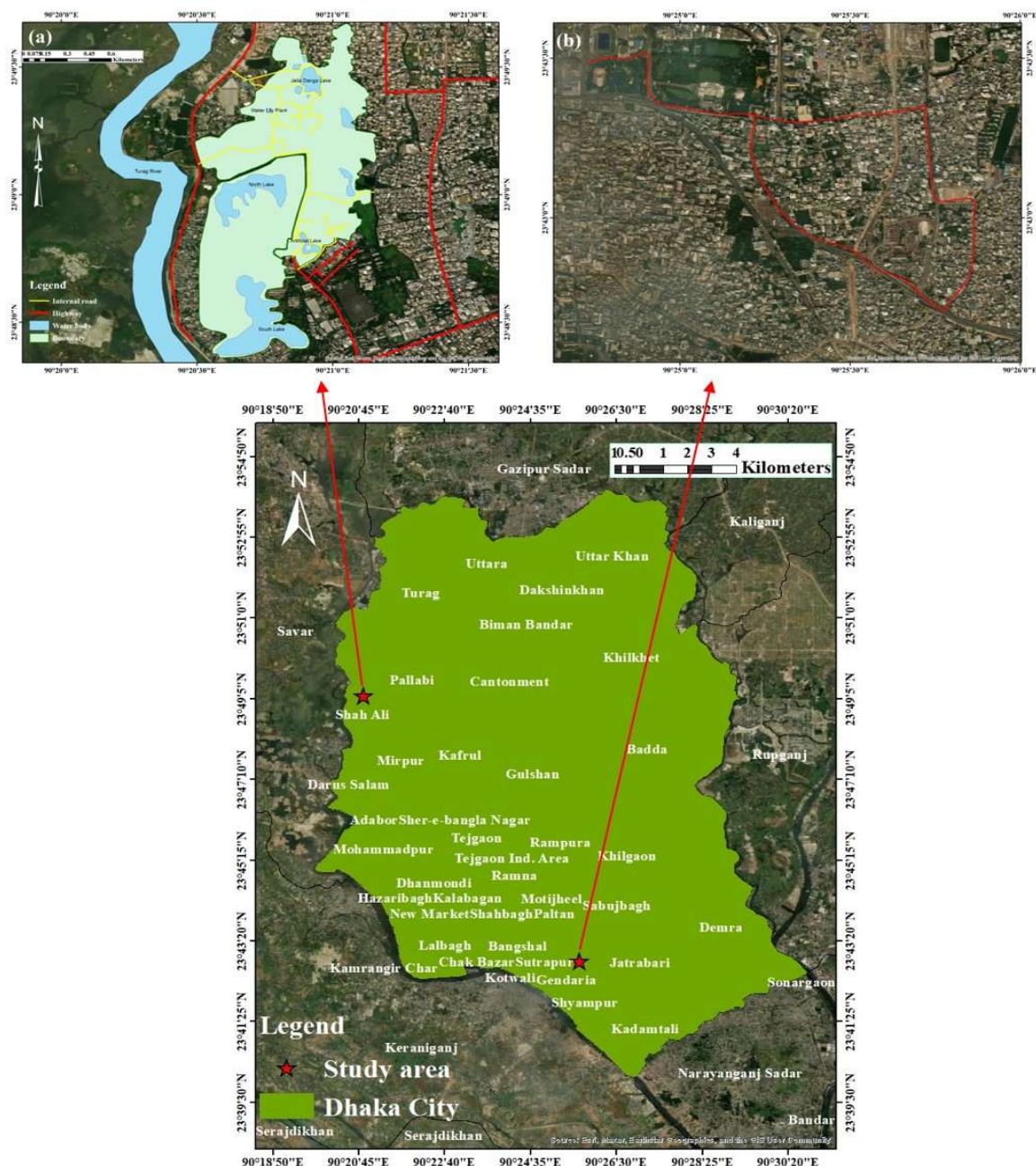


Figure 1. Map of the study area in Dhaka, Bangladesh, showing the Botanical Garden as the control site (a) and Motijheel–Sayedabad as the polluted site (b).

At each location, we selected three healthy mature trees of each species as biological replicates. From each tree, several leaves were collected; ten were randomly selected as subsamples for dust deposition, and more than ten for biochemical analyses. Mean values of subsampled leaves were calculated for each tree, and tree means ($n=3$ per species per site) were used in all statistical analyses. Leaves were collected during the dry season in March 2024 to minimize the confounding effects of heavy rainfall or seasonal leaf fall. After collection, leaf samples were placed in sealed polyethylene bags to reduce moisture loss and transported to the laboratory for further measurements.

2.3. MEASUREMENT OF DUST FALLING ON LEAVES

Dust deposition on leaves was measured via the dry technique [21]. In this method, each intact leaf is first weighed, and dust particles are then carefully separated from the leaf surface via a brush, after which the leaf

is weighed. The following formula was used to determine the quantity of dust deposition:

$$\text{Dust content (mg/cm}^2\text{)} = \frac{\text{Weight of intact leaf} - \text{initial weight of leaf}}{\text{Total surface area of leaf (cm}^2\text{)}}$$

2.4. BIOCHEMICAL TRAIT ANALYSIS OF DUST-FREE LEAF SAMPLES

2.4.1. pH

To determine the leaf extraction pH, approximately 1 g of homogenized fresh leaf tissue was placed in 10 ml of deionized water to release the cellular contents into the solution. The resulting suspension was thoroughly mixed to ensure uniformity, and its pH was measured with a Hanna pH meter (HI98107) after calibration to ensure accurate readings. This method follows the standardized procedures [13], which are commonly used in studies assessing plant responses to air pollution.

2.4.2. ASCORBIC ACID CONTENT (AAC)

The AAC of the leaf samples was determined via the 2,6-dichlorophenolindophenol (DCPIP) titration method [22], a common approach for assessing plant physiological responses via APTI calculations. A 5 g fresh leaf sample was homogenized in 10 ml of 4% oxalic acid solution, filtered to obtain a clear extract, and then titrated with a standard DCPIP solution until a persistent pink color indicated the endpoint, indicating the complete oxidation of ascorbic acid. The final values were corrected by subtracting the readings obtained from a blank.

2.4.3. TOTAL CHLOROPHYLL CONTENT (TCC)

The TCC was determined following the spectrophotometric procedure [23]. In this approach, 1 g of fresh leaf material was thoroughly ground, extracted with 20 ml of 80% acetone, and then centrifuged at 5000 RPM for 5 minutes to isolate the supernatant containing chlorophyll pigments. The absorbance of the supernatant was measured at 645 nm and 663 nm via a spectrophotometer (Shimadzu UV-1800), and the chlorophyll concentration was calculated via standard formulas as follows:

$$\text{TCC (mg/g)} = (20.2 \times A_{645} + 8.02 \times A_{663}) \times \frac{\text{Total volume of the extract}}{1000 \times \text{weight of leaf materials}}$$

2.4.4. RELATIVE WATER CONTENT (RWC)

To determine the RWC, leaves were immediately weighed to obtain the fresh weight (FW). The samples were then immersed in distilled water and incubated for 24 hours at room temperature in the dark to attain full turgidity. After incubation, the leaves were gently blotted with filter paper to remove surface moisture and weighed to obtain the turgid weight (TW). The leaves were subsequently dried in a drying oven (Memmert UF 1060) at 60°C for 24 hours until a constant weight was achieved, which was recorded as the dry weight (DW). The RWC was calculated via the following formula [24]:

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

2.5. AIR POLLUTION TOLERANCE INDEX (APTI) CALCULATION

The APTI value was calculated via the standard formula proposed in another study [25]. This index is based on four biochemical parameters: ascorbic acid content (A), total chlorophyll content (T), leaf extract pH (P), and relative water content (RWC). The formula used is as follows:

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

2.6. STATISTICAL ANALYSIS

All data were examined for normality and homogeneity of variance before analysis. Statistical analyses were performed using JMP Pro 17 (SAS Institute, Cary, NC, USA). Differences among traits were assessed by two-way ANOVA, with species and site as fixed factors. When significant effects were observed, Tukey's HSD test was used for post hoc multiple comparisons at $p < 0.05$. For multivariate analysis, variables were standardized to eliminate scale effects. Principal Component Analysis (PCA) was performed using the correlation matrix of standardized data, and principal components were retained based on eigenvalues > 1 (Kaiser criterion) and scree plot evaluation, with priority given to those explaining substantial variation and demonstrating clear biological relevance. Pearson's correlation analysis was conducted to examine the relationships between APTI and dust deposition, as well as between APTI and individual biochemical parameters.

3. RESULTS

3.1. DUST DEPOSITION ON LEAF SURFACES

Dust deposition on leaves showed the strongest differences, with highly significant effects of species ($F = 42.99$, $p < 0.001$), site ($F = 219.58$, $p < 0.001$), and their interaction ($F = 46.58$, $p < 0.001$) (Table 1).

Table 1. Two-way ANOVA statistics of the effects of site, species, and their interaction on the leaf biochemical properties and dust content in Dhaka city. Asterisks denote significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and ns indicates not significant.

Sources of variation	Species (df=9)	Site (df=1)	Species × Site (df=9)
pH	30.21***	8.68**	1.69ns
Chlorophyll	1099.22***	6768.04***	919.95***
AAC	7.51***	4.88*	1.28ns
RWC	46.30***	7.79**	3.63**
APTI	11.58***	17.35***	2.01*
Dust	42.99***	219.58***	46.58***

All the studied species exhibited markedly greater dust accumulation under polluted site conditions. Notably, *F. benghalensis* presented the highest dust load at the polluted site ($64.04 \pm 7.60 \text{ mg/cm}^2$), which was nearly 70 times greater than its corresponding value at the control site ($0.91 \pm 0.17 \text{ mg/cm}^2$), indicating its high dust-trapping potential due to its large leaf surface area, rough leaf texture, and slow growth. These factors allow more dust particles to adhere to the leaves and remain there longer (Table 2).

Table 2. Comparison of dust deposition on the surfaces of different tree species at the control and polluted sites.

Plants name	Dust (mg/cm ²)	
	Control site	Polluted site
<i>Artocarpus heterophyllus</i>	$2.47 \pm 0.19^{\text{cd}}$	$6.71 \pm 1.4^{\text{bcd}}$
<i>Ficus benghalensis</i>	$0.91 \pm 0.17^{\text{d}}$	$64.04 \pm 7.60^{\text{a}}$
<i>Ficus religiosa</i>	$2.09 \pm 0.37^{\text{cd}}$	$5.11 \pm 0.84^{\text{bcd}}$
<i>Mangifera indica</i>	$2.10 \pm 0.26^{\text{cd}}$	$11.98 \pm 1.35^{\text{bc}}$
<i>Mimusops elengi</i>	$0.63 \pm 0.01^{\text{d}}$	$12.04 \pm 1.15^{\text{bc}}$
<i>Polyalthia longifolia</i>	$1.69 \pm 0.17^{\text{d}}$	$4.37 \pm 0.12^{\text{cd}}$
<i>Syzygium cumini</i>	$1.76 \pm 0.07^{\text{d}}$	$10.29 \pm 0.91^{\text{bcd}}$
<i>Swietenia mahagoni</i>	$2.68 \pm 0.45^{\text{cd}}$	$4.51 \pm 0.39^{\text{cd}}$
<i>Terminalia arjuna</i>	$1.75 \pm 0.16^{\text{d}}$	$8.67 \pm 1.33^{\text{bcd}}$
<i>Terminalia catappa</i>	$1.61 \pm 0.01^{\text{d}}$	$15.06 \pm 2.17^{\text{b}}$

Similarly, species such as *M. indica* ($11.98 \pm 1.35 \text{ mg/cm}^2$), *M. elengi* ($12.04 \pm 1.15 \text{ mg/cm}^2$), and *T. catappa* ($15.06 \pm 2.17 \text{ mg/cm}^2$) also presented substantial dust retention under polluted conditions. In contrast, species such as *F. religiosa* and *S. cumini* accumulated relatively lower dust loads at polluted sites than at other sites, suggesting species-specific variation in dust accumulation potential. The higher dust deposition at the polluted site indicates poor air quality in the Saydabad-Mothejheel area.

3.2. BIOCHEMICAL PARAMETERS

3.2.1. pH

The pH of the leaf extracts was significantly influenced by species ($F = 30.21$, $p < 0.001$) and site ($F = 8.68$, $p < 0.01$), but their interaction was not significant (Table 1). The leaf pH of certain tree species in two diverse ecological situations (control and polluted sites) was measured to understand the physiological status of the vegetation under air pollution stress.

In general, there was an apparent tendency toward pH decrease under polluted conditions, indicating acidification of the leaf tissues. Among the species studied, *S. cumini* presented the greatest decrease (16.93%) in leaf pH (approximately 6.26 ± 0.09 to 5.20 ± 0.10) in the polluted region (Tables 3, 4). This marked decline indicates a high sensitivity to pollution stress, likely related to an increased accumulation of acidic pollutants or an increased metabolic production of acid. Similar reductions in pH were observed in the case of *P. longifolia* and *M. indica*, but to a lesser extent, which suggests moderate susceptibility to air pollutants. On the other hand, *F. benghalensis* presented a significant increase (4.98%) in leaf pH under polluted conditions (Table 4) compared with that under pristine conditions, ranging from approximately 7.43 ± 0.14 - 7.80 ± 0.05 . Other species, such as *A. heterophyllus*, *F. religiosa*, *M. elengi*, *S. mahagoni*, *T. arjuna*, and *T. catappa*, also presented mild to moderate reductions in leaf pH; however, among all the species, *F. religiosa* presented the highest pH at both sites, with 7.70 ± 0.10 at the control site and 7.53 ± 0.08 at the polluted site (Table 3).

Table 3. Biochemical traits of selected plant species from the control and polluted sites in Dhaka city. Different superscript letters within a column indicate significant differences among species according to Tukey's HSD test ($p < 0.05$).

Species	Site	pH	Chlorophyll (mg/g)	AAC (mg/g)	RWC (%)	APTI
<i>Artocarpus heterophyllus</i>	Control	$6.47 \pm 0.38^{\text{defg}}$	$2.67 \pm 0.02^{\text{b}}$	$4.26 \pm 0.59^{\text{abcd}}$	$85.30 \pm 1.65^{\text{gh}}$	$12.44 \pm 0.66^{\text{bcdef}}$
	Polluted	$6.30 \pm 0.61^{\text{efgh}}$	$2.16 \pm 0.01^{\text{d}}$	$4.53 \pm 0.60^{\text{abcd}}$	$86.96 \pm 1.64^{\text{fgh}}$	$12.45 \pm 0.28^{\text{bcdef}}$
<i>Ficus benghalensis</i>	Control	$7.43 \pm 0.14^{\text{abcd}}$	$1.07 \pm 0.01^{\text{i}}$	$5.46 \pm 0.01^{\text{abcd}}$	$97.20 \pm 0.01^{\text{a}}$	$14.31 \pm 0.10^{\text{abcd}}$
	Polluted	$7.80 \pm 0.05^{\text{a}}$	$0.54 \pm 0.02^{\text{l}}$	$2.98 \pm 0.00^{\text{bcd}}$	$96.83 \pm 0.26^{\text{a}}$	$12.16 \pm 0.04^{\text{cdef}}$
<i>Ficus religiosa</i>	Control	$7.70 \pm 0.10^{\text{ab}}$	$1.93 \pm 0.02^{\text{a}}$	$6.27 \pm 0.53^{\text{abc}}$	$91.80 \pm 0.50^{\text{bcdef}}$	$15.13 \pm 1.43^{\text{abc}}$
	Polluted	$7.53 \pm 0.08^{\text{abc}}$	$1.27 \pm 0.01^{\text{h}}$	$4.96 \pm 0.00^{\text{abcd}}$	$91.63 \pm 0.66^{\text{bcdef}}$	$13.53 \pm 0.10^{\text{abcde}}$
<i>Mimusops elengi</i>	Control	$6.70 \pm 0.10^{\text{bcdef}}$	$1.74 \pm 0.02^{\text{f}}$	$5.90 \pm 0.69^{\text{abcd}}$	$91.40 \pm 0.20^{\text{def}}$	$14.05 \pm 0.59^{\text{abcd}}$
	Polluted	$6.50 \pm 0.10^{\text{defg}}$	$1.76 \pm 0.03^{\text{f}}$	$6.52 \pm 0.33^{\text{abc}}$	$92.63 \pm 2.33^{\text{abcde}}$	$14.65 \pm 0.48^{\text{abcd}}$
<i>Polyalthia longifolia</i>	Control	$7.16 \pm 0.03^{\text{abcde}}$	$1.75 \pm 0.01^{\text{f}}$	$7.69 \pm 1.67^{\text{a}}$	$95.83 \pm 0.07^{\text{abcd}}$	$16.43 \pm 1.45^{\text{a}}$
	Polluted	$6.80 \pm 0.06^{\text{abcdef}}$	$1.64 \pm 0.01^{\text{g}}$	$7.22 \pm 1.20^{\text{a}}$	$93.10 \pm 0.61^{\text{abcde}}$	$15.41 \pm 1.06^{\text{abc}}$
<i>Syzygium cumini</i>	Control	$6.26 \pm 0.09^{\text{efgh}}$	$2.52 \pm 0.01^{\text{c}}$	$6.42 \pm 0.01^{\text{abc}}$	$87.36 \pm 0.16^{\text{fgh}}$	$14.34 \pm 0.05^{\text{abcd}}$
	Polluted	$5.20 \pm 0.10^{\text{i}}$	$0.95 \pm 0.00^{\text{j}}$	$5.59 \pm 0.00^{\text{abcd}}$	$88.36 \pm 1.83^{\text{efg}}$	$12.28 \pm 0.12^{\text{cdef}}$
<i>Swietenia mahagoni</i>	Control	$6.53 \pm 0.03^{\text{cdefg}}$	$3.07 \pm 0.00^{\text{a}}$	$6.38 \pm 0.00^{\text{abc}}$	$87.46 \pm 0.07^{\text{fgh}}$	$14.87 \pm 0.02^{\text{abc}}$
	Polluted	$6.20 \pm 0.10^{\text{efghi}}$	$0.83 \pm 0.02^{\text{k}}$	$4.05 \pm 0.02^{\text{abcd}}$	$85.06 \pm 1.33^{\text{gh}}$	$11.35 \pm 0.07^{\text{def}}$
<i>Terminalia arjuna</i>	Control	$5.86 \pm 0.03^{\text{fghi}}$	$1.64 \pm 0.01^{\text{g}}$	$5.79 \pm 0.67^{\text{abcd}}$	$96.40 \pm 0.20^{\text{abc}}$	$13.98 \pm 0.50^{\text{abcd}}$
	Polluted	$5.66 \pm 0.07^{\text{ghi}}$	$1.73 \pm 0.03^{\text{fg}}$	$6.67 \pm 0.00^{\text{abc}}$	$91.60 \pm 0.10^{\text{cdef}}$	$14.09 \pm 0.07^{\text{abcd}}$
<i>Terminalia catappa</i>	Control	$5.60 \pm 0.10^{\text{ghi}}$	$1.98 \pm 0.01^{\text{e}}$	$2.89 \pm 0.67^{\text{cd}}$	$83.50 \pm 0.20^{\text{gh}}$	$10.55 \pm 0.56^{\text{ef}}$
	Polluted	$5.43 \pm 0.03^{\text{hi}}$	$1.75 \pm 0.01^{\text{f}}$	$2.39 \pm 0.49^{\text{d}}$	$83.36 \pm 0.17^{\text{h}}$	$10.06 \pm 0.38^{\text{f}}$
<i>Mangifera indica</i>	Control	$6.80 \pm 0.05^{\text{abcdef}}$	$2.24 \pm 0.04^{\text{d}}$	$6.74 \pm 0.99^{\text{ab}}$	$96.60 \pm 0.10^{\text{ab}}$	$15.67 \pm 0.89^{\text{ab}}$
	Polluted	$6.60 \pm 0.28^{\text{cdefg}}$	$1.65 \pm 0.02^{\text{g}}$	$5.87 \pm 0.01^{\text{abcd}}$	$91.66 \pm 0.06^{\text{bcdef}}$	$14.01 \pm 0.16^{\text{abcd}}$

3.2.2. LEAF CHLOROPHYLL CONTENT

The chlorophyll content was highly significantly affected by species ($F = 1099.22$, $p < 0.001$) and site ($F = 6768.04$, $p < 0.001$), with a strong interaction effect ($F = 919.95$, $p < 0.001$), suggesting species-specific responses to site conditions (Table 1). The total chlorophyll content consistently decreased in the tree species sampled from the polluted site compared with those from the control site (Table 3). The highest chlorophyll content at the control site was recorded in *S. mahagoni* (3.07 ± 0.01 mg/g), followed by *S. cumini* (2.52 ± 0.01 mg/g), and *F. benghalensis* (1.07 ± 0.01 mg/g). In contrast, the corresponding values at the polluted site decreased sharply to 0.83 ± 0.02 mg/g, 0.95 ± 0.02 mg/g, and 0.54 ± 0.02 mg/g, respectively, indicating reductions of 72.96%, 62.3%, and 49.53%, respectively. Similarly, *F. religiosa* and *M. indica* presented marked declines in chlorophyll levels, from 1.93 ± 0.02 mg/g and 2.24 ± 0.04 mg/g at the control site to 1.27 ± 0.01 mg/g and 1.65 ± 0.02 mg/g at the polluted site, respectively. Among all the species studied, *S. mahagoni* showed the highest sensitivity to air pollution in terms of chlorophyll degradation, whereas *T. arjuna* and *M. elengi* showed a slight increase (5.49% and 1.15%, respectively), suggesting possible adaptive mechanisms or increased tolerance to pollution (Table 4). Species such as, *P. longifolia*, and *T. catappa* presented minimal variation in chlorophyll content between sites (Table 3).

Table 4. Change (increasing or decreasing %) in biochemical traits of leaf of selected tree species at two contrasting sites of Dhaka city. '+' indicates an increase in the amount of respective parameters of the studied tree species at polluted sites.

Species	pH (%)	Chlorophyll (%)	AAC (%)	RWC (%)	APTI (%)
<i>Artocarpus heterophyllus</i>	2.63	19.10	+6.34	+1.95	+0.08
<i>Ficus benghalensis</i>	+4.98	49.53	45.42	0.38	15.02
<i>Ficus religiosa</i>	2.21	34.20	20.89	0.19	10.58
<i>Mimusops elengi</i>	2.99	+1.15	+10.51	+1.35	+4.27
<i>Polyalthia longifolia</i>	5.03	6.29	6.11	2.85	6.21
<i>Syzygium cumini</i>	16.93	62.30	12.93	+1.14	14.37
<i>Swietenia mahagoni</i>	5.05	72.96	36.52	2.74	23.67
<i>Terminalia arjuna</i>	3.41	+5.49	+15.20	4.98	+0.79
<i>Terminalia catappa</i>	3.04	11.62	17.30	0.17	4.64
<i>Mangifera indica</i>	2.94	26.34	12.91	5.11	10.59

3.2.3. ASCORBIC ACID CONTENT

Ascorbic acid content varied notably across species and sites. For most species, the AAC was lower in leaves collected from polluted sites, likely because of oxidative degradation under pollution stress. For example, the AAC of *F. benghalensis* (45.42%) and *S. mahagoni* (36.52%) substantially decreased (from 5.46 ± 0.01 to 2.98 ± 0.02 mg/g and from 6.38 ± 0.02 to 4.05 ± 0.02 mg/g, respectively), indicating susceptibility to oxidative damage in polluted environments (Tables 3, 4). Interestingly, *M. elengi* and *T. arjuna* presented slightly greater AAC values under polluted conditions (5.90 ± 0.69 to 6.52 ± 0.33 mg/g and 5.79 ± 0.67 to 6.67 ± 0.67 mg/g, respectively), suggesting an adaptive increase in antioxidant activity to cope with elevated reactive oxygen species. *T. catappa* consistently presented the lowest AAC across both sites, indicating limited biochemical defense potential against pollution-induced oxidative stress. Moreover, ascorbic acid exhibited significant variation due to species ($F = 7.51$, $p < 0.001$) and site ($F = 4.88$, $p < 0.05$) but not their interaction (Table 1).

3.2.4. RELATIVE WATER CONTENT

The RWC was significantly affected by species ($F = 46.30$, $p < 0.001$) and site ($F = 7.19$, $p < 0.01$), along with a significant interaction ($F = 3.63$, $p < 0.01$) (Table 1). As presented in Table 3, the RWC was generally lower in the

plants from the polluted sites than in those from the control sites, indicating compromised water retention, possibly due to membrane damage and impaired stomatal function under oxidative stress conditions. Among the species, *T. arjuna*, *F. benghalensis*, *P. longifolia*, and *M. indica* maintained high RWC values in both environments (>90%), suggesting efficient water regulation and structural integrity of their cellular membranes. In contrast, the RWC of species such as *T. catappa* and *S. mahagoni* substantially decreased at polluted sites, with values decreasing below 85%, indicating increased susceptibility to air pollutants. More specifically, reductions were evident in *M. indica* (5.11%), *T. arjuna* (4.98%), and *P. longifolia* (2.85%), whereas slight increases occurred in *A. heterophyllum*, *M. elengi*, and *S. cumini* (Table 4).

3.3. AIR POLLUTION TOLERANCE INDEX

The air pollution tolerance index (APTI) varied significantly with both species ($F = 11.58$, $p < 0.001$) and site ($F = 17.35$, $p < 0.001$), as did their interaction ($F = 2.01$, $p < 0.05$) (Table 1). The APTI values of ten selected plant species were analyzed at both the control and polluted sites to evaluate their relative tolerances to air pollution (Table 4). The results demonstrate species-specific variability in APTI values, indicating differential susceptibility or tolerance to air pollutants. *P. longifolia* presented the highest APTI at both the control (16.43 ± 1.45) and polluted (15.41 ± 1.06) sites, suggesting its strong tolerance and potential as an effective bioindicator and greenbelt species in urban and industrial areas. Similarly, *M. indica* and *F. religiosa* also maintained relatively high APTI values under both sites, reflecting their moderate to high tolerance levels.

In contrast, species such as *S. mahagoni* (23.67%), *Ficus benghalensis* (15.02%), and *Syzygium cumini* (14.37%) demonstrated pronounced declines in APTI values under polluted conditions, indicating greater sensitivity, while marginal increases were observed in *A. heterophyllum* (0.08%) and *Terminalia arjuna* (0.79%). *T. catappa* presented the lowest APTI at the polluted site (10.06 ± 0.38), suggesting its vulnerability to airborne pollutants and its potential role as a sensitive bioindicator species. Interestingly, APTI increased in certain species, such as *M. elengi*, under polluted conditions (from 14.05 ± 0.59 to 14.65 ± 0.48), which may indicate physiological adaptability or an enhanced antioxidant response under stress. On the basis of the APTI values at the polluted site, the species from the most tolerant to the most sensitive were as follows: *P. longifolia* > *M. elengi* > *T. arjuna* > *M. indica* > *F. religiosa* > *A. heterophyllum* > *S. cumini* > *F. benghalensis* > *S. mahagoni* > *T. catappa*.

3.4. MULTIVARIATE ANALYSIS

3.4.1. PRINCIPAL COMPONENT ANALYSIS

Comparative principal component analysis revealed a clear shift in the structuring of plant traits between control and polluted sites (Fig. 2). At the control site, the first two components explained 80.01% of the total variance (PC1 = 47.98%, PC2 = 32.03%), with PC1 dominated by RWC, leaf pH, AAC, and air pollution tolerance index (APTI), reflecting intrinsic physiological regulation under non-stressed conditions. In contrast, chlorophyll content and dust load were primarily associated with PC2, indicating limited coupling between photosynthetic attributes and physiological status. Under polluted conditions, the first two components explained 79.91% of the variance (PC1 = 41.16%, PC2 = 38.75%), but the dominance of trait loadings shifted markedly. PC1 was strongly driven by AAC and APTI, highlighting the central role of antioxidative defense and tolerance mechanisms under pollution stress, while PC2 was governed by dust load, pH, and RWC, reflecting the influence of particulate deposition and altered water and acid–base regulation. Overall, the PCA demonstrates a pollution-induced reorganization of trait relationships, with a transition from intrinsic physiological control at the control site to stress-responsive biochemical and tolerance-driven regulation at the polluted site.

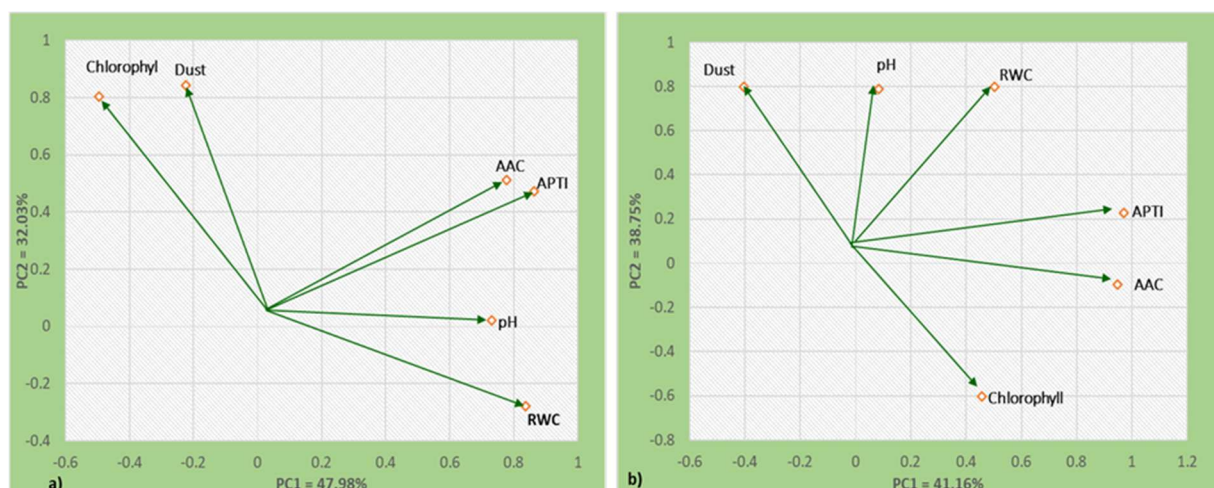


Figure 2. Principal component analysis (PCA) biplots showing trait relationships of urban tree species at (a) control and (b) polluted sites. Vectors represent the loadings of physiological and biochemical traits, including chlorophyll content, dust load, leaf pH, relative water content (RWC), ascorbic acid content (AAC), and air pollution tolerance index (APTI). The percentage of variance explained by PC1 and PC2 is indicated on the respective axes.

3.4.2. PEARSON CORRELATION

Comparative correlation analysis revealed a marked shift in trait interrelationships between control and polluted sites (Fig. 3). Under control conditions, APTI was strongly and positively correlated with ascorbic acid content (AAC; $r = 0.97$, $p < 0.001$) and moderately associated with RWC and leaf pH, indicating that baseline pollution tolerance was primarily governed by intrinsic antioxidant capacity and physiological stability. Chlorophyll content showed a significant negative correlation with RWC, while dust load was positively associated with chlorophyll, suggesting limited physiological stress and weak coupling between particulate deposition and tolerance mechanisms.

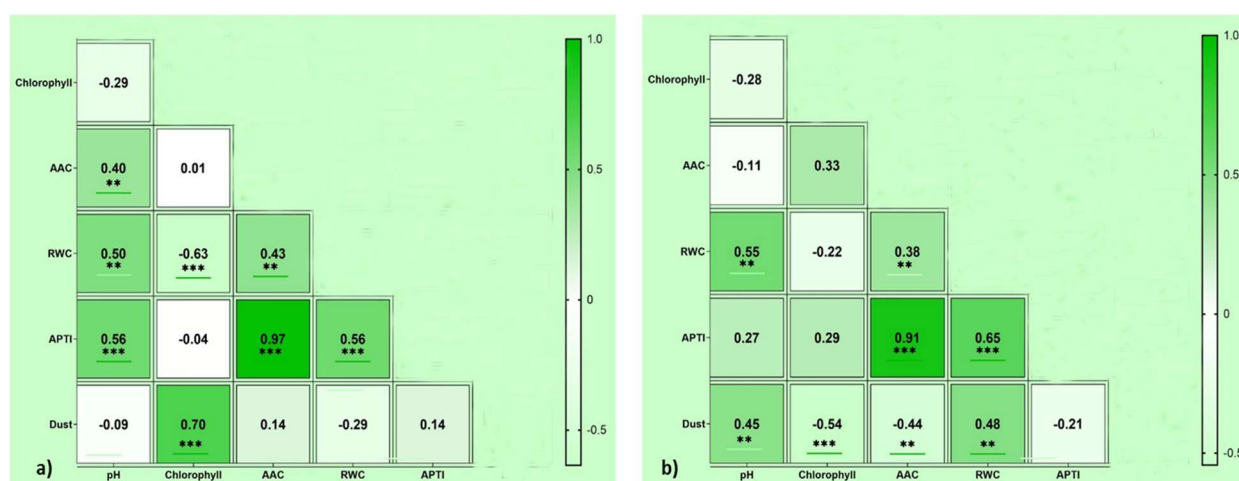


Figure 3. Pearson correlation matrices showing relationships among Leaf physiological and environmental traits at the control (a) and polluted (b) sites. Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

In contrast, at polluted sites, although APTI remained strongly linked to AAC ($r = 0.91$, $p < 0.001$) and RWC ($r = 0.65$, $p < 0.001$), chlorophyll and pH exhibited weak or non-significant associations with APTI, reflecting decoupling of photosynthetic traits from tolerance under stress. Notably, dust load shifted from a weak or indirect role at control sites to a stress indicator under polluted conditions, showing significant negative

correlations with chlorophyll content ($r = -0.54$, $p < 0.001$) and AAC ($r = -0.44$, $p < 0.01$). Overall, pollution exposure reorganized trait coordination from stable physiological integration at control sites to a stress-driven framework dominated by antioxidative defense and water relations at polluted sites.

4. DISCUSSION

This study comprehensively assessed the dust and biochemical responses of ten common urban tree species to air pollution stress by analyzing data from control and polluted sites in Dhaka, Bangladesh. The integration of multiple bioindicators reveals significant species-specific variations in resilience and susceptibility, offering insights into urban afforestation strategies and biomonitoring tools.

4.1. DUST DEPOSITION AS A PRIMARY DRIVER OF POLLUTION STRESS IN URBAN TREES

The markedly higher dust deposition observed at the polluted site across all species confirms the severe particulate pollution load in the Saydabad-Motijheel urban site and highlights the functional role of urban trees as passive particulate filters. The exceptionally high dust accumulation recorded in *F. benghalensis*, nearly 70-fold greater than at the control site, underscores the importance of leaf morphological attributes such as large surface area, coriaceous texture, and surface roughness in determining dust interception efficiency [16,26]. Excessive particulate accumulation can obstruct stomata, reduce transpiration and photosynthetic efficiency, and exacerbate oxidative stress, ultimately impairing plant growth and health [27]. However, the interaction between species and site indicates that dust retention is not merely a function of morphology but also reflects site-specific pollution intensity and microclimatic conditions [28-29].

4.2. LEAF PH AND CHLOROPHYLL AS INDICATORS OF PHYSIOLOGICAL STRESS

The general decline in leaf extract pH at polluted sites might be the uptake and internalization of acidic pollutants, which can disrupt cellular homeostasis and enzyme activity [30]. Species-specific variation in leaf pH influenced tolerance and sensitivity to urban stress [13]. Among the species, *S. cumini* presented the sharpest decline in pH, indicating high sensitivity to pollution stress. Moderate reductions were recorded in *P. longifolia* and *M. indica*, whereas *F. benghalensis* presented a slight increase in pH under pollution, suggesting increased buffering capacity or tolerance [30-32]. Recent studies further confirmed that declining leaf pH is a consistent physiological marker of atmospheric pollution stress, particularly in areas with high vehicular or industrial emissions [4,33]. Moreover, leaf surface pH changes have been proposed as early diagnostic tools for evaluating the impacts of urban air quality on vegetation. In line with this, species with minimal pH fluctuations under polluted conditions are now considered potential candidates for urban greenbelt development and phytoremediation [15].

The chlorophyll content was highly responsive to both species and site, with a significant interaction. The decrease in chlorophyll levels in all species at the polluted site indicates a negative effect of atmospheric pollutants on the photosynthetic system. The decrease in chlorophyll concentration is predominantly due to oxidative damage caused by SO_2 , NO_x , and particulates, which affect chloroplast ultrastructure and the inhibition of pigment biosynthesis [34-35]. *S. mahagoni* and *F. religiosa* showed the greatest decreases, indicating their greater susceptibility to oxidative damage, which may be caused by pollutants. These findings align with recent research indicating that pollutant exposure accelerates chlorophyll degradation through the increased activity of chlorophyllase and other catabolic enzymes [36]. However, the chlorophyll content in *P. longifolia* and *T. arjuna* did not fluctuate much, which was probably derived from effective antioxidative mechanisms [37]. However, the strong interaction effect on chlorophyll content suggests that some species maintain pigment stability better than others do, reflecting adaptive resilience in high-pollution environments.

4.3. ANTIOXIDANT RESPONSES AND WATER RELATIONS UNDER POLLUTION STRESS

Ascorbic acid content played a central role in mediating pollution tolerance, as evidenced by its strong positive association with APTI across both sites. The marked AAC reduction observed in *F. benghalensis* and *S. mahagoni* indicates that these plants are not as efficient in regulating redox homeostasis upon increased levels of ROS [34,38]. On the other hand, the small elevation in the AAC of *P. longifolia* and *T. arjuna* in polluted environments reflects the possible activation of antioxidant defense pathways, which have been correlated with greater tolerance of urban vegetation [9,39-40]. These adaptive responses are also related to the increased activity of ascorbate peroxidase and similar enzymes responsible for ROS scavenging and protection of the cellular structure [11]. The relatively low AAC of *T. catappa* indicated that it was sensitive to oxidative stress and had low tolerance for high-pollution urban areas. These results support the use of species with efficient antioxidant systems to improve the air quality of urban greening through the effects of air pollution [15].

The relative water content is influenced by species, site, and their interaction. A reduced RWC under polluted conditions suggests osmotic stress and impaired water balance, as previously reported for tree species exposed to particulate pollution [32]. The interactive effect highlights differential species capacities to regulate water relations in polluted environments [34,41]. The ability of *T. arjuna*, *F. benghalensis*, and *M. indica* to maintain high RWC under both conditions suggests stable water-conservation strategies and turgor maintenance, which can be assumed to make them sound anatomically and thus enable them to endure adverse conditions [42]. This resistance is related to improved antioxidant protection and osmoprotectant production, which protect against pollution-induced oxidative damage and dehydration [36,43]. On the other hand, severe reductions in the RWC of both *T. catappa* and *S. mahagoni* might indicate susceptibility to oxidative stress, possibly related to cell membrane stability and restricted osmotic adjustment ability [15]. The sudden increase in the RWC of *F. benghalensis* in the presence of pollution might be suggestive of adaptive plasticity involving changes in leaf surface characteristics or patterns of stomatal behavior to reduce water loss [33,44]. These results further highlight RWC as a consistent physiological marker of species sensitivity to urban air pollution and inform the selection of resilient species for greenbelt planning.

4.4. MULTIVARIATE RELATIONSHIPS AMONG TRAITS

Integrated PCA and correlation analyses revealed a clear pollution-induced reorganization of trait relationships in urban tree species. Under control conditions, trait variability was primarily governed by intrinsic physiological regulation, with RWC, leaf pH, AAC, and APTI forming a coherent functional axis [11,38,45]. Strong positive associations between APTI and AAC indicate that baseline tolerance is closely linked to antioxidant capacity and physiological stability, consistent with earlier reports emphasizing the role of ascorbic acid in mitigating oxidative stress in plants [14,36]. The relative independence of chlorophyll content and dust load under control conditions suggests minimal physiological stress and stable photosynthetic functioning [46].

In contrast, polluted sites exhibited a pronounced shift toward stress-responsive trait coordination. PCA identified AAC and APTI as dominant contributors to trait variability, and correlation analysis confirmed their strong coupling with RWC, underscoring the central role of antioxidative defense and water relations under pollution stress. Similar shifts toward antioxidant-dominated regulation under urban pollution have been widely documented [14,47]. The weakened or negative association of chlorophyll content with tolerance-related traits reflects pigment degradation and impaired photosynthetic efficiency under oxidative and particulate stress [33,36]. Furthermore, dust load emerged as a strong stress indicator, showing negative correlations with chlorophyll and AAC, highlighting the adverse effects of particulate deposition on leaf surface properties and metabolic functioning [3,48]. Overall, the integrated multivariate evidence demonstrates that pollution disrupts intrinsic physiological integration and redefines species performance through enhanced reliance on

antioxidant defense and water-regulation mechanisms. These trait-based responses provide a mechanistic basis for differential pollution tolerance among urban tree species and support the use of APTI-linked traits in selecting resilient species for urban greenbelt development [49-51].

4.5. INTEGRATIVE ASSESSMENT THROUGH APTI

The air pollution tolerance index, a composite indicator of pollution tolerance, varies significantly with species and site, with a modest but significant interaction. These results align with earlier studies that demonstrated considerable interspecific variation in APTI, suggesting that while some species are highly sensitive, others possess physiological traits conferring tolerance [38]. The high APTI values of *P. longifolia* also validate its ability to tolerate stress and maintain ecological balance and membrane integrity in heavy metal-contaminated environments, as this plant species was identified earlier as an effective urban pollution sink [34]. Its high tolerance can be attributed to robust antioxidant activity and favorable leaf surface traits, such as waxy coatings and dense foliage, which mitigate pollutant uptake [15].

M. indica and *F. religiosa* also presented moderately high APTI values under pollution stress, indicating their adaptive resilience and suitability for roadside plantations and urban forestry [14,52]. In contrast, *S. mahagoni* and *T. catappa* presented sharp declines in APTI, reflecting impaired physiological performance under oxidative stress, likely due to reduced ascorbic acid content and relative water content [11,36]. The low APTI value of *T. catappa* underscores its vulnerability, making it more appropriate for use as a sensitive bioindicator rather than for pollution mitigation purposes. Interestingly, *M. elengi* presented a slight increase in APTI at polluted sites, might be possible activation of stress-responsive metabolic pathways or upregulation of protective antioxidants such as ascorbate peroxidase and catalase [33,53]. This increase supports emerging evidence that some species may exhibit acclimatory responses under moderate pollutant loads. The derived APTI-based tolerance gradient - from *P. longifolia* (most tolerant) to *T. catappa* (most sensitive) - provides valuable insight for targeted greenbelt development and urban ecological planning. Species with high APTI values can effectively function as pollution filters by absorbing and immobilizing airborne contaminants, thus improving urban air quality [54,55]. Moreover, given their pronounced physiological sensitivity, species with lower APTI values can serve as early warning systems for air quality deterioration. The decline in APTI values observed in most species aligns with established links between air pollution and oxidative stress, which impairs photosynthetic efficiency, disrupts enzymatic functions, and leads to membrane lipid peroxidation [14,36].

Therefore, integrating APTI analysis into urban tree selection protocols can enhance the functional resilience of green infrastructure. The strategic deployment of tolerant species such as *P. longifolia*, *M. indica*, and *F. religiosa* can significantly strengthen the capacity of urban ecosystems to withstand pollution stress. Simultaneously, monitoring the physiological responses of sensitive species such as *T. catappa* and *S. mahagoni* can provide actionable data for environmental assessment. These findings reaffirm APTI as a practical and scientifically robust metric for evaluating vegetation performance in polluted urban environments. Future research integrating APTI with molecular and transcriptomic approaches could further elucidate the mechanisms underlying species-specific tolerance.

5. CONCLUSION

This study demonstrates that chronic urban air pollution profoundly alters leaf biochemical traits, water relations, and tolerance mechanisms in tropical urban tree species. Elevated dust deposition at polluted sites emerged as a key driver of physiological stress, contributing to chlorophyll degradation, leaf acidification, and oxidative imbalance. Species exhibited distinct tolerance strategies, with pollution-resilient species maintaining higher antioxidant capacity, stable water status, and elevated APTI values despite severe

environmental stress. Among the studied species, *P. longifolia* and *M. elengi* are recommended for pollution-prone urban planting, whereas sensitive taxa *T. catappa* and *S. mahagoni* may serve as bioindicators, underscoring their contrasting suitability for polluted urban environments. Overall, this research provides a mechanistic, trait-based framework for evaluating urban tree tolerance to pollution-associated urban stress and offers actionable guidance for urban forestry planning and greenbelt development in pollution-prone megacities.

Authors' Contribution: MAK: Sampling and data collection, writing of the original draft, review and editing, Resources, Methodology, Project supervisor. MAR: Sampling and data collection, Methodology, Formal analysis, Software. TS: Writing – review & editing, Writing – original draft. MZH: Methodology, Formal analysis, Writing original draft. All authors read and approved the final manuscript.

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