

SEASONAL VARIATION IN LEAF MORPHOLOGICAL RESPONSES TO DUST POLLUTION IN BHAIRAHAWA, WESTERN NEPAL

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Abstract

Green vegetation in residential and industrial zones offers a cost-effective and environmentally sustainable approach in mitigating air pollution, making the selection of suitable plant species for green belt development highly important. This study evaluated 8 plant species across 4 contrasting land-use types within Siddharthanagar Municipality; industrial, roadside, residential, and garden areas during the winter (January) and monsoon (June) seasons of 2024. The effects of dust deposition on leaf morphology were assessed by comparing polluted sites with a less polluted garden site. Overall, dust accumulation was consistently higher in industrial and roadside areas than in residential and garden sites, with more pronounced effects during the dry winter season. Species with broad, rough, and hairy leaves, particularly *Tectona grandis* (L.f), showed higher dust retention, whereas smoother-leaved species accumulated comparatively less dust. Increased dust load was generally associated with reductions in leaf area and specific leaf area (SLA), indicating morphological adjustments under pollution stress. The most pronounced reductions were observed in highly exposed roadside and industrial environments, while species such as *Azadirachta indica* (A. Juss.), *Ficus religiosa* (L.), *Psidium guajava* (L.), and *Saraca asoca* (L.), exhibited comparatively smaller changes in leaf traits across seasons. These findings suggest that certain urban plant species possess greater tolerance to dust pollution and may be suitable candidates for green belt development and urban greening initiatives in the Terai region of Nepal.

Key words: Dust; Leaf area; Plant species; Pollution; Specific leaf area

Introduction

Air pollution occurs when chemical substances exceed their natural concentrations in the environment, resulting in measurable adverse impacts on both living organisms and physical structures (Seinfeld & Pandis, 2006). Common air pollutants include heavy metals, nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), ozone (O₃), benzene, unburnt hydrocarbons, and particulate matter (PM). Among plant organs, leaves are the most vulnerable to these pollutants because they perform essential physiological processes and are directly exposed to the atmosphere. Pollutants, particularly those derived from vehicular and industrial emissions, can penetrate leaf tissues, damage cellular structures, interfere with stomatal functioning, reduce photosynthetic efficiency, and ultimately suppress plant growth and productivity. Urban air pollution, therefore, remains one of the most pressing environmental challenges, particularly in rapidly urbanizing regions of developing countries (Mage *et al.*, 1996). More recent studies have further demonstrated that atmospheric dust and PM not only impair physiological performance but also induce measurable changes in leaf morphology, surface architecture, and internal anatomy, making leaves reliable indicators of environmental stress (Bierza & Bierza, 2024; Xu *et al.*, 2024; Nkansah, 2025).

Dust deposition on leaves is strongly influenced by morphological characteristics such as surface texture,

trichome density, petiole length, leaf orientation, shape, size, and wax properties (Prusty *et al.*, 2005; Rai & Panda, 2014a). Recent research has shown that species possessing rough surfaces, grooves, ridges, dense trichomes, and waxy cuticles are generally more effective at intercepting and retaining atmospheric particles than smooth-leaved species (Kwak *et al.*, 2023; Xu *et al.*, 2024). Such foliar micro-morphological traits are increasingly recognized as important determinants of both dust capture efficiency and pollution tolerance. Specific leaf area (SLA), defined as the leaf area per unit dry mass, is an important morphological and functional trait reflecting a plant's ecological strategy and adaptability to varying environmental conditions (Liu *et al.*, 2018). Within a single tree, SLA may vary significantly in response to differences in light intensity, water availability, canopy temperature, and wind exposure (Poorter *et al.*, 2009). Under polluted and stressful urban environments, SLA often declines as leaves become smaller, thicker, or denser, reflecting structural adjustments that may enhance stress tolerance (Bierza & Bierza, 2024). Similarly, leaf thickness, stomatal traits, and epidermal organization have also been reported to change under prolonged exposure to particulate pollution, indicating that dust stress can influence both external and internal leaf structure (Nkansah, 2025; Krir *et al.*, 2025).

Leaves also serve as effective natural filters by capturing, absorbing, metabolizing, and detoxifying pollutants through a range of morphological, physiological,

and biochemical mechanisms, including stomatal features, trichomes, leaf pH, ascorbic acid content, epicuticular wax, and surface roughness (Shannigrahi *et al.*, 2004; Agbaire & Esiefarienrhe, 2009). In addition to their filtering function, leaves can reflect cumulative environmental stress through modifications in leaf area, SLA, leaf dry matter, and stomatal behavior, which are increasingly used in urban ecological studies and biomonitoring programs (Xu *et al.*, 2024; Bierza & Bierza, 2024). Recent studies also indicate that particulate pollution should be interpreted as part of a broader multi-stressor urban environment, often interacting with trace metals, traffic-derived emissions, heat stress, and atmospheric dryness, all of them may intensify foliar stress responses (Bierza & Bierza, 2024). Therefore, examining leaf morphological traits provides a valuable and low-cost approach for understanding plant adaptation and tolerance in polluted environments.

Despite increasing concern over dust pollution in Nepal's rapidly expanding urban regions, very few studies have examined how dust load influences leaf morphological and functional traits under real field conditions, particularly across different seasons. Existing research in the region has focused largely on biochemical parameters, metal accumulation, or single-season assessments, leaving a substantial gap in understanding the seasonal dynamics of dust deposition and its impacts on leaf macromorphology. This gap is especially important because recent studies have emphasized that dust accumulation and plant responses are strongly influenced by seasonal changes in rainfall, wind, atmospheric dryness, and pollutant wash-off, with greater dust loads often recorded during dry periods than during wet seasons (Kwak *et al.*, 2023). However, such seasonal trait-based evidence remains extremely limited in Nepal, particularly in the Terai lowlands, where prolonged dry periods, road dust resuspension, industrial emissions, and increasing urbanization may jointly intensify particulate stress. Moreover, limited information exists on which commonly occurring urban plant species in the Terai region are most tolerant or sensitive to dust pollution based on their leaf morphological characteristics.

To address this gap, the present study investigates the effects of dust deposition on leaf macromorphology across two contrasting seasons; winter and monsoon in Bhairahawa, western Nepal. By comparing plant species from industrial, roadside, residential, and less polluted garden areas, this research aims to identify such plant species having high dust tolerance that can be recommended for green-belt development, roadside plantation, and urban greening initiatives in the Terai region. This study was conducted in Siddharthanagar Municipality and Mayadevi Rural Municipality, both located in the Rupandehi District of Lumbini Province, Nepal. Siddharthanagar serves as the district's administrative headquarters and covers an area of 36.03 km². The municipality experiences a mean annual maximum temperature of 30.9°C and a mean annual minimum temperature of 18.9°C. January is the coldest month, with an average temperature of 8.7°C, while May is the hottest, averaging 36.6°C. The area receives an annual mean rainfall of 1,633.2 mm. Siddharthanagar hosts around 30 industrial establishments, including cement, steel, and brick factories, which contribute significantly to local air pollution.

Mayadevi Rural Municipality, located in Kapilvastu District of Lumbini Province and covering 88.53 km², has been implementing various development plans to address social, economic, and environmental challenges. Key environmental issues in the area include groundwater depletion, drought, air and water pollution, and ineffective solid waste management (MoFE, 2021). Industrial activities are among the major contributors in deteriorating air quality in the area. The municipality is also classified as highly sensitive to climate change, with a sensitivity index ranging from 0.674 to 1 (MoFE, 2021). These environmental conditions make the broader Bhairahawa–Mayadevi landscape a particularly relevant setting for examining seasonal variation in leaf morphological responses to dust pollution.

Material and Methods

Site description: A total of 6 locations were initially selected for sample collection (Table 1). These sites were subsequently grouped into four major categories based on land use pattern, dominant pollution sources (industrial and/or vehicular), and relative particulate matter deposition. Area 2 (Custom Office) and Area 5 (Devkota Chowk) are combined because both are located along busy roadside corridors with high vehicular movement, associated emissions, and considerable dust accumulation. Similarly, Area 3 (Newdihawa Path) and Area 4 (Bethari) are grouped together as they represent predominantly residential environments with relatively lower traffic intensity and less direct industrial influence. Therefore, the site classification reflects the combined influence of surrounding land use and prevailing pollution exposure conditions (Figs. 1 and 2).

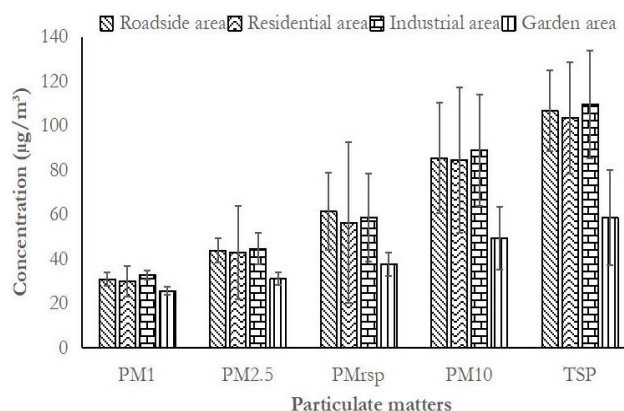


Fig. 1. Air quality of different areas; Legends (Source: Sampler Aeroqual); *Error bars represent standard error of the mean (n=5)

Selection of plant species: A purposive sampling approach was employed to select plant species for the study. Tree species that were commonly found across the sampling sites, widely distributed, and easily accessible for repeated sampling were included in the study to ensure comparability among sites. Based on these criteria, a total of 8 tree species were selected. The botanical and physiological characteristics of the selected species are presented in Table 2. The 8 tree species are *Azadirachta indica* A. Juss, *Dalbergia sissoo* Roxb ex DC, *Ficus bengalensis* L., *Ficus religiosa* L., *Mangifera indica* L., *Psidium guajava* L., *Saraca asoca* and *Tectona grandis* L.f.

Table 1. Sampling sites with description.

S. No.	Name of sampling site	Coordinates	Description of site	Category
1.	Bhairahawa campus (Industrial area)	27.507° N 83.4641° E	It is near an industrial area that covers the whole area of the Bhairahawa campus. It is located aside from the main road covering many industrial areas	Polluted
2.	Custom office and Devkota chowk (Roadside area)	27.4773° N, 83.4695° E 27.5168° N, 83.4398° E	It covers the whole area of the custom office which lies on the Nepal-India border. Due to the border area, the movement of vehicles is very high and Devkota chowk covers the main roadside area	Polluted
3.	Newdihawa path and Bethari (Residential area)	27.4848° N, 83.4605° E 27.5197° N, 83.4077° E	Newdihawa path is a APF office which is located near a residential area and a bit far from the main road and Bethari is a typical residential area	Moderately polluted
4.	Prithivi park/Garden area (less polluted area)	27.4905° N, 83.4305° E	It covers the area around Prithvi Park near Bahira Bal Secondary School which is a less polluted area	Less polluted

Table 2. List of plant species and their family collected from all study sites.

Scientific name	Local name	Family
<i>Azadirachta indica</i> A. Juss.	Neem	Meliaceae
<i>Dalbergia sissoo</i> Roxb ex DC.	Sissoo	Fabaceae
<i>Ficus benghalensis</i> L.	Bar	Moraceae
<i>Ficus religiosa</i> L.	Peepal	Moraceae
<i>Mangifera indica</i> L.	Mango	Anacardiaceae
<i>Psidium guajava</i> L.	Guava	Myrtaceae
<i>Saraca asoca</i> L.	Ashoka	Fabaceae
<i>Tectona grandis</i> L.f.	Teak	Lamiaceae

Fully mature leaves were collected in triplicates from each selected species during January 2024 (winter) and May 2024 (monsoon) across all study sites. To maintain uniformity, leaf samples were harvested using a tree pruner from a height above 2 m, thereby minimizing contamination from ground-level dust deposition. Immediately after collection, the leaves were placed in zip-lock plastic bags and stored in an icebox to preserve their physiological integrity. The samples were then transported to the Central Department of Botany laboratory, Tribhuvan University Kathmandu for further analysis of biochemical and morphological parameters. The biological parameters are chlorophyll –a, chlorophyll –b and total chlorophyll content whereas morphological parameters are dust load, leaf area, specific leaf area, leaf length and leaf breadth.

Dust content / Dust load: Triplicate leaf samples were first weighed using an electronic balance (S303, 0.001 g precision) to obtain their initial weight (with deposited surface particulates). Thereafter, the leaves were gently cleaned with tissue paper to remove loosely adhered surface deposits, and their final weight (without surface particulates) was recorded. To ensure consistency in dust removal, all leaf samples were gently wiped using the same type of soft tissue paper under uniform pressure. Care was taken to minimize damage to the leaf surface during cleaning. However, it is acknowledged that slight loss of epicuticular waxes and some tightly adhered particulates may occur during wiping, which may influence the absolute dust load values.

In this study, dust load refers to the total particulate matter deposited on the leaf surface, which may include road dust, soil particles, vehicular soot, industrial particulates, and other atmospheric deposits. Since the deposited material was not chemically fractionated, the values represent overall surface particulate deposition

rather than only mineral dust. Dust deposition was determined by calculating the difference between the initial and final weights. Leaf area was measured using Image J software from photographs taken with a scale as reference. Dust load per square centimeter was then computed using the formula provided by Rai & Panda (2014a):

$$W(\text{mg}/\text{cm}^2) = \frac{W1 - W2}{A}$$

where, W= dust load, W1= weight of leaves with dust, W2= weight of leaves without dust and A= area of leaves

Morphological characteristics: For this study, the three biggest leaves of each plant at each area were gathered. Following a gentle wet cloth cleaning and rinsing of the dust from the leaf samples, photographs were taken of the scales. The photos were organized on a computer in a folder and were employed to measure two morphological characteristics (Specific Leaf Area and Leaf Area). The ImageJ Software version 1.54 g was used to measure the leaf area based on the captured images. For the SLA, the samples used for the leaf area were dried for 24 hours at 60°C in a hot air oven. Subsequently, using three digital electronic scales (0.001 g), the weight of the dried leaves was determined equilibrium. At the end, SLA (cm²/g) was calculated using Chaturvedi *et al.*, (2013).

$$\text{SLA (cm}^2/\text{g)} = \text{Leaf area/dry weight}$$

The length and breadth were measured from the photograph using ImageJ Software version 1.54 g. The percentage increase or decrease in leaf area, SLA, length, and width was determined by comparing the data of the corresponding parameters in polluted, moderately polluted and less polluted areas.

Statistical analysis

MS Excel 2013 (Microsoft Corporation, USA) was used for all data calculations, while SPSS Statistics 20 Version (IBM Corporation) was used for statistical analysis. One-way ANOVA was used to assess significant differences in the mean among plant species from different study areas across two seasons. Duncan's multiple range test was then used to determine which specific means differed from one another. A scatter plot was constructed to demonstrate the correlations between pairs of variables.

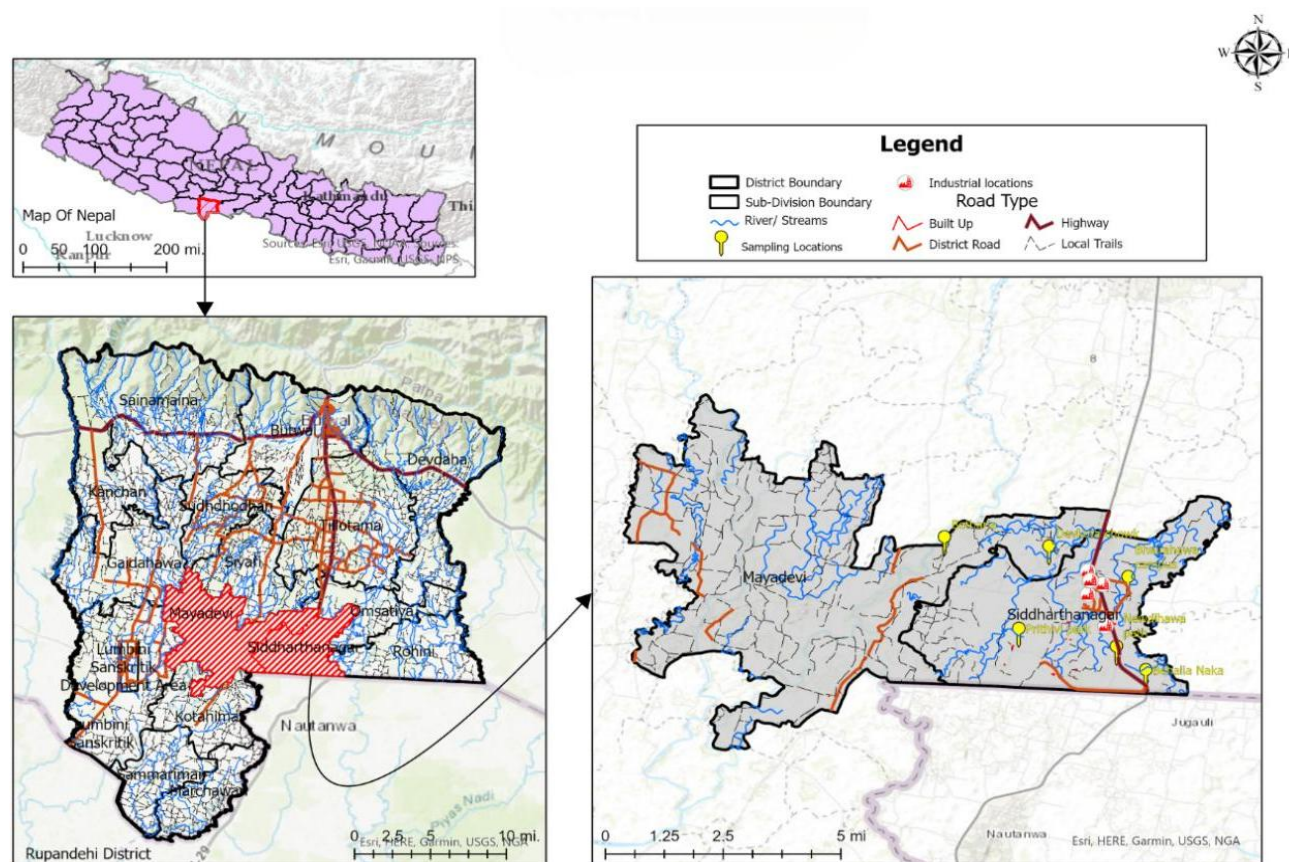


Fig. 2. Map of study area with sampling points; A= Map of Nepal, B= Rupandehi District, C= Study area with sampling points.

Results

Dust load: Dust load was comparatively higher in winter than in the monsoon season at roadside area, followed by industrial, residential and garden areas in both seasons (Fig. 3). During winter season, *T. grandis* showed highest dust load in industrial (5.09 mg/cm^2), roadside (4.90 mg/cm^2) and residential areas (4 mg/cm^2) but *P. guajava* L. showed highest dust load at garden area (0.29 mg/cm^2). During monsoon season, *T. grandis* and *M. indica* showed highest dust in residential and roadside area with 0.48 mg/cm^2 and 0.88 mg/cm^2 respectively. Mostly, *A. indica* recorded lowest dust load than other plant species during both season (Table 3).

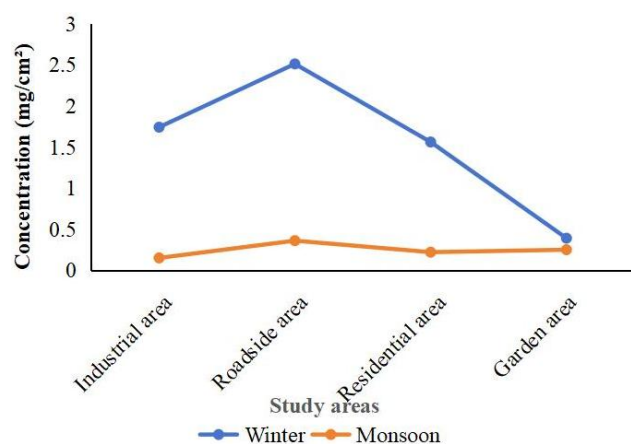


Fig. 3. Average dust load (mg/cm^2) on leaves of trees at different study areas.

Leaf area: In winter, leaf area ranged from 8.48 cm^2 in *A. indica* A. Juss. at the residential area to 656.35 cm^2 in *T. grandis* L.f in the industrial area. During the monsoon, the range was little broader in highest leaf area, with the lowest leaf area of 4.77 cm^2 in *A. indica* and the highest of 980.24 cm^2 in *T. grandis* in the garden area (Table 4). In winter seasons, higher leaf area reduction was observed in *D. sissoo* (75.91%) at industrial, in *Saraca asoca* at roadside (73.75%) and in *T. grandis* at residential (62.09%) areas. In monsoon seasons, maximum leaf area reduction was observed among *A. indica* at industrial (46.39%), *T. grandis* at roadside (64.15%) and *F. religiosa* at residential (38.56%) areas. *P. guajava* recorded minimum leaf area reduction (22.22%) from industrial areas during winter season and *S. asoca* (6.32%) from residential area during monsoon season (Fig. 4).

Specific leaf area (SLA): During winter, the specific leaf area (SLA) ranged from $22.75 \text{ cm}^2 \text{ g}^{-1}$ in *F. benghalensis* at the industrial area to $437.85 \text{ cm}^2 \text{ g}^{-1}$ in *A. indica* at the roadside area. During the monsoon season, SLA ranged from $74.20 \text{ cm}^2 \text{ g}^{-1}$ in *F. benghalensis* at the industrial area to $410.63 \text{ cm}^2 \text{ g}^{-1}$ in *A. indica* at the roadside area (Table 5). Overall, SLA was generally lower in industrial and roadside than in the garden area during both study seasons (Fig. 5). In winter, the greatest reduction in SLA was observed in *M. indica* at the industrial (86.09%) and residential (67.10%) areas, while *S. asoca* showed the highest reduction at the roadside area (87.41%). During the monsoon season, the maximum SLA reduction was recorded in *A. indica* at the industrial area (45.83%), *M. indica* at the roadside area (20.76%), and *T. grandis* at the residential area (24.50%).

Table 3. Dust load (mg/cm²) on leaves of different plant species comparing two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	0.34 ± 0.17 ^a	0.33 ± 0.11 ^a	1.01 ± 0.19 ^b	0.20 ± 0.05 ^{abcd}	0.59 ± 0.11 ^a	0.17 ± 0.03 ^a	0.23 ± 0.06 ^{ab}	0.83 ± 0.65 ^b
<i>Dalbergia sissoo</i>	2.80 ± 0.57 ^c	0.32 ± 0.19 ^a	1.29 ± 0.17 ^b	0.32 ± 0.15 ^{abcd}	0.51 ± 0.35 ^a	0.44 ± 0.12 ^{ab}	0.07 ± 0.00 ^{ab}	0.20 ± 0.06 ^a
<i>Ficus benghalensis</i>	1.78 ± 0.03 ^b	0.11 ± 0.05 ^a	2.58 ± 1.03 ^b	0.32 ± 0.02 ^{abcd}	1.57 ± 0.23 ^{ab}	0.05 ± 0.02 ^a	0.36 ± 0.07 ^{bc}	0.18 ± 0.08 ^a
<i>Ficus religiosa</i>	1.39 ± 0.23 ^b	0.14 ± 0.04 ^a	2.10 ± 0.54 ^b	0.24 ± 0.07 ^{abcd}	0.86 ± 0.17 ^a	0.13 ± 0.09 ^a	0.57 ± 0.17 ^c	0.09 ± 0.04 ^a
<i>Mangifera indica</i>	2.12 ± 0.46 ^{bc}	0.11 ± 0.02 ^a	2.16 ± 0.24 ^b	0.88 ± 0.11 ^{ef}	1.65 ± 0.53 ^{ab}	0.37 ± 0.07 ^{ab}	0.18 ± 0.08 ^{ab}	0.14 ± 0.05 ^a
<i>Psidium guajava</i>	0.14 ± 0.03 ^a	0.08 ± 0.07 ^a	1.68 ± 0.20 ^b	0.31 ± 0.04 ^{abcd}	1.63 ± 0.22 ^{ab}	0.13 ± 0.04 ^a	0.93 ± 0.03 ^d	0.13 ± 0.06 ^a
<i>Saraca asoca</i>	0.26 ± 0.02 ^a	0.08 ± 0.04 ^a	4.42 ± 0.85 ^c	0.12 ± 0.03 ^{abc}	1.73 ± 0.27 ^{ab}	0.04 ± 0.01 ^a	0.62 ± 0.06 ^c	0.29 ± 0.02 ^a
<i>Tectona grandis</i>	5.09 ± 1.19 ^a	0.09 ± 0.02 ^a	4.90 ± 0.50 ^a	0.56 ± 0.08 ^{cde}	4.00 ± 1.27 ^b	0.48 ± 0.15 ^{ab}	0.23 ± 0.20 ^{ab}	0.20 ± 0.15 ^a
p-value	0.000	0.350	0.000	0.000	0.087	0.015	0.000	0.020
F-value	14.82	1.14	22.53	6.21	2.13	2.10	8.66	2.11

(The data were expressed as Mean ± S.E and statistical analysis using one-way ANOVA for obtaining F and p-values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 4. Leaf area (cm²) at different study areas of different plant species during two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	15.99±2.92 ^a	9.04±1.01 ^a	23.85±2.66 ^{ab}	9.77±0.37 ^a	8.48±0.60 ^a	7.25±1.05 ^a	13.21±0.92 ^a	4.77±0.31 ^a
<i>Dalbergia sissoo</i>	11.03±1.07 ^a	14.53±0.41 ^a	13.84±1.12 ^{ab}	20.81±3.40 ^a	19.50±3.05 ^a	11.40±1.80 ^a	46.60±3.00 ^a	13.7±1.49 ^a
<i>Ficus benghalensis</i>	74.88±13.64 ^a	103.94±22.69 ^b	59.84±12.44 ^{ab}	181.85±9.61 ^{ab}	75.37±6.50 ^c	244.16±36.13 ^c	129.64±10.03 ^a	114.31±6.22 ^a
<i>Ficus religiosa</i>	25.84±2.43 ^a	113.14±4.42 ^b	62.74±8.80 ^{ab}	62.55±8.83 ^a	60.84±10.75 ^{bc}	69.52±6.72 ^{ab}	102.29±37.98 ^a	72.71±6.44 ^a
<i>Mangifera indica</i>	28.31±3.80 ^a	85.10±16.01 ^b	149.50±12.17 ^b	81.29±2.10 ^a	56.47±4.05 ^{bc}	96.56±9.59 ^b	141.68±12.58 ^a	52.63±13.11 ^a
<i>Psidium guajava</i>	48.40±2.17 ^a	49.41±9.02 ^{ab}	60.06±2.72 ^{ab}	50.49±7.00 ^a	10.87±0.62 ^a	59.11±8.67 ^{ab}	56.92±6.12 ^a	32.36±2.72 ^a
<i>Saraca asoca</i>	82.72±10.93 ^a	50.35±5.11 ^{ab}	30.18±5.68 ^{ab}	58.86±1.38 ^a	35.27±2.62 ^{ab}	54.14±2.99 ^{ab}	113.63±6.28 ^a	32.03±3.16 ^a
<i>Tectona grandis</i>	656.35±144.45 ^b	584.53±47.22 ^c	613.61±119.71 ^c	298.36±155.34 ^b	196.83±26.46 ^d	601.07±49.72 ^d	548.72±125.10 ^b	980.24±217.45 ^b
p-value	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000
F-value	18.39	91.38	22.47	3.10	40.38	79.42	13.79	18.55

(The data were expressed as Mean ± S.E and statistical analysis using one-way ANOVA for obtaining F and p values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 5. Specific leaf area (cm²/g) at different study areas of different plant species during two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	400.83±45.37 ^c	359.72±21.67 ^c	437.85±31.56 ^f	410.63±42.56 ^c	349.85±78.40 ^e	400.45±13.25 ^d	569.18±89.73 ^d	195.10±18.68 ^c
<i>Dalbergia sissoo</i>	178.23±28.60 ^{ab}	135.66±5.42 ^{bc}	141.35±6.62 ^{de}	158.72±7.01 ^{bc}	165.43±7.88 ^b	129.19±19.53 ^{ab}	410.59±37.41 ^c	125.20±4.59 ^c
<i>Ficus benghalensis</i>	22.91±1.63 ^a	74.20±2.17 ^a	22.75±5.15 ^a	101.26±2.80 ^{ab}	32.90±2.55 ^a	94.87±3.57 ^a	63.66±2.38 ^a	95.17±8.23 ^{abc}
<i>Ficus religiosa</i>	40.81±7.67 ^a	121.85±2.30 ^{bc}	70.54±15.56 ^{abc}	148.70±14.95 ^{abc}	59.86±17.24 ^a	121.18±8.66 ^{ab}	111.94±15.02 ^a	110.07±5.76 ^{bc}
<i>Mangifera indica</i>	22.77±1.99 ^a	99.13±9.25 ^{ab}	120.21±21.60 ^{cde}	90.47±11.99 ^a	51.96±3.55 ^a	86.70±7.04 ^a	154.21±20.38 ^a	84.80±1.72 ^{ab}
<i>Psidium guajava</i>	87.75±1.24 ^a	135.51±12.48 ^{bc}	88.95±1.03 ^{bcd}	138.61±8.08 ^{abc}	32.48±1.06 ^a	130.11±10.15 ^{ab}	106.68±4.19 ^a	69.52±11.20 ^a
<i>Saraca asoca</i>	165.31±5.68 ^{ab}	192.07±19.23 ^d	38.82±2.55 ^{ab}	219.59±17.21 ^d	59.45±4.33 ^a	195.19±4.64 ^c	315.69±28.67 ^{bc}	132.18±18.96 ^{cd}
<i>Tectona grandis</i>	178.18±70.12 ^{ab}	157.72±23.83 ^{cd}	143.76±19.88 ^c	180.72±6.90 ^{cd}	45.03±6.08 ^a	161.55±36.85 ^{bc}	74.54±25.88 ^a	166.58±10.11 ^{de}
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F-value	7.17	36.98	54.98	31.15	14.34	37.69	21.20	13.39

(The data were expressed as Mean ± S.E and statistical analysis using one-way ANOVA for obtaining F and p values. Significance mean values among different plant species are indicated by different letters (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 6. Leaf length (cm) at different study areas of different plant species during two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	7.29 ± 0.45 ^{ab}	6.72 ± 0.20 ^a	8.15 ± 0.91 ^{ab}	5.54 ± 0.29 ^a	6.13 ± 0.35 ^a	5.65 ± 0.34 ^a	8.54 ± 0.36 ^{ab}	5.36 ± 0.26 ^a
<i>Dalbergia sissoo</i>	4.70 ± 0.50 ^a	4.94 ± 0.20 ^a	7.69 ± 0.12 ^a	5.75 ± 0.67 ^a	6.32 ± 0.50 ^a	4.44 ± 0.34 ^a	4.23 ± 0.11 ^a	5.53 ± 0.32 ^a
<i>Ficus benghalensis</i>	17.64 ± 1.99 ^{cd}	14.28 ± 1.69 ^{bc}	17.80 ± 1.16 ^{cd}	18.52 ± 0.47 ^{bc}	18.19 ± 0.95 ^c	19.34 ± 1.63 ^c	13.85 ± 0.22 ^{cd}	15.72 ± 0.34 ^b
<i>Ficus religiosa</i>	12.13 ± 0.26 ^{bc}	13.85 ± 0.15 ^{bc}	15.61 ± 3.76 ^{cd}	13.63 ± 1.84 ^b	11.68 ± 0.81 ^b	12.88 ± 0.58 ^b	17.00 ± 0.39 ^{de}	14.19 ± 1.10 ^b
<i>Mangifera indica</i>	23.16 ± 1.27 ^d	20.31 ± 0.76 ^d	19.56 ± 0.93 ^d	21.44 ± 0.90 ^c	20.97 ± 1.24 ^{cd}	22.04 ± 1.91 ^c	22.87 ± 1.65 ^f	16.31 ± 2.44 ^b
<i>Psidium guajava</i>	8.74 ± 0.03 ^{ab}	11.77 ± 0.49 ^b	13.63 ± 0.21 ^{bc}	11.87 ± 1.25 ^{ab}	10.94 ± 0.18 ^b	13.54 ± 0.85 ^b	11.68 ± 0.69 ^{bc}	9.66 ± 0.82 ^a
<i>Saraca asoca</i>	23.46 ± 1.11 ^d	15.95 ± 0.36 ^c	20.56 ± 1.20 ^d	21.11 ± 0.61 ^c	23.88 ± 0.72 ^d	18.77 ± 0.59 ^c	20.16 ± 1.88 ^{ef}	14.62 ± 1.01 ^b
<i>Tectona grandis</i>	38.39 ± 5.02 ^{de}	34.92 ± 2.90 ^c	28.11 ± 2.84 ^c	20.96 ± 5.82 ^c	36.45 ± 3.46 ^c	35.07 ± 2.80 ^d	32.39 ± 3.72 ^g	41.89 ± 5.68 ^c
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F-value	30.59	56.20	13.25	8.76	49.50	48.55	29.84	25.78

(The data were expressed as Mean ± S.E and statistical analysis using one-way ANOVA for obtaining F and p values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 7. Leaf width (cm) at different study areas of different plant species during two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	1.93 ± 0.17 ^a	2.42 ± 0.07 ^a	2.01 ± 0.13 ^a	2.69 ± 0.22 ^a	1.91 ± 0.14 ^a	1.93 ± 0.11 ^a	2.50 ± 0.08 ^{ab}	1.81 ± 0.09 ^a
<i>Dalbergia sissoo</i>	3.55 ± 0.16 ^{ab}	4.55 ± 0.12 ^{ab}	4.18 ± 0.26 ^{ab}	5.04 ± 0.40 ^{ab}	5.03 ± 0.07 ^b	3.41 ± 0.36 ^{ab}	3.42 ± 0.34 ^{ab}	4.18 ± 0.19 ^a
<i>Ficus benghalensis</i>	13.15 ± 1.38 ^d	10.15 ± 1.00 ^c	10.69 ± 0.68 ^c	12.76 ± 0.32 ^{cd}	10.66 ± 0.38 ^c	15.16 ± 1.41 ^c	8.47 ± 0.95 ^{de}	10.28 ± 0.36 ^b
<i>Ficus religiosa</i>	9.52 ± 0.75 ^c	11.78 ± 0.35 ^c	9.59 ± 2.04 ^c	8.70 ± 0.88 ^{bc}	7.70 ± 0.74 ^b	9.06 ± 0.56 ^d	10.97 ± 0.79 ^c	9.25 ± 0.46 ^b
<i>Mangifera indica</i>	4.85 ± 0.50 ^b	5.71 ± 0.40 ^b	5.80 ± 0.18 ^b	5.30 ± 0.06 ^{ab}	4.77 ± 0.30 ^b	6.04 ± 0.26 ^c	6.25 ± 0.21 ^{cd}	4.86 ± 0.28 ^a
<i>Psidium guajava</i>	4.20 ± 0.21 ^{ab}	5.81 ± 0.92 ^b	6.16 ± 0.29 ^b	5.52 ± 0.04 ^{ab}	5.45 ± 0.02 ^b	5.46 ± 0.43 ^{bc}	4.67 ± 0.38 ^{bc}	4.61 ± 0.08 ^a
<i>Saraca asoca</i>	5.22 ± 0.66 ^b	5.02 ± 0.40 ^{ab}	3.73 ± 0.28 ^{ab}	4.66 ± 0.11 ^{ab}	5.03 ± 0.32 ^b	3.87 ± 0.28 ^{ab}	4.78 ± 0.10 ^{bc}	3.43 ± 0.38 ^a
<i>Tectona grandis</i>	22.57 ± 1.99 ^c	23.86 ± 2.14 ^d	18.95 ± 1.63 ^d	17.44 ± 4.76 ^d	22.64 ± 2.61 ^d	24.54 ± 0.81 ^f	22.22 ± 2.15 ^f	33.18 ± 3.66 ^e
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F-value	54.96	54.16	35.00	8.32	47.09	134.29	54.44	59.33

(The data were expressed as Mean± S.E and statistical analysis using one-way ANOVA for obtaining F and *p* values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 8. Chlorophyll-a at different study areas of different plant species during two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	0.35 ± 0.03 ^a	0.91 ± 0.09 ^b	0.77 ± 0.10 ^{ab}	0.76 ± 0.22 ^{bcd}	0.55 ± 0.12 ^{abc}	1.06 ± 0.23 ^c	0.63 ± 0.23 ^{ab}	1.09 ± 0.06 ^{bc}
<i>Dalbergia sissoo</i>	1.34 ± 0.25 ^{cd}	1.19 ± 0.09 ^c	2.04 ± 0.33 ^c	1.06 ± 0.18 ^{cd}	1.40 ± 0.25 ^{bc}	0.60 ± 0.01 ^{ab}	1.16 ± 0.23 ^{ab}	0.92 ± 0.06 ^{bc}
<i>Ficus benghalensis</i>	0.79 ± 0.23 ^{abc}	0.68 ± 0.02 ^b	0.67 ± 0.09 ^{ab}	0.55 ± 0.02 ^a	0.90 ± 0.22 ^{abc}	0.33 ± 0.06 ^a	0.52 ± 0.18 ^a	0.31 ± 0.08 ^a
<i>Ficus religiosa</i>	1.14 ± 0.02 ^{bc}	0.28 ± 0.05 ^a	0.76 ± 0.10 ^{ab}	0.52 ± 0.08 ^{ab}	1.58 ± 0.20 ^c	0.29 ± 0.05 ^a	0.87 ± 0.31 ^{abc}	0.35 ± 0.04 ^a
<i>Mangifera indica</i>	0.60 ± 0.37 ^{ab}	0.69 ± 0.12 ^b	1.95 ± 0.86 ^c	1.11 ± 0.21 ^d	1.55 ± 0.72 ^c	0.58 ± 0.09 ^{ab}	1.78 ± 0.73 ^{bc}	1.17 ± 0.18 ^c
<i>Psidium guajava</i>	0.34 ± 0.04 ^a	0.73 ± 0.09 ^b	1.45 ± 0.50 ^{bc}	0.15 ± 0.02 ^a	2.69 ± 0.24 ^d	0.27 ± 0.02 ^a	1.10 ± 0.11 ^{abc}	0.27 ± 0.06 ^a
<i>Saraca asoca</i>	1.85 ± 0.19 ^d	0.69 ± 0.02 ^b	1.26 ± 0.14 ^{abc}	0.67 ± 0.02 ^{bc}	1.55 ± 0.32 ^c	0.81 ± 0.09 ^{bc}	1.97 ± 0.44 ^c	0.85 ± 0.02 ^b
<i>Tectona grandis</i>	0.48 ± 0.31 ^{ab}	0.78 ± 0.02 ^b	0.10 ± 0.07 ^a	0.53 ± 0.01 ^{ab}	0.45 ± 0.30 ^{ab}	0.83 ± 0.03 ^{bc}	0.66 ± 0.45 ^{ab}	1.03 ± 0.09 ^{bc}
p-value	0.000	0.000	0.009	0.002	0.002	0.000	0.069	0.000
F-value	6.95	10.74	3.81	5.43	5.36	7.62	2.29	18.50

(The data were expressed as Mean± S.E and statistical analysis using one-way ANOVA for obtaining F and *p* values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 9. Chlorophyll-b at different study areas of different plant species during two seasons.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	0.11 ± 0.00 ^{ab}	0.20 ± 0.02 ^b	0.18 ± 0.02 ^{abc}	0.20 ± 0.02 ^{bcd}	0.13 ± 0.02 ^{ab}	0.38 ± 0.08 ^c	0.14 ± 0.04 ^a	0.32 ± 0.02 ^c
<i>Dalbergia sissoo</i>	0.25 ± 0.04 ^{cd}	0.30 ± 0.02 ^b	0.35 ± 0.07 ^{bc}	0.35 ± 0.03 ^c	0.25 ± 0.03 ^{ab}	0.25 ± 0.04 ^d	0.23 ± 0.04 ^{ab}	0.16 ± 0.00 ^{ab}
<i>Ficus benghalensis</i>	0.16 ± 0.04 ^{ab}	0.16 ± 0.01 ^{ab}	0.15 ± 0.01 ^{ab}	0.11 ± 0.00 ^a	0.19 ± 0.03 ^{ab}	0.13 ± 0.02 ^{abc}	0.29 ± 0.16 ^{ab}	0.10 ± 0.02 ^a
<i>Ficus religiosa</i>	0.15 ± 0.00 ^{ab}	0.10 ± 0.01 ^a	0.13 ± 0.01 ^{ab}	0.13 ± 0.02 ^{ab}	0.14 ± 0.00 ^{ab}	0.09 ± 0.02 ^{ab}	0.14 ± 0.01 ^a	0.07 ± 0.01 ^a
<i>Mangifera indica</i>	0.13 ± 0.06 ^{abc}	0.52 ± 0.10 ^c	0.47 ± 0.21 ^c	0.24 ± 0.03 ^{cd}	0.35 ± 0.19 ^{ab}	0.24 ± 0.03 ^{cd}	0.23 ± 0.09 ^{ab}	0.50 ± 0.11 ^d
<i>Psidium guajava</i>	0.15 ± 0.00 ^{ab}	0.19 ± 0.02 ^b	0.31 ± 0.08 ^{abc}	0.06 ± 0.00 ^a	0.71 ± 0.11 ^b	0.07 ± 0.01 ^a	0.23 ± 0.01 ^{ab}	0.08 ± 0.01 ^a
<i>Saraca asoca</i>	0.30 ± 0.04 ^d	0.24 ± 0.02 ^b	0.28 ± 0.00 ^{abc}	0.18 ± 0.00 ^{bc}	0.34 ± 0.04 ^{ab}	0.19 ± 0.00 ^{abcd}	0.42 ± 0.07 ^b	0.16 ± 0.00 ^{ab}
<i>Tectona grandis</i>	0.09 ± 0.06 ^{ab}	0.29 ± 0.01 ^b	0.20 ± 0.14 ^{abc}	0.26 ± 0.02 ^d	0.68 ± 0.46 ^b	0.26 ± 0.00 ^d	0.21 ± 0.12 ^{ab}	0.26 ± 0.03 ^{bc}
p-value	0.005	0.000	0.107	0.000	0.122	0.000	0.180	0.000
F-value	4.32	9.02	1.99	15.72	1.90	6.52	1.64	11.28

(The data were expressed as Mean± S.E and statistical analysis using one-way ANOVA for obtaining F and *p* values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

Table 10. Total chlorophyll content (mg/g) on leaf of different plant species at different study areas.

Plant species	Industrial		Roadside		Residential		Garden	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
<i>Azadirachta indica</i>	0.47 ± 0.04 ^{ab}	0.56 ± 0.06 ^{abc}	1.01 ± 0.06 ^{bcd}	0.51 ± 0.18 ^{abcd}	0.74 ± 0.07 ^{abc}	0.83 ± 0.12 ^{cde}	0.92 ± 0.12 ^{bcd}	0.72 ± 0.10 ^{bcd}
<i>Dalbergia sissoo</i>	1.59 ± 0.30 ^{de}	1.63 ± 0.15 ^c	2.40 ± 0.40 ^e	1.52 ± 0.06 ^{efg}	1.65 ± 0.29 ^{cdef}	0.95 ± 0.09 ^{def}	1.40 ± 0.27 ^{de}	1.20 ± 0.09 ^c
<i>Ficus benghalensis</i>	1.04 ± 0.26 ^{bcd}	1.37 ± 0.19 ^{de}	0.80 ± 0.19 ^{abcde}	1.07 ± 0.09 ^{cdef}	1.16 ± 0.20 ^{abcd}	0.78 ± 0.23 ^{cde}	0.88 ± 0.02 ^{bcd}	0.65 ± 0.15 ^{bcd}
<i>Ficus religiosa</i>	1.29 ± 0.02 ^{cd}	0.90 ± 0.06 ^{bcd}	1.26 ± 0.15 ^{def}	1.56 ± 0.04 ^{efg}	1.63 ± 0.23 ^{cdef}	0.89 ± 0.07 ^{de}	1.01 ± 0.32 ^{bcd}	1.02 ± 0.11 ^{de}
<i>Mangifera indica</i>	0.85 ± 0.34 ^{bc}	0.77 ± 0.30 ^{bcd}	3.05 ± 0.46 ^{hg}	0.89 ± 0.36 ^{abcde}	2.26 ± 0.30 ^{efg}	0.01 ± 0.00 ^a	2.38 ± 0.35 ^{fg}	0.02 ± 0.00 ^a
<i>Psidium guajava</i>	0.49 ± 0.04 ^{ab}	2.39 ± 0.15 ^f	1.56 ± 0.28 ^{ef}	0.58 ± 0.07 ^{abcde}	2.62 ± 0.39 ^g	0.93 ± 0.05 ^{de}	1.34 ± 0.13 ^{de}	0.92 ± 0.22 ^{de}
<i>Saraca asoca</i>	2.15 ± 0.23 ^c	1.00 ± 0.12 ^{cde}	1.55 ± 0.14 ^{ef}	0.92 ± 0.12 ^{abcde}	2.46 ± 0.35 ^{fg}	1.05 ± 0.06 ^{def}	3.12 ± 0.16 ^h	1.10 ± 0.13 ^c
<i>Tectona grandis</i>	1.14 ± 0.13 ^{cd}	0.59 ± 0.40 ^{abc}	0.50 ± 0.12 ^{abcd}	0.48 ± 0.35 ^{abcd}	1.76 ± 0.24 ^{defg}	0.59 ± 0.26 ^{bcd}	1.84 ± 0.12 ^{ef}	0.78 ± 0.56 ^{cde}
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F-value	9.48	6.18	8.68	4.42	11.14	6.25	16.52	3.93

(The data were expressed as Mean± S.E and statistical analysis using one-way ANOVA for obtaining F and *p* values. Significance mean values among different plant species are indicated by different letters. (Duncan multiple tests, $p \leq 0.05$, (n=24))

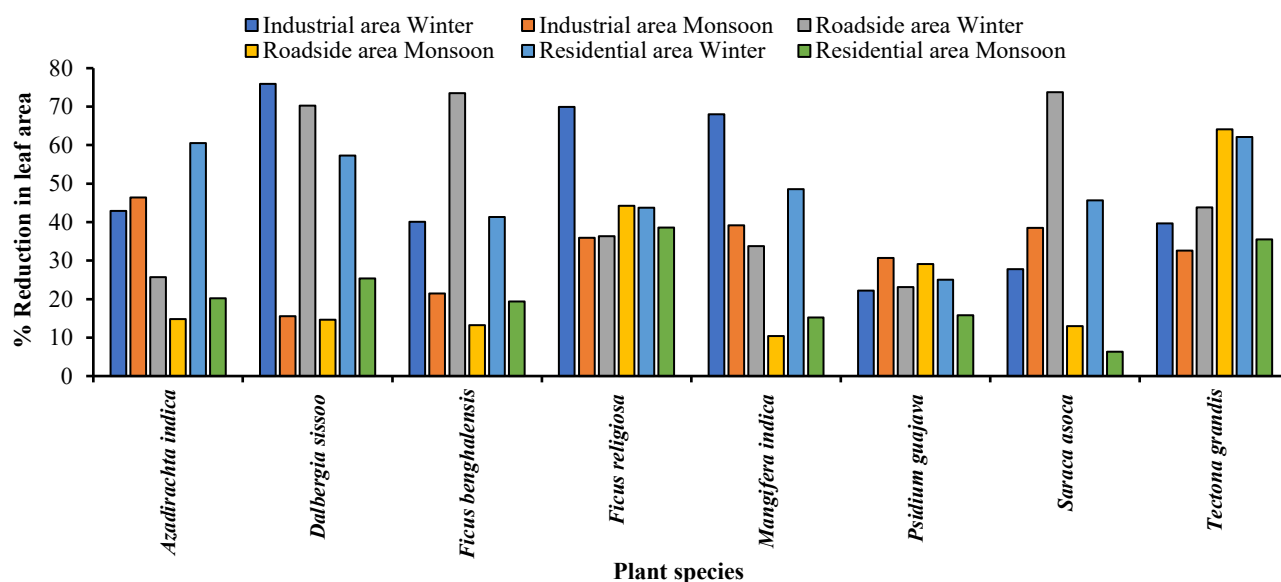


Fig. 4. Percentage (%) reduction in leaf area of different plant species in two seasons.

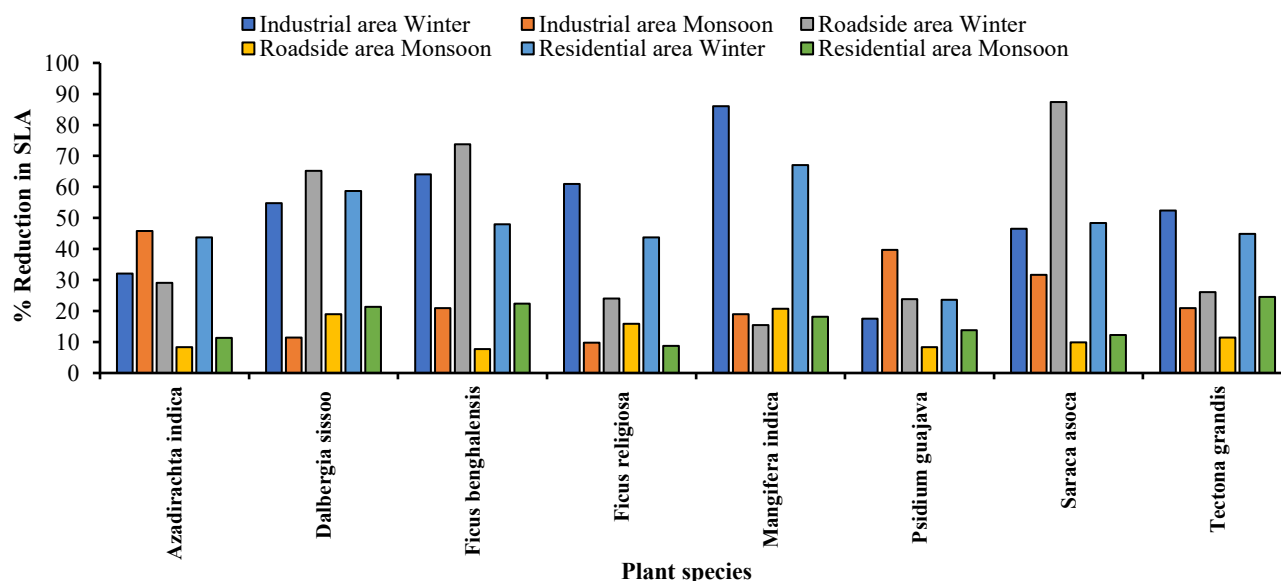


Fig. 5. Percentage (%) reduction in SLA of different plant species in two seasons.

Regression analysis revealed a weak negative relationship between dust load and SLA during the winter season ($R^2 = 0.117$), indicating that SLA tended to decrease with increasing dust deposition (Fig. 6a). In contrast, during the monsoon season, a very weak positive relationship was observed ($R^2 = 0.018$), suggesting only a negligible increase in SLA with increasing dust load (Fig. 6b). These findings showed that the relationship between dust deposition and SLA was seasonally variable but weak, and that other environmental and species-specific factors likely contributed to SLA variation.

Leaf length: During the winter, the leaf length was shortest in *D. sissoo*. (4.23 ± 0.11 cm) in the garden area, while the longest was recorded in *Tectona grandis* (38.39 ± 5.02 cm) in the industrial area (Table 6). During monsoon, *D. sissoo* Roxb ex DC. had the shortest leaves (4.44 ± 0.34 cm) in the residential area, while *T. grandis* L.f had the longest (41.89 ± 5.68 cm) in the garden area. Overall, *T. grandis* L.f consistently exhibited the largest leaf lengths across all studied areas, while *D. sissoo* Roxb ex DC. had the smallest.

The percentage of leaf length reduced mostly in industrial and roadside areas during winter compared to other areas and monsoon season (Fig. 7). In industrial areas, *P. guajava* exhibited maximum leaf length reduction (42.93%) during winter but in monsoon it was exhibited by *M. indica* (23.77%). At roadside, *D. sissoo* in winter (41.81%) and *T. grandis* in monsoon (46.98%) exhibited maximum leaf length reduction. At residential areas, *F. religiosa* showed maximum reduction during winter (31.44%) but in monsoon maximum reduction (18.91%) was in *D. sissoo*.

Leaf width: During winter, the smallest leaf width was recorded in *A. indica* (1.91 ± 0.14 cm), while the largest was recorded in *T. grandis* (22.64 ± 2.61 cm) in the residential area (Table 7). During monsoon, *A. indica* had the smallest leaf width (1.81 ± 0.09 cm), while *T. grandis* had the largest one (33.18 ± 3.66 cm) in the garden area. *T. grandis* exhibited the widest leaves across all studied areas and seasons, whereas *A. indica* had the narrowest.

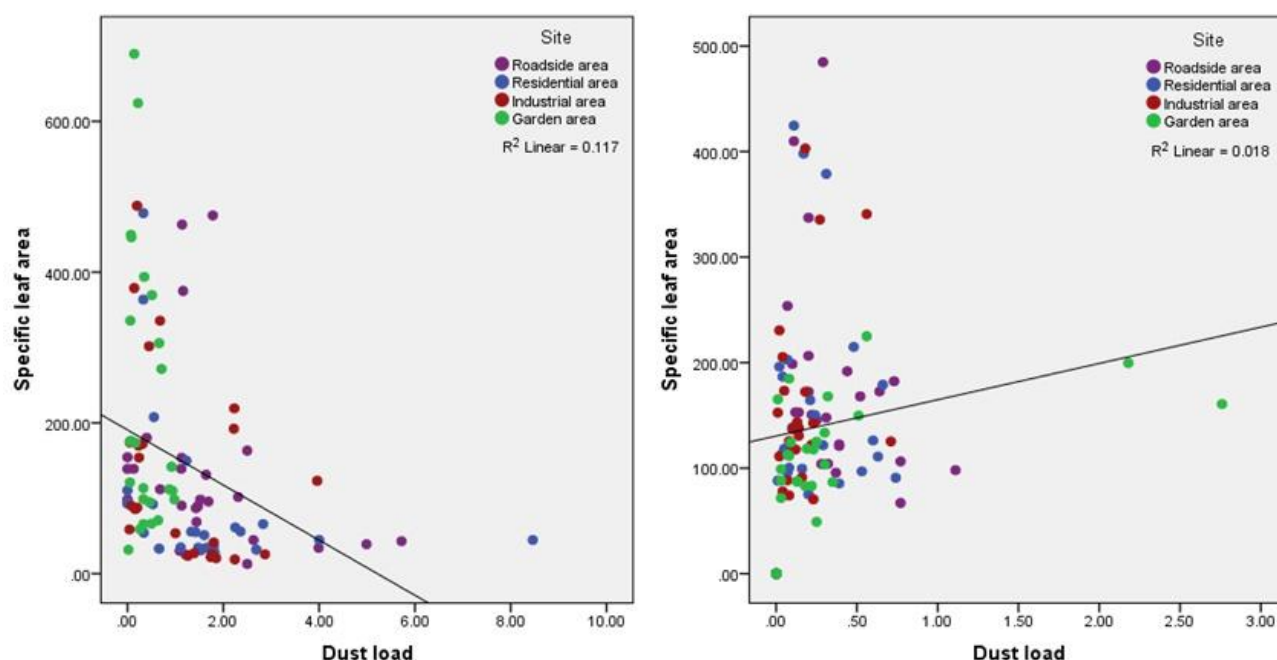


Fig. 6. Analysis between SLA and dust load in winter (a) and monsoon (b) seasons.

The percentage of leaf width reduction was higher in polluted during monsoon than in the less polluted area (Fig. 8). In industrial areas, *F. benghalensis* during winter (41.79%) and *S. asoca* during monsoon (31.82%) season recorded the highest reduction. At the roadside and residential, *S. asoca* during winter (47.21 and 31.51%) respectively showed the highest reduction. Similarly, in road side and residential areas, *T. grandis* and *D. sissoo* showed the maximum leaf width reduction during monsoon season (55.28% and 26.06% respectively).

Chlorophyll-a: Chlorophyll-a levels generally increased during the winter compared to the monsoon season, with industrial, roadside and residential areas showed significantly higher values than garden area (Table 8). However, certain plant species like, *A. indica*, *D. sissoo* and *M. indica* exhibited higher chlorophyll-a levels during the monsoon season. During the winter season, chlorophyll-a ranged from 0.10 mg/g in *T. grandis* in roadside area to 2.69 mg/g in *P. guajava* in residential area. Similarly, during monsoon season, it ranged from 0.15 mg/g in *P. guajava* in roadside area to 1.19 mg/g in *D. sissoo* in industrial area.

Reduction in chlorophyll-a: *S. asoca* from industrial area, *D. sissoo* from roadside and *F. religiosa* from the residential area exhibited the lowest reduction (%) in chlorophyll-a during winter seasons (Fig. 9). During monsoon season, plants like *D. sissoo* and *S. asoca* exhibited less percent of reduction in chlorophyll-a from different study areas.

Chlorophyll-b: Chlorophyll-b was increased during the monsoon, with significant variations across study areas and species ($p < 0.05$ in most cases). During the winter season, the chlorophyll-b ranged from 0.09 mg/g in *T. grandis* in industrial areas to 0.71 mg/g in *P. guajava* L. in residential areas (Table 9). During monsoon, Chlorophyll-b ranged from 0.06 mg/g in *P. guajava* in roadside to 0.52 mg/g in *M. indica* in industrial areas.

Reduction in Chlorophyll-b: The leaves of plants like *P. guajava*, *F. religiosa*, and *S. asoca* showed a minimum percentage of reduction in chlorophyll-b from polluted areas during winter season while (Fig. 9), species like *M. indica*, and *T. grandis* showed less percentage of reduction in chlorophyll-b during monsoon season.

Total chlorophyll: Generally, during winter seasons species in question showed higher total chlorophyll levels, especially at roadside and industrial areas. However, plants like *A. indica*, *D. sissoo* and *P. guajava* showed higher amount of total chlorophyll in monsoon season (Table 10). During winter season, the total chlorophyll content ranged from 0.47 mg/g in *A. indica* at industrial area to 3.05 mg/g in *M. indica* at residential area. During monsoon season, it ranged from 0.01mg/g in *M. indica*. at residential area to 2.39 mg/g in *P. guajava* at industrial area. Total chlorophyll content in the leaves of the plants like *F. religiosa* L., *M. indica* L., and *T. grandis* were less reduced from the polluted areas during winter seasons (Fig. 11). Conversely, *S. asoca* and *D. sissoo* exhibited less reduction in total chlorophyll content during monsoon seasons.

Discussion

Dust load: Average dust load was found to be higher in roadside areas in both seasons. Dust deposition on leaves of the plants growing along roadsides is likely to be elevated due to heavy traffic activities, which release unburned oil residues from fuel or gasoline on leaf surfaces, as supported by Rahul & Jain (2014) and Younis *et al.*, (2013). In the present study, dust accumulation on *T. grandis* was higher in industrial and roadside areas compared to less polluted sites during both winter and monsoon seasons. This may be attributed to emissions from construction activities, automobiles, and industrial operations, consistent with findings by Gupta *et al.*, (2016).

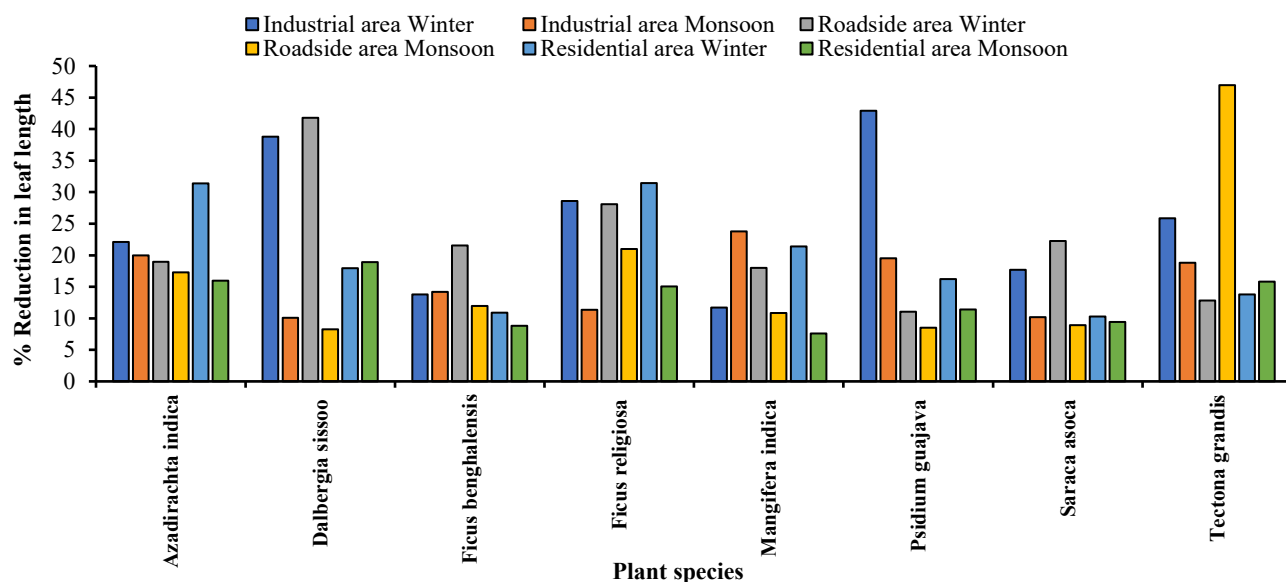


Fig. 7. Percentage (%) reduction in leaf length of different plant species in two seasons.

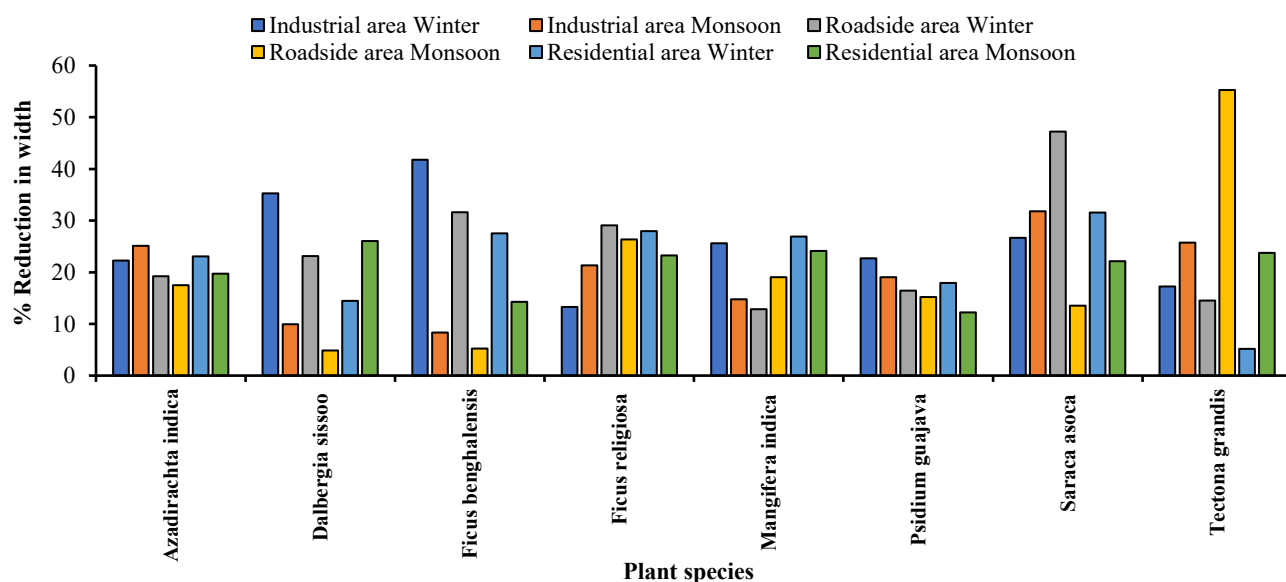


Fig. 8. Percentage (%) reduction in leaf width of different plant species in two seasons.

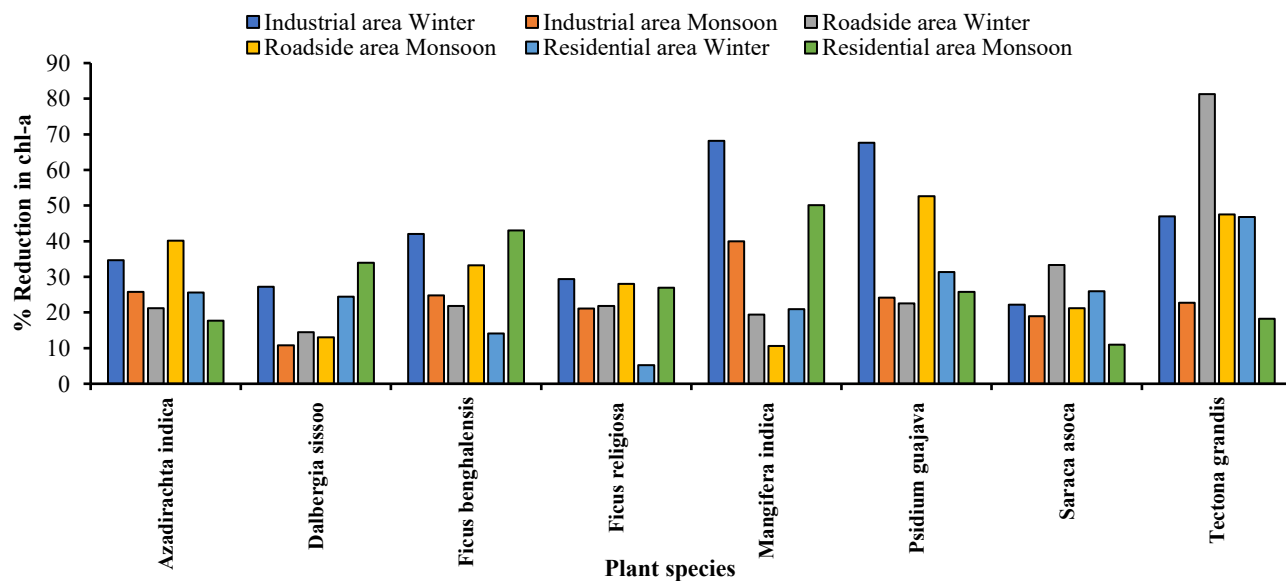


Fig. 9. Percentage (%) reduction in Chlorophyll-a of plant species in two seasons.

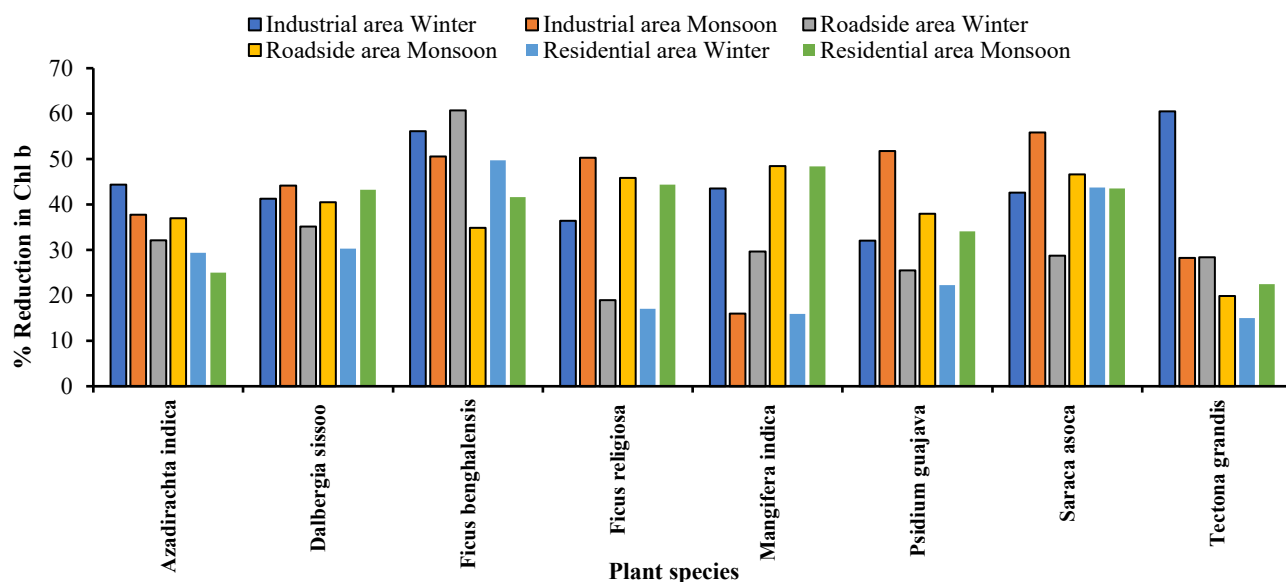


Fig. 10. Percentage (%) reduction in Chlorophyll-b of plant species in two seasons.

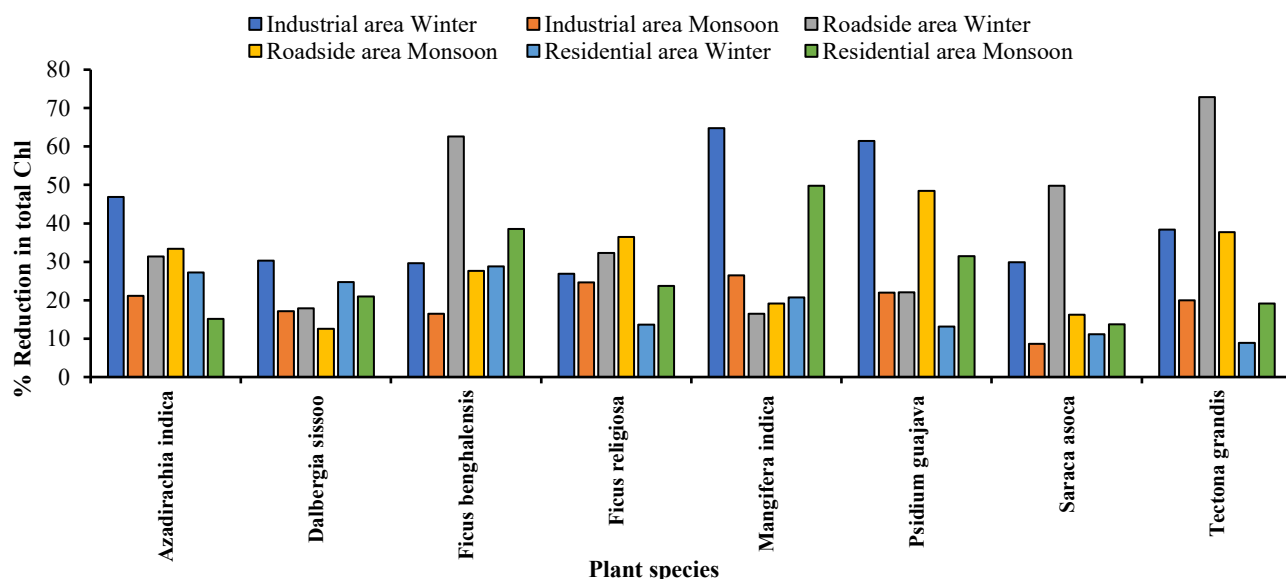


Fig. 11. Percentage reduction in total Chlorophyll content of different plant species in two seasons.

The variation in dust load observed across different study sites is further supported by the ambient air quality patterns (Fig. 1). Higher particulate matter concentrations at industrial and roadside areas correspond with increased dust deposition on leaf surfaces, indicating that atmospheric particulate pollution plays a significant role in dust accumulation. Several leaf characteristics, including size, shape, orientation, surface texture, presence or absence of trichomes, and petiole length, are known to influence dust deposition capacity (Rai, 2013). *T. grandis* exhibited the highest dust capturing ability, may be due to its rough surface, large leaf size, short petiole, and mid-leaf depression (Rai & Panda, 2014a). In contrast, *A. indica* showed the lowest dust accumulation, possibly due to its smoother leaf surface and absence of central depressions (Rai & Panda, 2014a). Tree species with higher dust capturing capacity can significantly contribute to air pollution mitigation (Chaphekar, 1972; Dwivedi & Tripathi, 2007; Prajapati & Tripathi, 2008).

Reduction in leaf morphology: Polluted areas generally exhibited smaller leaf area and specific leaf area (SLA) compared to less polluted areas consistent with previous studies (Hamal & Chettri, 2017; Hamal, 2023). During the winter season, reduction in leaf area was greatest in industrial areas, followed by roadside and residential areas. In the monsoon season, greater reductions in leaf length and width were observed in polluted areas compared to less polluted sites, except for *T. grandis* similar reductions in SLA near polluted areas during winter have also been reported by Balasooriya *et al.*, (2009).

The observed reductions in leaf area, width, and length under polluted conditions were in agreement with Rai & Panda (2014b). These changes may be attributed to pollutant-induced stress, which can damage leaf tissues, accelerate senescence, reduce photosynthetic activity, alter membrane permeability, and ultimately decrease plant productivity (Tiwari *et al.*, 2006). Reduced leaf production and increased

senescence may contribute to decreased leaf area, thereby limiting radiation absorption and lowering photosynthetic efficiency (Tiwari *et al.*, 2006). Similar findings have been reported in *Albizia lebbek* and *Newbouldia laevis* from polluted environments (Kayode & Otoide, 2007).

The relationship between dust load and specific leaf area (SLA) varied seasonally, with a weak negative trend during winter and a very weak positive trend during the monsoon season. In winter SLA is declined under higher dust deposition may reflect the development of thicker or denser leaves, which can be interpreted as an adaptive response to pollution stress. Overall, SLA was consistently lower in polluted sites than in less polluted areas across the studied species, indicating that exposure to dust and associated environmental stress may alter leaf structural traits. Reduced SLA is often associated with lower transpiration and water loss, thereby contributing to improved stress tolerance and resource conservation under adverse conditions (Xu *et al.*, 2009).

Importantly, the reduction in morphological traits corresponds with the ambient air quality trends (Fig. 1), where higher particulate matter concentrations at industrial and roadside sites are associated with greater morphological alterations. Although a detailed statistical correlation between PM₁₀/PM_{2.5} levels and morphological parameters was not performed, the observed patterns strongly indicate a close relationship between ambient particulate pollution and plant responses. Future studies incorporating quantitative correlation or regression analyses with continuous air quality monitoring data would further strengthen this relationship.

Species-wise tolerance and sensitivity: Overall, species responses indicated clear interspecific variation in tolerance to dust pollution. *A. indica*, *F. religiosa*, *P. guajava*, and *S. asoca* generally exhibited lower reductions in leaf morphological traits across polluted sites, suggesting comparatively greater tolerance. In contrast, *T. grandis* and *D. sissoo* showed greater reductions in several parameters under polluted conditions, indicating relatively higher sensitivity. However, despite its comparatively greater sensitivity in some morphological traits, *T. grandis* also exhibited strong dust capturing capacity, highlighting its potential ecological value in pollution mitigation and green belt development.

The observed patterns in this study are closely linked to the local environmental setting of Bhairahawa and the Terai region, where industrial emissions, traffic activity, and dry seasonal conditions contribute to elevated particulate pollution. Industries such as cement, steel, and brick manufacturing, together with frequent vehicular movement, are major sources of dust in the study area. Moreover, the dry winter climate of the Terai may enhance dust suspension and deposition on leaves, explaining the higher dust load recorded during winter. This local context strengthens the practical relevance of the study for species selection in urban greening and green belt development.

Chlorophyll content: Chlorophyll a and b was higher in winter, especially in less polluted areas. Similar to the findings of Giri *et al.*, (2013) and Talebzadeh & Valeo (2022), the study revealed that chlorophyll-a was more

influenced than chlorophyll-b. Chlorophyll-a and- b reduction was highest during the winter. During the winter, the total amount of chlorophyll in the leaves of plants such as *T. grandis*, *M. indica*, and *F. religiosa* was lower in the contaminated areas. On the other hand, during monsoon seasons, *S. asoca* and *D. sissoo* showed reduced drop in total chlorophyll content.

One of the most prevalent organic compounds on Earth is chlorophyll (Reinbothe *et al.*, 2010). Because of environmental contamination issues, the chlorophyll performances of the species under study were under stress (Leghari *et al.*, 2013). To mitigate the stress that causes the chlorophyll concentration to drop in contaminated areas, the photosynthetic pigments go through a number of photochemical processes, including oxidations, reductions, and pheophytinization (Tripathi & Gautam, 2007). The detrimental effects of industrial and vehicle emissions on plant physiology may also be the cause of the decrease in chlorophyll content in plants growing in contaminated locations (Dhyani *et al.*, 2019). The absorption of heavy metals like Cu, Zn, and Pb by the leaves may be the cause of the decrease in chlorophyll concentrations.

The present study provides useful insights into the morphological and biochemical responses of selected tree species to dust pollution across different land-use settings and seasons. However, some limitations should be acknowledged. First, the assessment of dust load was based on total surface particulate deposition and did not distinguish between specific particulate components such as mineral dust, vehicular soot, or industrial particulates. Second, although the selected morphological traits were effective for comparative evaluation, the inclusion of leaf anatomical characteristics such as stomatal density, cuticle thickness, and epidermal structure could have provided deeper mechanistic understanding of plant adaptation to pollution stress. Third, the observed relationships between dust deposition and some leaf traits, such as specific leaf area (SLA), were relatively weak, suggesting that additional environmental and species-specific factors may also influence plant responses. Therefore, future studies should integrate particulate characterization, anatomical analyses, and broader environmental variables to achieve a more comprehensive understanding of plant tolerance and biomonitoring potential under urban dust pollution.

Conclusion

The current study highlighted that during the winter season, air pollutants had a greater effect on the trees growing along roadsides and around industrial areas compared to the residential and garden area. Based on the deposition of dust on the leaf surface, the roadside area was determined to be the most polluted of the 4 sites. While leaves with smooth and small leaf areas (*A. indica*) showed a reduced dust load from the contaminated areas, leaves with rough, textured, big, and abrupt structures (*T. grandis*) indicated a larger deposition of dust. In contrast to garden area, plant leaf morphological characteristics were reduced in industrial, roadside, and residential areas during the winter than during the monsoon seasons. Plants like *A. indica*, *F. religiosa*, *P. guajava*, and *S. asoca* showed the least reduction in various leaf traits which could be used to reduce pollution.

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References

- Agbaire, P.O. and E. Esiefarienrhe. 2009. Air pollution tolerance indices (APTI) of some plants around Otorogun Gas Plant in Delta State, Nigeria. *J. Appl. Sci. Environ. Manag.*, 13(1): 11-14.
- Balasooriya, B.L.W.K., R. Samson, F. Mbikwa, P. Boeckx and M. Van Meirvenne. 2009. Biomonitoring of urban habitat quality by anatomical and chemical leaf characteristics. *Environ. Exp. Bot.*, 65(2-3): 386-394.
- Bierza, K. and W. Bierza. 2024. The effect of industrial and urban dust pollution on the ecophysiology and leaf element concentration of *Tilia cordata* Mill. *Environ. Sci. Pollut. Res.*, 31(48): 58413–58429. <https://doi.org/10.1007/s11356-024-34999-9>.
- Chaphekar, S.B. 1972. Effects of atmospheric pollutants on plants in Bombay. *J. Biol. Sci.*, 15: 1-2.
- Chaturvedi, R.K., S. Prasad, S. Rana, S.M. Obaidullah, V. Pandey and H. Singh. 2013. Effect of dust load on the leaf attributes of the tree species growing along the roadside. *Environ. Monit. Assess.*, 185(1): 383-391.
- Dhyani, S., A. Devkota, S.D. Shrestha and P.K. Jha. 2019. Effect of particulate matters on chlorophyll content in shrubby species growing along roadside of Kathmandu Valley. *Bot. Orient. Journal of Plant Science*, 13: 13-21.
- Dwivedi, A. K. and B. D. Tripathi. 2007. Pollution tolerance and distribution pattern of plants in surrounding area of coal-fired industries. *J. Environ. Biol.*, 28(2): 257-263.
- Giri, S., D.M. Shrivastava, K. Deshmukh and P. Dubey. 2013. Effect of Air pollution on chlorophyll content of leaves. *Curr. Agric. Res. J.*, 1(2): 93-98.
- Gupta, G.P., B. Kumar and U.C. Kulshrestha. 2016. Impact and pollution indices of urban dust on selected plant species for green belt development: Mitigation of the air pollution in NCR Delhi, India. *Arab. J. Geosci.*, 9: 1-15.
- Hamal, J.P. 2023. *Assessment of road side trees in Kathmandu Valley or their air pollution tolerance index and heavy metal biomonitoring ability*. Ph.D. Thesis. Central Department of Botany. Institute of Science and Technology. Tribhuvan University. Nepal.
- Hamal, J.P. and M.K. Chettri. 2017. Air pollution tolerance index of some selected gymnosperm species along the road side of Kathmandu Valley, Nepal. *Ecoprint*, 24: 13-19.
- Kayode, J. and J.E. Otoide. 2007. Environmental pollution and leaf cuticular variations in *Newbouldia laevis* Seem. ex Bureau. *Asian J. Plant Sci.*, 6(6): 1024-1026.
- Krir, N., M.M. Guedri, M. Romdhane and M.A. Alshaqha. 2025. Anatomical adaptations of halophyte leaves (*Nitraria retusa* [Forsskal] Asch. and *Atriplex halimus* L.) in response to cement dust pollution in arid environments, *Life*, 15(1): 61. doi:10.3390/life15010061.
- Kwak, M.J., J. Lee, S. Park, Y.J. Lim, H. Kim, S.G. Jeong, J. Son, S.M. Je, H. Chang and C.Y. Oh. 2023. Understanding particulate matter retention and wash-off during rainfall in relation to leaf traits of urban forest tree species. *Horticulturae*, 9(2): 165. <https://doi.org/10.3390/horticulturae9020165>
- Leghari, S.K., M.A. Zaidi, F.M. Sarangzai, G.R. Shawani and W. Ali. 2013. Effect of road side dust pollution on the growth and total chlorophyll contents in *Vitis vinefera* L. (grapes). *Afr. J. Biotechnol.*, 13: 1237-1242.
- Liu, G., L. Wang, L. Jiang, X. Pan, Z. Huang, M. Dong and J.H. Cornelissen. 2018. Specific leaf area predicts dry land litter decomposition via two mechanisms. *J. Ecol.*, 106(1): 218-229.
- Mage, D., G. Ozolins, P. Peterson, A. Webster, R. Orthofer, V. Wandeweerd and M. Gwynne. 1996. Urban air pollution in megacities of the world. *Atmos. Environ.*, 30: 681-686.
- Mo, F.E. 2021. Vulnerability and risk assessment and identifying adaptation options: Summary for policy makers. Ministry of Forests and Environment, Government of Nepal. Kathmandu, Nepal.
- Nkansah, F.K. 2025. Air pollution and plant responses: A study on morphological and anatomical changes in roadside trees along traffic-dense roads', *BMC Environ. Sci.*, 2 :16. doi:10.1186/s44329-025-00031-9.
- Poorter, H., U. Niinemets, L. Poorter, I.J. Wright and R. Villar. 2009. Transley review: causes and consequences of variation in leaf mass area (LMA): A meta-analysis. *New Phytol.*, 182: 565-588.
- Prajapati, S.K. and B.D. Tripathi. 2008. Anticipated Performance Index of some tree species considered for green belt development in and around an urban area: A case study of Varanasi city, India. *J. Environ. Manag.*, 88(4): 1343-1349.
- Prusty, B.A.K., P.C. Mishra and P.A. Azeez. 2005. Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. *Ecotoxicol. Environ. Saf.*, 60(2): 228-235.
- Rahul, J. and M.K. Jain. 2014. An investigation into the impact of particulate matter on vegetation along the national highway: A review. *Res. J. Environ. Sci.*, 8(7): 356-372.
- Rai, P.K. 2013. Environmental magnetic studies of particulates with special reference to biomagnetic monitoring using roadside plant leaves. *Atmos. Environ.*, 72: 113-129.
- Rai, P.K. and L.L. Panda. 2014a. Dust capturing potential and air pollution tolerance index (APTI) of some roadside tree vegetation in Aizawl, Mizoram, India: an Indo-Burma hot spot region. *Air Qual. Atmos. Health*, 7: 93-101.
- Rai, P.K. and L.L. Panda. 2014b. Leaf dust deposition and its impact on biochemical aspect of some roadside plants of Aizawl, Mizoram, North East India. *Int. Res. J. Environ. Sci.*, 3(11): 14-19.
- Reinbothe, C., M. E.I. Bakkouri, F. Buhr, N. Muraki, J. Nomata, G. Kurisu, Y. Fujita and S. Reinbothe. 2010. Chlorophyll biosynthesis: Spotlight on protochlorophyllide reduction. *Trends Plant Sci.*, 15: 614- 624.
- Seinfeld, J.H. and S.N. Pandias. 2006. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. New York, Wiley, 1225.
- Shannigrahi, A.S., T. Fukushima and R.C. Sharma. 2004. Anticipated air pollution tolerance of some plant species considered for green belt development in and around an industrial/urban area in India: an overview. *Int. J. Environ. Stud.*, 61(2): 125-137.

- Talebzadeh, F. and C. Valeo. 2022. Evaluating the effects of environmental stress on leaf chlorophyll content as an index for tree health. *IOP Conf. Ser.: Earth Environ. Sci.*, 1006. 012007. doi10.1088/1755-1315/1006/1/012007
- Tiwari, S., M. Agrawal and F.M. Marshall. 2006. Evaluation of ambient air pollution impact on carrot plants at a sub urban area using open top chambers. *Environ. Monit. Assess.*, 119(1-3): 15-30.
- Tripathi, A.K. and M. Gautam. 2007. Biochemical parameters of plants as indicators of air pollution. *J. Environ. Biol.*, 28: 127-132.
- Xu, F., W. Guo, W. Xu, Y. Wei and R. Wang. 2009. Leaf morphology correlates with water and light availability: What consequences for simple and compound leaves? *Prog. Nat. Sci.*, 19(12): 1789-1798.
- Xu, L., Y. Liu, S. Feng, C. Liu, X. Zhong and Y. Ren. 2024. The relationship between atmospheric particulate matter, leaf surface microstructure, and the phyllosphere microbial diversity of *Ulmus* L. *BMC Plant Biol.*, 24: 566. <https://doi.org/10.1186/s12870-024-05232-z>
- Younis, U., T.Z. Bokhari, M.H.R Shah, S. Mahmood and S.A. Malik. 2013. Variations in leaf dust accumulation, foliage and pigment attributes in fruiting plant species exposed to particulate pollution from Multan. *Int. J. Agri. Sci. Res.*, 201; 3(3): 1-12.