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Effects of dust pollution on leaf morphology and chlorophyll content: A comparative study across two seasons in Biratnagar, Nepal

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The effect of dust on leaf morphology and chlorophyll content in industrial, roadside, residential, and campus areas during the winter (January) and monsoon (June) season of 2024 was investigated. The highest dust load on the leaves of *Tectona grandis* was recorded in industrial areas during the winter season. The greatest leaf area reduction was observed in *Azadirachta indica* (13.25%) in winter and *Citrus maxima* (14.32%) in the monsoon season. The specific leaf area (SLA) of *Ficus religiosa* decreased by 20.48% in winter, and that of *Nephelium litchi* decreased by 28.46% in monsoon, particularly in industrial areas, likely due to their dust-trapping capacity and stress tolerance. Total chlorophyll was mostly reduced in polluted areas (industrial, roadside areas) in the winter season. During the studied seasons, chlorophyll-a ranged from 0.04 to 2.56 mg/g, chlorophyll-b ranged from 0.66 to 2.56 mg/g, and total chlorophyll ranged from 0.13 to 3.08 mg/g. Both chlorophyll-a and chlorophyll-b showed greater reduction during the monsoon season compared to winter. Less reduction in chlorophyll-a was observed in *Ficus benghalensis, Ficus religiosa, Mangifera indica, Neolamarckia cadamba*, and *Syzygium cumini*. But the species like *Artocarpus heterophyllus, Citrus maxima, Syzygium cumini*, and *Mangifera indica* exhibited less reduction in chlorophyll-b. The chlorophyll a:b ratio was generally higher during the winter season, particularly in the campus area (a less polluted site), whereas the ratio was reduced in more polluted areas. Physiological characteristics were more affected by dust accumulation than morphological characteristics. Plant species like *Artocarpus heterophyllus, Ficus benghalensis, Ficus religiosa, Mangifera indica, Neolamarckia cadamba, Nephelium litchi* and *Psidium guajava* showed comparatively less impact from dust, indicating their potential use in minimizing air pollution and enhancing urban green spaces.

Key words: Chlorophyll ratio; Dust; Leaf area; Plant species; Specific leaf area (SLA).

Air pollution, a pervasive issue in urban and industrial areas, consists of various pollutants such as particulate matters (PMs), gases, and heavy metals that adversely affect living organisms, including plants (Sharma et al., 2007; Jitin & Jain, 2014). Leaves which are the primary site for photosynthesis, are the most exposed part of a plant and are often the first to exhibit signs of damage when exposed to pollutants (Prajapati & Tripathi, 2008). Air pollution impacts plants through the accumulation of dust and particulate matter on leaf surfaces. Due to their large surface area, airborne pollutants get trapped and block stomata function, reduce photosynthetic efficiency, and alter metabolic processes (Javanmard et al., 2019). Studies have shown that increased dust accumulation lead to higher relative water content (RWC) and ascorbic acid levels, while simultaneously reducing chlorophyll content and leaf pH (Pandey et al., 2015; Bharti et al., 2017; Sapkota & Shrestha, 2024). One of the most

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common impacts of plant exposure to pollutants is a reduction in chlorophyll concentrations (Nithamathi & Indira, 2005), along with leaf yellowing, which consequently decreases the photosynthetic rate (Joshi & Swami, 2007). The ratio of chlorophyll-a to chlorophyll-b helps in the identification of changes in light perceptions in plants (Kushwaha et al., 2024).

Specific leaf area (SLA) is the ratio of leaf area to its dry mass. It is an important morphological and functional trait that reflects a plant's adaptability to its environmental conditions (Liu et al., 2018). SLA is closely related to photosynthesis, respiration, and biomass production. Changes in SLA due to environmental stressors indicate shifts in resource allocation and overall plant health. Additionally, leaf shape parameters, including leaf area, length, and width, serve as key indicators for evaluating the impact of air pollution on plant morphology and functioning (Wang et al., 2021).

Understanding the extent of dust accumulation and its effects on leaf morphology is crucial for assessing the implications of air pollution on plant growth and development. This study aimed to investigate the impact of dust load on leaf macro morphology and chlorophyll content with the objective of identifying tolerant and sensitive plant species suitable for plantation in urban areas of the Terai region, Nepal.

Materials and methods

Study area

The study was conducted in Biratnagar, located in Morang district, Koshi Province (26°28'60" N latitude and 87°16'60" E longitude). Biratnagar, is an industrial city in the eastern Terai region of Nepal. Located in the tropical zone, Biratnagar experienced temperature variations ranging from 9.76 °C in January to 33.58 °C in April. The highest recorded precipitation was 353 mm in September, while no rainfall was recorded in November during the period from 2019 to 2024 (Biratnagar station).

According to the Department of Industry (DOI, 2022), a total of 302 industries were registered in Morang District in the fiscal year 2078/2079. The most polluted industrial areas were Budhiganga and Gidhaniya, surrounded by various industries like Swastika Jute Mills, Surya Chemical Pvt. Ltd, located within an aerial distance of 250 to 500 m (Figure 1). Roadside areas were Titariya, Ghinaghat and Malaya Road, which are road networks connected to Biratnagar. Residential areas were from the Rani temple area nearer to the Biratngar custom office. The Mahendra Morang Multiple Campus, Biratnagar was considered as relatively less polluted area.

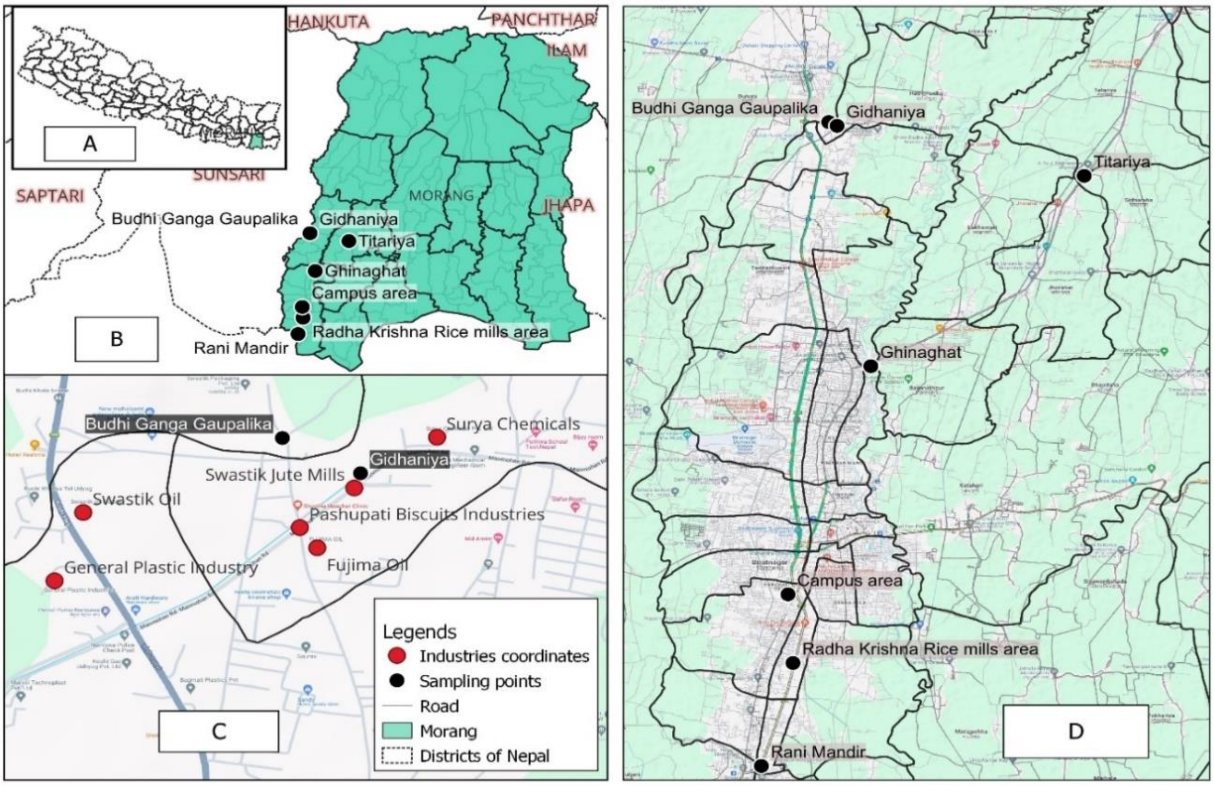


Figure 1: Map of the study area (A=Nepal, B= Morang, C= Industrial and D= Roadside, residential and campus, Source: QGIS version 3.28)

Study areas were categorized based on the average concentrations of particulate matter (PM), respirable suspended particles (RSP) and total suspended particles (TSP) (measured in µg/m³) recorded at different sites using Aeroqual Air Sampler, USA (Table 1).

Sampling design

Purposive sampling was conducted in January for winter and July for monsoon season of 2024 in Biratnagar, Morang district because ambient air quality during winter months mostly remains polluted due to dry weather conditions. Altogether 12 plant species (Table 2) were selected based on their availability and natural occurrence in the study area. Plant species were identified through direct field observations prior to sample collection. Secondary sources, including references books (Flora of Nepal) and the Tribhuvan University Central Herbarium (TUCH), were also consulted for accurate identification. Broad and mature leaves (25-30 samples per species) were collected using a pruner from approximately 2 meters above ground level to ensure the optimal dust accumulation and to standardize the average height of trees.

For comparative study between polluted and less polluted campus areas, 12 plant species were found to be common between the industrial and less polluted campus areas, 10 species were common between the roadside and less polluted campus areas and only 4 plant species were recorded as common between residential and less polluted campus areas.

Laboratory analysis

Morphological characteristics

Triplicate leaf samples were collected from each plant species. Leaf length, leaf width and leaf area of the respective plant species were measured using ImageJ Software version 1.54 (Hamal, 2023).

Dust load

Dust load on the leaves was measured following Prusty et al. (2005) protocol. First, three mature leaf samples of each species from each site were collected and weighed with dust (W1). The leaves were then thoroughly cleaned and weighed again (W2). The leaf area was calculated using ImageJ software version 1.54g (Hamal, 2023). The dust load accumulated on

Table 1: Classification of study areas based on average concentrations of PM, RSP and TSP on the different sites (µg/m³) (mean± SD, n=60)

Study area	Category	Locations	PM_1	$PM_{2.5}$	PM_{10}	RSP	TSP
Industrial	Polluted	Budhiganga and Gidhaniya	32.95±3.86^d	46.20±4.63^d	75.70±12.27^d	56.05±6.23^c	86.68±17.22^d
Roadside	Polluted	Titariya, Ghinaghat and Malaya	26.71±0.99^c	34.17±1.14^c	64.37±1.92^c	43.09±1.55^b	80.62±2.38^c
Residential	Moderately Polluted	Rani Temple	21.67±1.85^b	25.28±1.42^b	36.77±2.30^b	28.39±1.83 ^{a}	34.28±2.60^a
Campus area	Less Polluted	Mahendra Morang campus	17.10±0.99^a	22.78±1.18 ^{a}	31.87±1.89 ^{a}	28.87±1.76 ^{a}	42.84±2.27^b

Note: Significance mean values among different plant species are indicated by different letters. (Duncan multiple test, $p \leq 0.05$)

Table 2: List of plant species collected from different sites

SN	Name of plant species	Common name	Family
1.	*Artocarpus heterophyllus* Lam.	Jackfruit	Moraceae
2.	*Azadirachta indica* A.Juss.	Neem	Meliaceae
3.	*Citrus maxima* (Burm). Merr.	Bhogate	Rutaceae
4.	*Ficus benghalensis* L.	Bar	Moraceae
5.	*Ficus religiosa* L.	Peepal	Moraceae
6.	*Mangifera indica* L.	Mango	Anacardiaceae
7.	*Neolamarckia cadamba* (Roxb.) Bosser	Kadam	Rubiaceae
8.	*Nephelium litchi* Steud	Litchi	Sapindaceae
9.	*Psidium guajava* L.	Guava	Myrtaceae
10.	*Syzygium cumini* (L.) Skeels	Jamun	Myrtaceae
11.	*Saraca ascosa* (Roxb.) Wild.	Ashoka	Fabaceae
12.	*Tectona grandis* L. f.	Teak	Lamiaceae

the leaves was calculated using the formula given by Prusty et al. (2005):

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

Specific leaf area (SLA)

For the measurement of SLA, broad and mature leaf samples were selected, and their photographs were taken alongside a scale using Redmi mobile phone. Triplicate leaf samples were taken. The leaves were then oven-dried at 70°C, and their dry weight was recorded using a digital balance (S303, 0.001g). The fresh leaf area was calculated using the ImageJ software version 1.54g. SLA for each leaf was determined according to Cornelissen et al. (1996).

$$SLA\ (cm^2/g) = \frac{Area\ of\ leaves}{Dry\ weight\ of\ leaves}$$

Chlorophyll content

Disc of fresh leaves (weighing 0.09 g) were punched and kept in an Eppendorf tube containing 1 ml of $DMSO_4$ (Dimethyl Sulfoxide) solvent immediately after collection. Chlorophyll content was determined according to Barnes et al. (1992) with slight modifications. Specifically, triplicate leaf disc samples from each species were immersed in $DMSO_4$ and kept in an ice box for 24-48 hours to extract the chlorophyll and prevent chlorophyll degradation prior to laboratory analysis. After that, the solution along with leaf samples was kept in a water bath at 60-70°C for 2-3 hours till the complete extraction of chlorophyll. The resulting extract was pipetted in a micro-plate using a micropipette, and the absorbance was measured at 665 nm and 648 nm using a microplate spectrophotometer (BioTek Epoch 2). Chlorophyll contents in the leaves were then calculated by using the formula given by Barnes et al. (1992).

$$\text{Chlorophyll a (mg/g)} = (14.85 \times A_{665} - 5.14 \times A_{648}) \times \frac{V}{(W \times 1000)}$$

$$\text{Chlorophyll b (mg/g)} = (25.48 \times A_{648} - 7.36 \times A_{665}) \times \frac{V}{(W \times 1000)}$$

$$\text{Total Chlorphyll(mg/g)} = (7.49 \times A_{665} + 20.34 \times A_{648}) \times \frac{V}{(W \times 1000)}$$

Where, V= volume of $DMSO_4$ solvent, W= weight of fresh leaves used

Statistical analysis

All data calculation was done in MS Excel 2013, and statistical analyses were performed using IBM SPSS Statistics 20 version. One-way ANOVA was used to assess significant differences in the mean and percentage decrease of specific leaf area (SLA), leaf area, leaf length, leaf width, chlorophyll concentrations, and chlorophyll-a to chlorophyll-b ratio (a:b) among plant species from different study areas across the two seasons. Pearson's Correlation test was performed to determine the relationship between dust load per leaf area, leaf morphology, and chlorophyll concentration reduction across both seasons. A scatter plot was drawn to visualize the relationships between selected pairs of variables.

Results

Dust load

Dust load was comparatively higher in the winter season than in the monsoon (Figure 2), with industrial areas recording the highest average dust load accumulation, followed by residential, roadside, and campus areas in both seasons. Among the sample species, *Tectona grandis* in winter and *Saraca asoca* in the monsoon recorded the highest dust load in industrial areas with 12.29 mg/cm^2 and 0.28 mg/cm^2 respectively (Table 3). At roadside locations, *Azadirachta indica* exhibited the highest dust accumulation in both seasons, with 2.61 mg/cm^2 in winter and 0.31 mg/cm^2 in the monsoon. Similarly, *Saraca asoca* (winter) and *Mangifera indica* (monsoon) recorded significantly higher dust load ($p < 0.05$) in residential areas, with 2.20 mg/cm^2 and 0.21 mg/cm^2. *Syzygium cumini* in winter and *Nephelium litchi* in the monsoon recorded the highest dust load at 0.67 and 0.54 mg/cm^2, respectively. The dust levels in residential areas were higher than those near the roads due to ongoing construction activities and increased vehicle movement.

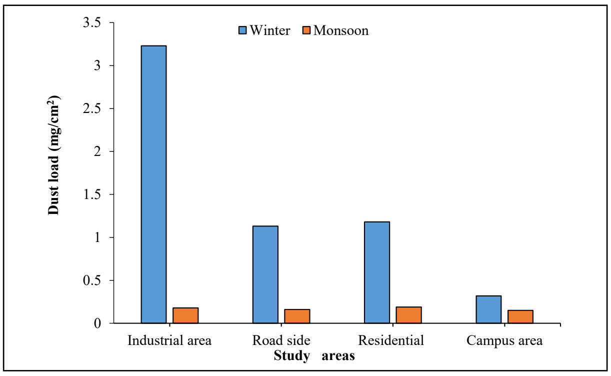


Figure 2: Dust accumulation on leaves at different study areas across two seasons

Leaf area

In winter, the leaf area ranged from 8.63 cm^2 in *Azadirachta indica* at the industrial area to 194.98 cm^2 in *Tectona grandis* at the roadside area. During the monsoon, the range was broader, with the lowest leaf area of 10.28 cm^2 in *Azadirachta indica* in the industrial area and the highest of 904.58 cm^2 in *Tectona grandis* in the campus area (Table 4).

The percentage of leaf area reduction was lower in industrial areas compared to campus areas during both seasons. In the winter season, the greatest leaf area reduction was observed in *Azadirachta indica* (13.25%) at industrial, and in *Neolamarckia cadamba* at both roadside (12.65%) and residential (8.35%) areas. During the monsoon season, the maximum reduction in leaf area was recorded in *Citrus maxima* at industrial (14.32%) and *Psidium guajava* at both roadside (21.88%) and residential (13.91%) areas. *Ficus religiosa* showed the least leaf area reduction (0.42%) in industrial areas during the winter season (Figure 3).

Table 3: Dust load (mg/cm^2) on leaves of different plant species comparing two seasons

Plant species	Industrial		Roadside		Residential		Campus	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	1.05±0.10^{a}	0.15±0.27^{abcd}	0.48±0.09^{ab}	0.09±0.01^{ab}	-	-	0.26±0.10^{abc}	0.15±0.04^{a}
Azadirachta indica	1.89±0.64^{a}	0.20±0.02^{cd}	2.61±0.43^{g}	0.32±0.10^{c}	-	-	0.23±0.09^{ab}	0.14±0.01^{a}
Citrus maxima	9.60±0.89^{bc}	0.05±0.01^{a}	1.84±0.32^{efg}	0.10±0.04^{ab}	-	-	0.24±0.14^{ab}	0.12±0.08^{a}
Ficus benghalensis	1.73±0.22^{a}	0.12±0.01^{abc}	0.88±0.19^{abcde}	0.07±0.03^{a}	-	-	0.63±0.21^{cd}	0.10±0.03^{a}
Ficus religiosa	1.87±0.13^{a}	0.11±0.00^{abc}	1.71±0.32^{defg}	0.11±0.01^{ab}	-	-	0.27±0.06^{abc}	0.13±0.03^{a}
Mangifera indica	6.99±0.94^{b}	0.19±0.01^{bcd}	1.56±0.29^{cdef}	0.11±0.03^{ab}	1.45±0.29^{bc}	0.26±0.08^{b}	0.40±0.10^{abcd}	0.54±0.03^{b}
Neolamarckia cadamba	1.78±0.16^{a}	0.11±0.01^{abc}	0.70±0.19^{abcd}	0.10±0.01^{ab}	0.87±0.13^{ab}	0.04±0.01^{a}	0.16±0.05^{ab}	0.04±0.01^{a}
Nephelium litchi	3.14±0.24^{a}	0.14±0.07^{abc}	0.66±0.12^{abcd}	0.04±0.02^{a}	-	-	0.13±0.03^{a}	0.08±0.03^{a}
Psidium guajava	0.87±0.02^{a}	0.15±0.10^{abcd}	1.51±0.29^{bcdef}	0.23±0.04^{bc}	0.84±0.15^{ab}	0.23±0.01^{ab}	0.15±0.03^{ab}	0.40±0.16^{b}
Syzygium cumini	2.89±0.23^{a}	0.06±0.01^{ab}	2.23±0.39^{fg}	0.07±0.03^{a}	-	-	0.67±0.08^{d}	0.06±0.02^{a}
Saraca asoca	2.64±0.029^{a}	0.28±0.01^{d}	-	-	2.20±0.57^{c}	0.21±0.07^{ab}	0.33±0.04^{abcd}	0.01±0.01^{a}
Tectona grandis	12.29±2.51^{c}	0.21±0.05^{cd}	1.57±0.41^{cdef}	0.15±0.03^{ab}	-	-	0.12±0.03^{a}	0.05±0.02^{a}
F-value	14.12	2.48	5.16	3.40	4.25	2.98	2.53	7.14

Note: Data are 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 test, $p \leq 0.05$, (n=12 to 36)

Table 4: Leaf area (cm^2) of different plant species at study areas during two seasons

Plant species	Industrial		Roadside		Residential		Campus	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	67.91±9.25^{cd}	70.67±6.21^{bc}	68.55±12.73^{cd}	76.97±3.49^{ab}	-	-	72.53±10.12^{de}	78.23±3.58^{bc}
Azadirachta indica	8.63±0.23^{a}	10.28±1.81^{a}	8.71±0.22^{a}	10.49±1.77^{a}	-	-	9.95±0.18^{a}	11.26±1.49^{a}
Citrus maxima	55.66±1.27^{bcd}	48.89±7.10^{bc}	58.44±5.34^{bc}	51.43±2.64^{a}	-	-	58.65±5.37^{bcd}	57.02±2.65^{b}
Ficus benghalensis	89.64±8.60^{e}	145.05±19.19^{e}	86.10±5.66^{d}	141.26±19.84^{bc}	-	-	90.61±8.06^{e}	161.46±17.48^{d}
Ficus religiosa	74.30±3.64^{de}	51.40±2.59^{bc}	66.39±6.41^{cd}	51.05±2.60^{a}	-	-	75.38±7.24^{de}	54.81±3.18^{b}
Magnifera indica	60.36±5.04^{cd}	81.71±10.73^{d}	64.79±4.74^{c}	86.08±8.98^{ab}	65.86±13.20^{a}	83.31±17.32^{a}	67.02±4.69^{cd}	92.35±10.33^{c}
Neolamarckia cadamba	114.48±2.76^{f}	195.06±9.02^{f}	106.82±4.35^{e}	189.39±6.26^{c}	112.00±3.84^{b}	195.38±9.80^{b}	122.32±4.31^{f}	199.41±8.74^{e}
Nephelium litchi	39.92±4.98^{b}	45.97±4.57^{b}	41.13±2.75^{b}	48.54±4.71^{a}	-	-	41.74±3.16^{b}	54.52±7.32^{b}
Psidium guajava	73.91±7.43^{de}	74.71±12.50^{cd}	71.61±3.96^{cd}	67.00±12.01^{ab}	70.74±4.84^{a}	72.80±7.04^{a}	74.61±7.15^{de}	85.16±9.59$_{c}$
Syzygium cumini	50.78±4.69^{bc}	71.75±3.42^{bc}	56.72±6.90^{bc}	70.95±5.59^{ab}	-	-	58.17±4.41^{bcd}	77.69±1.21^{bc}
Saraca asoca	51.34±4.30^{bc}	55.01±5.20^{bc}	-	-	48.41±2.37^{a}	52.48±1.04^{a}	51.95±4.13^{bc}	59.42±3.67^{b}
Tectona grandis	174.13±12.35^{g}	895.94±1.65^{g}	194.98±7.85^{f}	809.43±79.56^{d}	-	-	196.57±7.35^{g}	904.58±0.29^{f}
F-value	42.850	790.69	55.036	79.03	13.285	36.88	58.623	1029.69

Note: Data are 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 test, $p \leq 0.05$, (n=12 to 36)

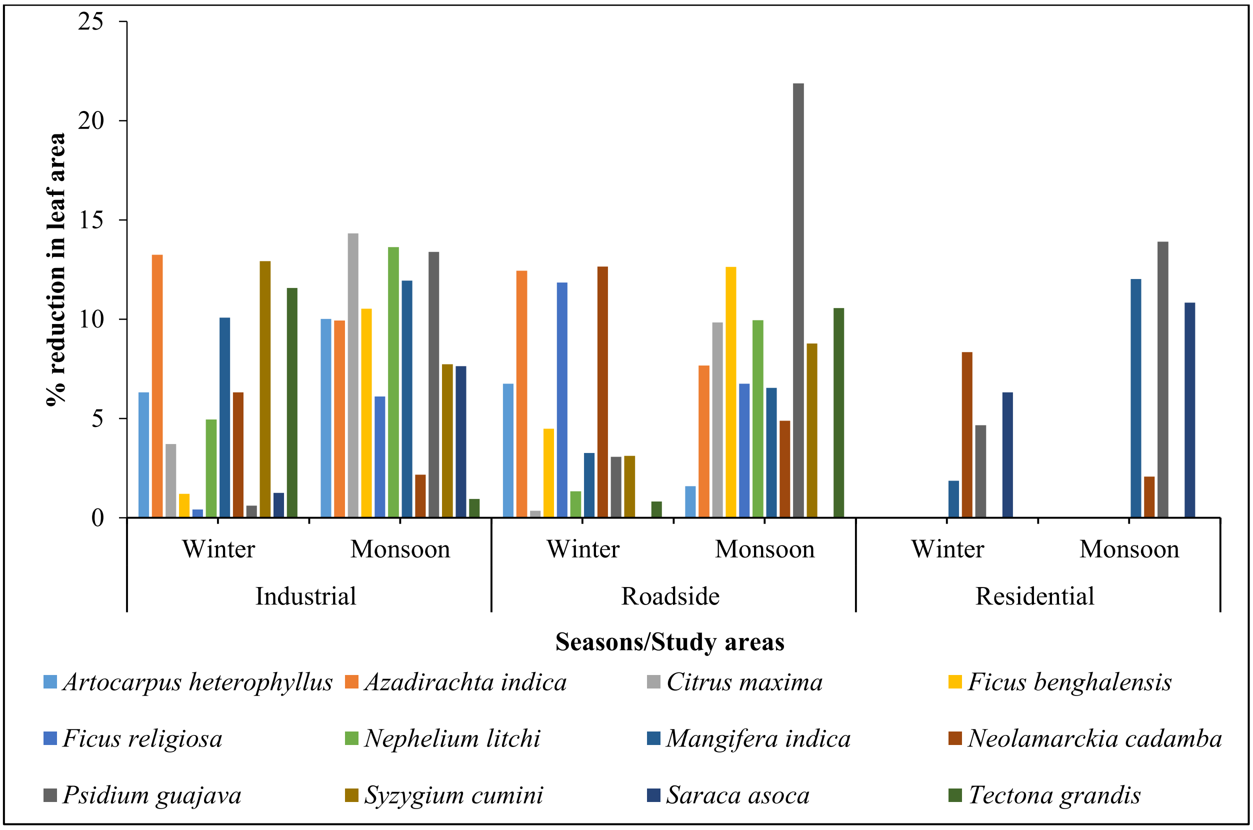


Figure 3: Percentage (%) reduction in leaf area of different plant species in two seasons

Specific leaf area (SLA)

During the winter season, the SLA varied from 55.10 cm^2/g in *Syzygium cumini* at the industrial area to 187.93 cm^2/g in *Azadirachta indica* at the roadside area. In the monsoon season, the SLA ranged from 49.68 cm^2/g in *Ficus benghalensis* at the roadside to 179.08 cm^2/g in *Citrus maxima* at the campus area (Table 5).

SLA was reduced in industrial areas and roadside compared to the campus area during both studied seasons (Figure 4). In industrial areas, *Ficus religiosa* showed the highest SLA reduction (20.48%) during

Table 5: Specific leaf area (cm^2/g) areas of different plant species at study areas during two seasons

Plant species	Industrial		Roadside		Residential		Campus	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	97.03±14.74^{b}	140.50±10.58^{de}	84.86±6.86^{abc}	141.99±11.67^{de}	-	-	111.71±34.70^{bc}	143.13±11.06^{cde}
Azadirachta indica	150.28±1.69^{c}	125.09±13.12^{cde}	187.93±2.52^{f}	117.73±15.52^{bcd}	-	-	172.58±2.36^{d}	129.88±22.24^{bcd}
Citrus maxima	102.99±2.50^{b}	166.94±7.88^{e}	123.49±15.71^{de}	174.57±2.42^{e}	-	-	110.57±6.51^{b}	179.08±0.81^{e}
Ficus benghalensis	82.61±3.74^{b}	61.38±5.49^{a}	55.54±7.08^{ab}	49.68±1.02^{a}	-	-	86.13±1.45^{ab}	68.50±7.97^{a}
Ficus religiosa	85.69±0.23^{b}	86.18±7.08^{abc}	76.09±28.76^{abc}	92.32±7.15^{abc}	-	-	114.70±18.47^{bc}	101.49±4.15^{abc}
Magnifera indica	82.46±2.54^{b}	87.83±23.67^{abc}	55.06±1.99^{ab}	56.18±3.78^{a}	59.82±6.99^{a}	85.46±22.74^{a}	86.70±7.54^{ab}	91.41±24.28^{ab}
Neolamarckia cadamba	146.60±10.77^{c}	146.08±22.67^{de}	130.95±1.43^{e}	148.98±14.19^{de}	96.66±4.13^{b}	144.81±21.89^{a}	153.61±5.92^{cd}	154.72±18.65^{de}
Nephelium litchi	82.44±6.60^{b}	116.20±6.92^{bcd}	77.78±7.81^{abc}	135.19±32.33^{cde}	-	-	83.76±1.54^{ab}	162.63±4.61^{de}
Psidium guajava	80.62±8.01^{b}	73.94±26.90^{ab}	89.22±1.00^{bc}	71.92±25.55^{ab}	88.94±4.72^{b}	79.71±30.03^{a}	93.50±2.95^{ab}	81.49±29.91^{a}
Syzygium cumini	55.10±0.95^{a}	80.06±6.50^{abc}	49.68±3.10^{a}	87.24±1.84^{ab}	-	-	60.35±1.64^{a}	89.50±1.45^{ab}
Saraca asoca	142.33±12.67^{c}	138.71±9.44^{de}	-	-	99.04±4.82^{b}	140.81±4.62^{a}	152.94±11.55^{cd}	142.05±4.28^{cde}
Tectona grandis	105.00±3.37^{b}	141.48±17.27^{de}	94.84±7.27^{cd}	150.87±6.26^{de}	-	-	119.82±14.25^{bc}	157.57±5.18^{de}
F-value	16.998	5.25	14.044	8.21	11.684	2.53	6.563	6.27

Note: Data are 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 test, $p \leq 0.05$, (n=12 to 36)

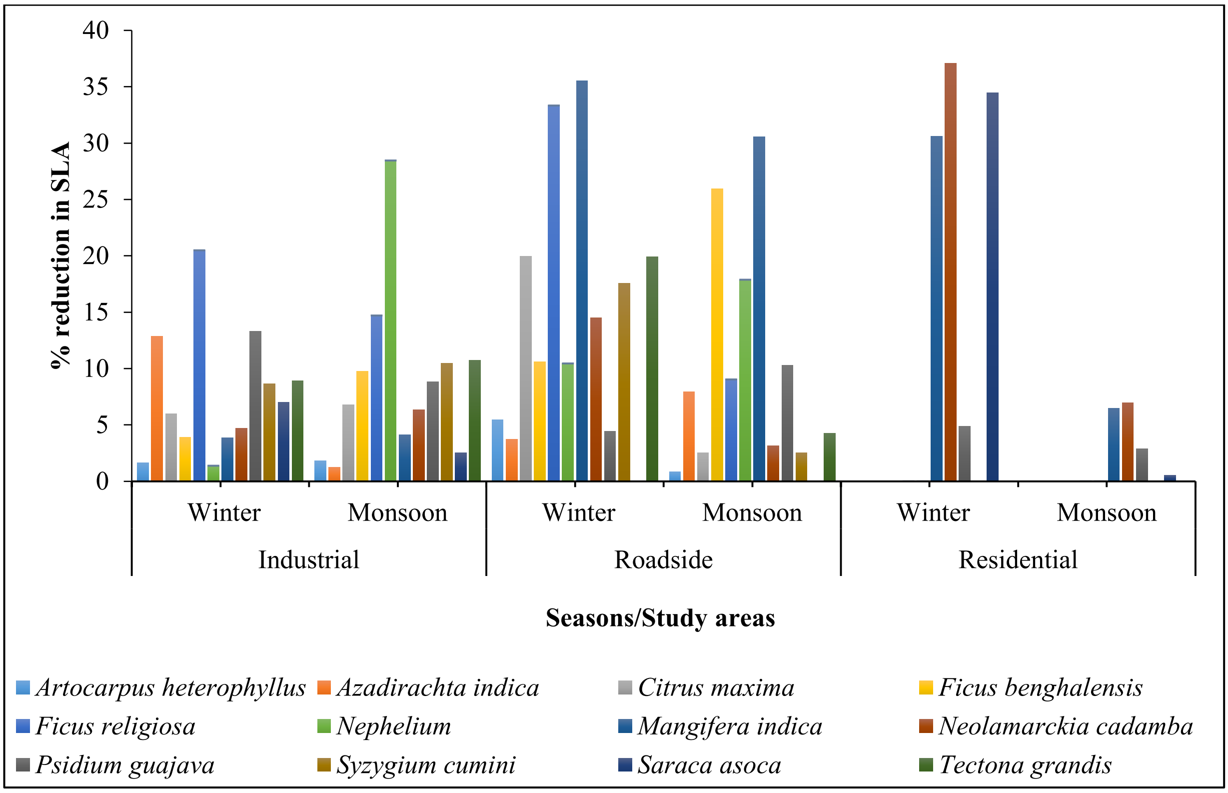
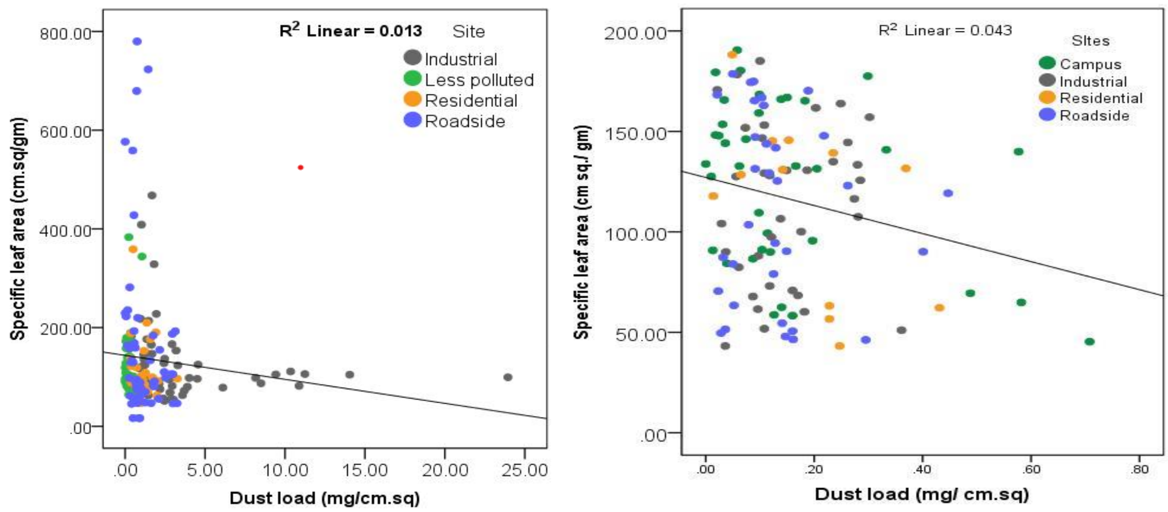


Figure 4: Percentage (%) reduction in SLA of different plant species in two seasons



(a) (b)

Figure 5: Analysis between SLA and dust load in winter (a) and monsoon (b) seasons

winter, while *Nephelium litchi* showed the highest reduction (28.46%) during the monsoon. Similarly, *Mangifera indica* at roadside (35.55% and 30.57%) and *Neolamarckia cadamba* at residential areas (37.08% and 6.98%) recorded maximum SLA reduction during both seasons.

An inverse relationship was observed between dust load and specific leaf area (SLA) (Figure 5), indicating that an increase in dust load corresponds to a decrease in the SLA of plant species.

Leaf length

During winter, the leaf length was shortest in *Azadirachta indica* (6.11 ± 0.32 cm) at the industrial area), while the longest was recorded in *Tectona grandis* (41.44 ± 0.79 cm) at the roadside area (Table

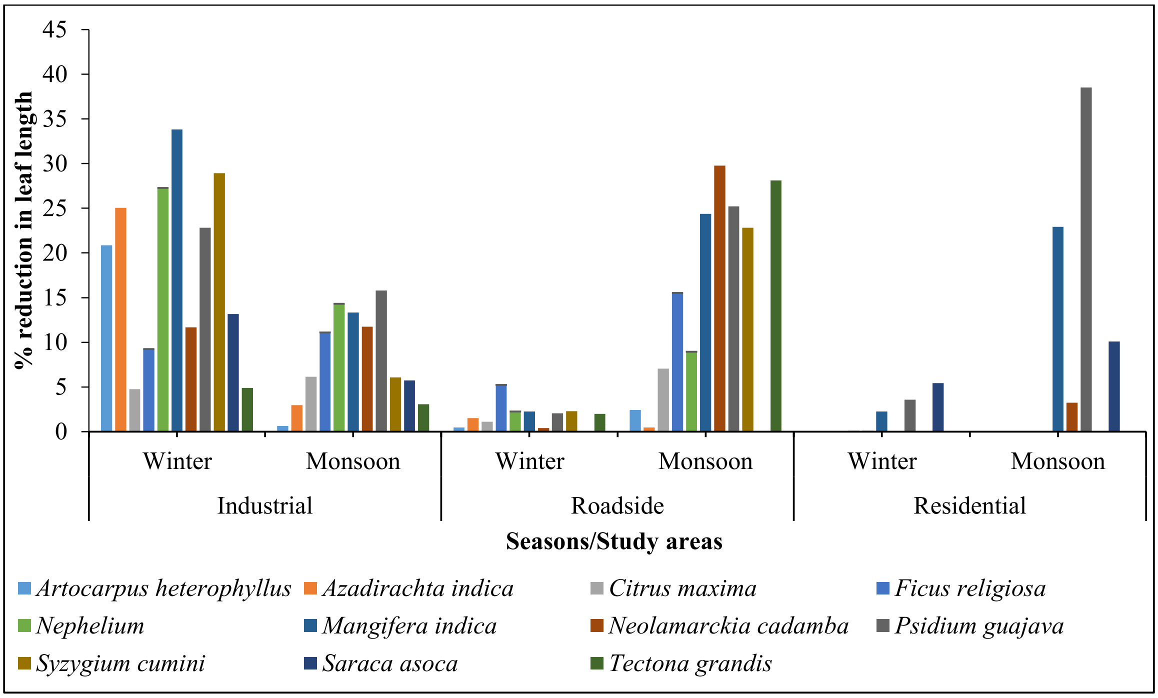


Figure 6: Percentage (%) reduction in leaf length of different plant species in two seasons

6). During monsoon, *Azadirachta indica* had the shortest leaves (8.27 ± 0.19 cm) in the industrial area, while *Tectona grandis* had the longest (48.31 ± 1.17 cm) in the campus area. Overall, *Tectona grandis* consistently exhibited the largest leaf lengths across all studied areas, whereas *Azadirachta indica* had the smallest.

The percentage of leaf length reduced mostly in industrial and roadside areas during winter compared to other areas and the monsoon season (Figure 6). In industrial areas, *Mangifera indica* exhibited maximum leaf length reduction (33.81%) during winter, but in monsoon *Ficus benghalensis* showed the greatest reduction (28.56%). At roadside locations, *Ficus religiosa* showed the maximum reduction in winter (5.21%), while *Neolamarckia cadamba* exhibited the highest reduction (29.79%) during monsoon. In residential areas, *Saraca asoca* showed maximum reduction during winter (5.43%), but in winter *Psidium guajava* showed the maximum reduction (38.51%).

Leaf width

During the winter season, the smallest leaf width was observed in *Azadirachta indica* (3.39 ± 0.02 cm), while the largest was in *Tectona grandis* (22.84 ± 0.93

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

Plant species	Industrial		Roadside		Residential		Campus	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	12.08 ± 0.36^{b}	15.66 ± 0.92^{bc}	15.03 ± 0.46^{bc}	15.24 ± 0.47^{bc}	-	-	15.26 ± 0.36^{b}	15.75 ± 0.81^{bc}
Azadirachta indica	6.11 ± 0.32^{a}	8.27 ± 0.19^{a}	8.26 ± 0.78^{a}	8.47 ± 0.28^{a}	-	-	8.36 ± 0.79^{a}	8.52 ± 0.15^{a}
Citrus maxima	21.55 ± 0.93^{d}	11.88 ± 0.25^{ab}	22.08 ± 0.95^{f}	11.80 ± 1.03^{ab}	-	-	22.62 ± 0.78^{e}	12.66 ± 0.35^{b}
Ficus benghalensis	12.36 ± 0.28^{b}	16.61 ± 2.90^{bcd}	16.35 ± 0.79^{bc}	16.70 ± 0.69^{b}	-	-	17.25 ± 0.70^{bc}	23.21 ± 0.20^{d}
Ficus religiosa	13.57 ± 0.17^{bc}	12.23 ± 1.53^{ab}	14.61 ± 0.18^{b}	$11.53\pm0.58_{ab}$	-	-	14.98 ± 0.46^{b}	13.68 ± 0.42^{b}
Magnifera indica	14.14 ± 0.51^{bc}	19.49 ± 2.31^{cd}	21.29 ± 0.21^{ef}	17.00 ± 2.00^{c}	20.90 ± 0.30^{a}	17.30 ± 3.26^{ab}	21.38 ± 0.21^{de}	22.41 ± 2.14^{d}
Neolamarckia cadamba	17.20 ± 0.86^{c}	21.00 ± 1.54^{de}	19.86 ± 1.42^{def}	16.69 ± 1.41^{c}	19.58 ± 0.67^{a}	23.01 ± 1.04^{b}	19.60 ± 0.69^{cde}	23.75 ± 0.49^{d}
Nephelium licthi	13.64 ± 1.48^{bc}	14.18 ± 1.05^{b}	18.31 ± 1.90^{cde}	15.42 ± 1.29^{bc}	-	-	18.78 ± 2.09^{cd}	16.92±1.33c
Psidium guajava	15.78 ± 0.64^{bc}	$15.64\pm1.60_{bc}$	20.93 ± 1.87^{ef}	13.81 ± 0.43^{bc}	21.66 ± 2.47^{a}	11.46 ± 0.68^{a}	20.48 ± 1.13^{cde}	18.79 ± 1.70^{c}
Syzygium cumini	12.24 ± 1.21^{b}	16.21 ± 0.39^{bc}	17.00 ± 0.49^{bcd}	13.44 ± 2.24^{bc}	-	-	17.35 ± 0.57^{bc}	17.29 ± 0.70^{c}
Saraca asoca	23.31 ± 3.44^{d}	20.91 ± 0.51^{d}	-	-	25.18 ± 2.37^{a}	19.90 ± 0.97^{b}	26.57 ± 2.17^{f}	22.23 ± 0.61^{d}
Tectona grandis	40.41 ± 1.31^{es}	46.84 ± 1.51^{e}	41.44 ± 0.79^{g}	34.58 ± 2.76^{d}	-	-	42.52 ± 0.93^{g}	48.31 ± 1.17^{e}
F-value	45.241	44.02	59.894	21.90	1.864	7.28	57.988	93.43

Note: Data are 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 test, $p\leq0.05$, (n=12 to 36)

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

Plant species	Industrial		Roadside		Residential		Campus	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	9.48±0.32^{de}	7.79±0.65^{e}	10.36±0.59^{ef}	7.42±0.76^{d}	-	-	10.69±0.36^{f}	8.40±0.22^{e}
Azadirachta indica	3.39±0.02^{a}	1.87±0.08^{a}	3.36±0.02^{a}	1.81±0.39^{a}	-	-	3.56±0.52^{a}	2.37±0.09^{a}
Citrus maxima	7.51±0.56^{c}	4.90±0.04^{bc}	8.15±0.51^{cd}	5.03±0.38^{b}	-	-	8.25±0.56^{de}	5.59±0.34^{bc}
Ficus benghalensis	12.15±0.72^{f}	10.47±0.80^{f}	12.19±0.85^{fg}	10.32±0.43^{e}	-	-	12.93±0.88^{g}	12.18±0.20^{f}
Ficus religiosa	10.85±0.46^{ef}	7.26±0.38^{de}	11.70±0.21^{fg}	6.86±0.43^{cd}	-	-	11.80±0.28^{fg}	8.17±0.17^{e}
Magnifera indica	6.33±0.49^{cd}	6.02±0.28^{cd}	6.90±0.40^{bc}	5.45±0.26^{bc}	7.40±0.59^{b}	6.24±0.78^{b}	6.95±0.38^{cd}	6.34±0.20^{cd}
Neolamarckia cadamba	11.17±0.80^{ef}	12.76±1.14^{g}	12.64±0.41^{g}	10.30±0.65^{e}	11.82±0.07^{c}	12.60±0.08^{c}	12.73±0.39^{g}	13.65±0.43^{g}
Nephelium litchi	5.14±0.13^{ab}	4.18±0.21^{b}	5.59±0.40^{b}	5.03±0.36^{b}			5.94±0.18^{bc}	5.21±0.33^{bc}
Psidium guajava	7.87±0.75^{cd}	6.30±0.74^{cde}	8.81±0.60^{cde}	5.47±0.04^{bc}	8.98±0.67b	5.35±0.10^{b}	9.09±0.65^{e}	8.01±0.52^{e}
Syzygium cumini	10.29±0.074^{ef}	6.38±0.14^{cde}	9.58±1.40^{de}	6.47±0.31^{bcd}	-	-	10.81±0.66^{f}	6.99±0.77^{de}
Saraca asoca	4.74±0.42^{ab}	4.16±0.22^{b}	-	-	5.03±0.43^{a}	3.53±0.34^{a}	5.31±0.38^{b}	4.44±0.23^{b}
Tectona grandis	22.84±0.93^{g}	29.67±0.30^{h}	22.30±0.54^{h}	26.92±1.19^{f}	-	-	24.10±0.41^{h}	33.48±1.25^{h}
F-value	73.125	187.62	59.198	141.93	32.341	82.08	120.122	319.43

Note: Data are 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 test, $p \leq 0.05$, n=12 to 36)

cm) in the industrial area (Table 7). During monsoon, *Azadirachta indica* had the smallest leaf width (1.87 ± 0.08 cm) in the industrial area, while *Tectona grandis* had the largest (33.48 ± 1.25 cm) in the campus area. Overall, *Tectona grandis* exhibited the greatest leaf width across all study areas and seasons, whereas *Azadirachta indica* had the narrowest leaves.

The percentage of leaf width reduction was higher in polluted area during monsoon season compared to the less polluted area (Figure 7). In industrial areas, *Nephelium litchi* during winter (13.30%) and *Psidium guajava* during monsoon (21.77%) season showed the highest reduction. At roadside, *Syzygium cumini* during winter (12.39%) and *Neolamarckia cadamba* during monsoon season (24.61%) showed the highest reduction. Similarly, in residential areas, *Saraca asoca* showed the maximum leaf width reduction in both seasons (5.30% in winter and 19.92% in monsoon).

Chlorophyll-a

Chlorophyll-a levels generally increased during the monsoon compared to the winter season, with industrial and less polluted areas showing significantly higher values than roadside and residential areas (Table 8). However, certain plant species like, *Artocarpus heterophyllus, Ficus religiosa, Mangifera indica, Neolamarckia cadamba, Nephelium litchi, Psidium guajava, Syzygium cumini,* and *Saraca asoca* exhibited higher chlorophyll-a levels during the winter season. In winter, chlorophyll-a ranged from 0.09 mg/g in *Tectona grandis* in industrial areas

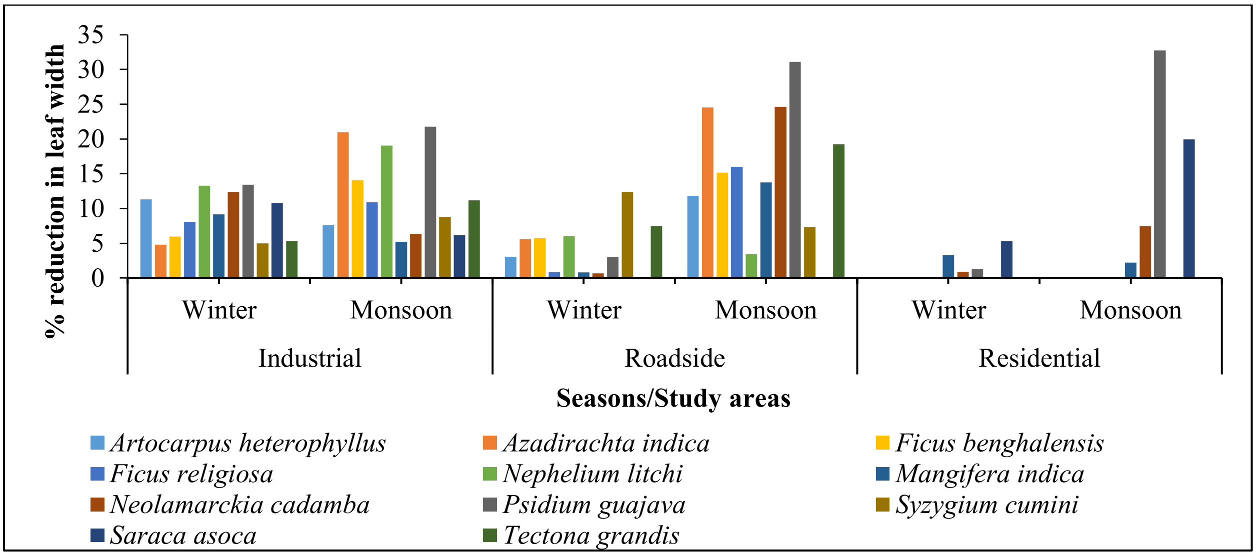


Figure 7: Percentage (%) reduction in leaf width of different plant species in two seasons

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

Plant species	Industrial		Roadside		Residential		Campus	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	1.15±0.09^{d}	0.95±0.12^{abc}	0.68±0.15^{b}	0.87±0.02^{bc}	-	-	1.34±0.12^{bc}	1.95±0.10^{d}
Azadirachta indica	0.61±0.06^{bc}	0.78±0.04^{a}	0.65±0.11^{b}	1.54±0.26^{d}	-	-	0.66±0.04^{a}	1.64±0.36^{bcd}
Citrus maxima	0.45±0.03^{b}	0.82±0.10^{ab}	0.48±0.07^{b}	1.00±0.08^{c}	-	-	0.57±0.07^{a}	1.69±0.32^{cd}
Ficus benghalensis	0.19±0.02^{a}	1.16±0.08^{bcd}	0.47±0.12^{b}	0.99±0.07^{c}	-	-	0.57±0.03^{a}	1.45±0.30^{abcd}
Ficus religiosa	0.50±0.06^{b}	0.94±0.07^{abc}	1.25±0.07^{cd}	0.95±0.04^{c}	-	-	1.68±0.07^{bcd}	1.00±0.05^{ab}
Mangifera indica	1.65±0.02^{e}	1.51±0.00^{d}	1.19±0.06^{c}	0.93±0.17^{c}	1.39±0.06^{b}	1.21±0.18^{a}	1.76±0.10^{cd}	1.52±0.12^{abcd}
Neolamarckia cadamba	0.82±0.02^{c}	1.41±0.07^{d}	1.52±0.04^{d}	0.97±0.09^{c}	0.42±0.03$_{a}$	1.59±0.35^{a}	1.56±0.03^{bcd}	1.78±0.31^{d}
Nephelium litchi	0.58±0.03^{bc}	1.16±0.05^{bcd}	1.04±0.02^{c}	0.92±0.11^{c}	-	-	1.60±0.04^{bcd}	1.41±0.01^{abcd}
Psidium guajava	1.58±0.01^{e}	1.35±0.19^{d}	1.11±0.09^{c}	0.50±0.04^{a}	1.16±0.23^{b}	0.92±0.08^{a}	1.83±0.05^{d}	1.73±0.10^{d}
Syzygium cumini	1.12±0.18^{d}	0.94±0.13^{abc}	1.12±0.18^{c}	0.55±0.05^{ab}	-	-	1.26±0.26^{b}	1.05±0.11^{abc}
Saraca asoca	2.08±0.12^{f}	1.26±0.04^{cd}	-	-	0.64±0.06^{a}	1.06±0.15+^{a}	2.56±0.35^{e}	1.63±0.00^{bcd}
Tectona grandis	0.09±0.01^{a}	0.74±0.19^{a}	0.11±0.01^{a}	0.75±0.02^{abc}	-	-	0.30±0.03^{a}	0.94±0.02^{a}
F-value	56.24	5.69	17.52	5.53	12.55	1.74	21.47	2.65
p-value	*0.00*	0.00	*0.00*	0.00	*0.00*	*0.23*	*0.00*	*0.02*

Note: Data are 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 test, $p \leq 0.05$, n=12 to 36)

to 2.56 mg/g in *Saraca asoca* in less polluted areas. Similarly, during monsoon season, it ranged from 0.74 mg/g in *Tectona grandis* in industrial areas to 2.56 mg/g in *Saraca asoca* in less polluted areas.

Reduction in Chlorophyll-a

Mangifera indica from both industrial and residential areas, and *Neolamarckia cadamba* from the roadside, exhibited the lowest percentage of reduction in chlorophyll-a during the winter season (Figure 8). During monsoon season, plants species like *Ficus benghalensis, Ficus religiosa, Magnifera indica, Neolamarckia cadamba* and *Syzygium cumini* exhibited less percent of reduction in chlorophyll-a from different study areas.

Chlorophyll-b

Chlorophyll-b increased during the monsoon, with significant variations across study areas and plant species ($p<0.05$ in most cases). During the winter season, chlorophyll-b ranged from 0.04 mg/g in *Tectona grandis* in industrial areas to 0.52 mg/g in *Saraca asoca* in less polluted areas (Table 9). During monsoon, chlorophyll-b levels ranged from 0.66 mg/g in *Nephelium litchi* in industrial area to 1.05 mg/g in *Psidium guajava* in less polluted areas.

Reduction in Chlorophyll-b

The leaves of plants like *Artocarpus heterophyllus, Citrus maxima, Neolamarckia cadamba* and *Ficus*

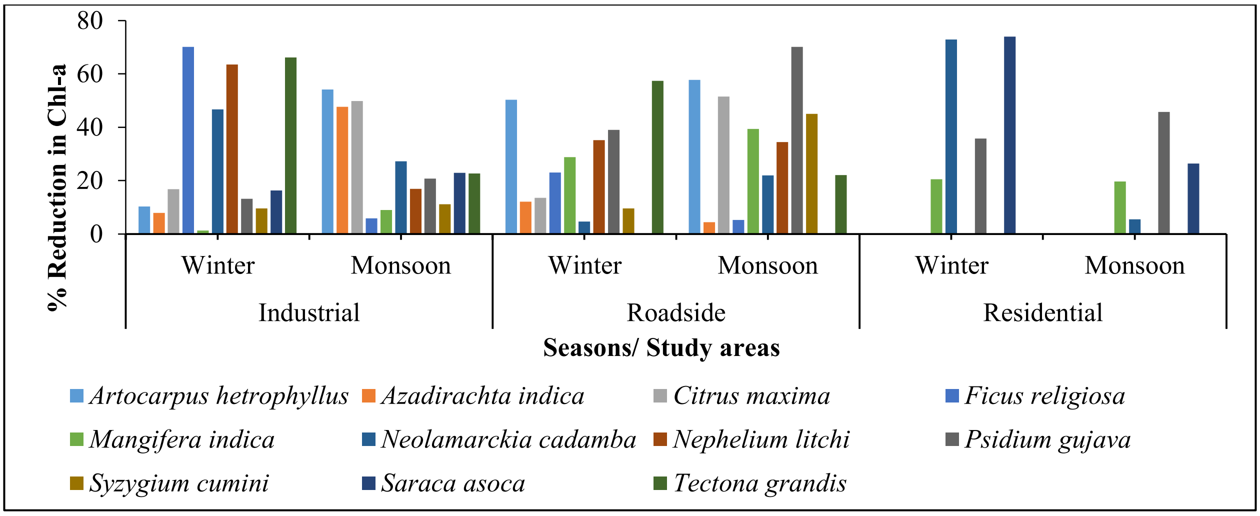


Figure 8: Percentage (%) reduction in Chlorophyll-a of plant species in two seasons

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

Plant species	Industrial		Roadside		Residential		Less polluted	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	0.22 ± 0.05^{cde}	0.21 ± 0.00^{ab}	0.15 ± 0.01^{ab}	0.20 ± 0.02^{abc}	-	-	0.20 ± 0.08^{a}	0.23 ± 0.02^{ab}
Azadirachta indica	0.11 ± 0.06^{abc}	0.20 ± 0.05^{ab}	0.11 ± 0.00^{ab}	0.14 ± 0.06^{ab}	-	-	0.16 ± 0.04^{a}	0.31 ± 0.07^{a}
Citrus maxima	0.10 ± 0.05^{abc}	0.18 ± 0.00^{a}	0.16 ± 0.03^{ab}	0.23 ± 0.05^{abcd}	-	-	0.15 ± 0.02^{a}	1.07 ± 0.49^{c}
Ficus benghalensis	0.11 ± 0.02^{abc}	0.34 ± 0.06^{abcd}	0.14 ± 0.02^{ab}	0.10 ± 0.03^{a}	-	-	0.16 ± 0.01^{a}	0.60 ± 0.15^{abc}
Ficus religiosa	0.10 ± 0.01^{abc}	0.42 ± 0.03^{cde}	0.20 ± 0.01^{bc}	0.11 ± 0.04^{a}	-	-	0.56 ± 0.21^{b}	0.48 ± 0.02^{ab}
Mangifera indica	0.32 ± 0.01^{e}	0.36 ± 0.02^{bcde}	0.30 ± 0.04^{c}	0.82 ± 0.08^{e}	0.30 ± 0.05^{b}	0.41 ± 0.13^{a}	0.40 ± 0.03^{ab}	0.83 ± 0.06^{bc}
Neolamarckia cadamba	0.21 ± 0.03^{bcd}	0.44 ± 0.01^{cde}	0.31 ± 0.02^{c}	0.31 ± 0.02^{bcd}	0.13 ± 0.00^{a}	0.42 ± 0.08^{a}	0.35 ± 0.01^{ab}	0.58 ± 0.12^{abc}
Nephelium litchi	0.15 ± 0.01^{bcd}	0.66 ± 0.04^{f}	0.18 ± 0.04^{ab}	0.37 ± 0.11^{cd}	-	-	0.24 ± 0.01^{a}	0.66 ± 0.02^{abc}
Psidium guajava	0.26 ± 0.02^{de}	0.50 ± 0.04^{def}	0.22 ± 0.00^{bc}	0.13 ± 0.00^{ab}	0.19 ± 0.00^{a}	0.39 ± 0.015^{a}	0.37 ± 0.01^{ab}	1.05 ± 0.04^{c}
Syzygium cumini	0.17 ± 0.09^{bcd}	0.30 ± 0.02^{abc}	0.17 ± 0.09^{ab}	0.17 ± 0.00^{ab}	-	-	0.26 ± 0.05^{a}	0.31 ± 0.03^{ab}
Saraca asoca	0.40 ± 0.02^{d}	0.47 ± 0.14^{cde}	-	-	0.14 ± 0.01^{a}	0.68 ± 0.25^{a}	0.52 ± 0.10^{b}	0.80 ± 0.08^{bc}
Tectona grandis	0.04 ± 0.01^{a}	0.53 ± 0.02^{ef}	0.06 ± 0.02^{a}	0.40 ± 0.02^{d}	-	-	0.18 ± 0.01^{a}	0.61 ± 0.10^{abc}
F-value	8.92	7.19	4.17	14.87	9.20	0.84	3.44	2.84
p-value	*0.00*	0.00	*0.00*	0.00	*0.00*	*0.50*	*0.00*	*0..01*

Note: Data are 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 test, $p\leq0.05$, n=12-36)

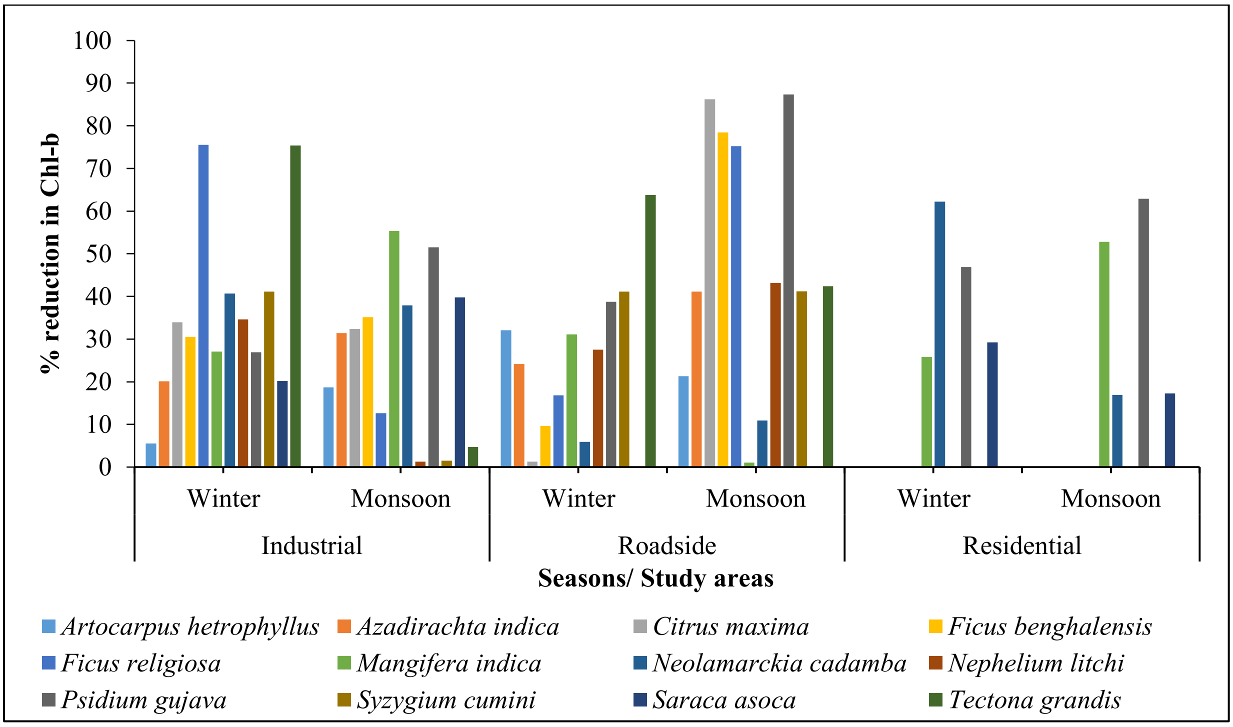


Figure 9: Percentage (%) reduction in Chlorophyll-b of plant species in two seasons

benghalensis showed a minimum percentage of reduction in chlorophyll-b from polluted areas during winter season while (Figure 9), species like *Nephelium litchi, Syzygium cumini* and *Mangifera indica* showed less percentage of reduction in chlorophyll-b during monsoon season.

Ratio of chlorophyll (a:b)

The chlorophyll *a:b* ratio was higher during the winter season, particularly in less polluted areas, as observed in species like *Artocarpus heterophyllus* (Table 10). In contrast, industrial and roadside areas exhibited more variable levels of chlorophyll content. Notable species-specific trends were observed, such as *Syzygium cumini* showing elevated chlorophyll content in industrial and roadside during winter, while *Tectona grandis* consistently displayed low chlorophyll levels across all areas and seasons.

Total chlorophyll

Generally, plant species during monsoon seasons showed higher total chlorophyll levels, especially

Table 10: **Ratio of Chl (a:b) of different plant species in two seasons**

Plant species	Industrial		Roadside		Residential		Campus area	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	6.06±1.78[c]	4.49±0.48[bc]	4.34±0.59[a]	4.36±0.39[ab]	-	-	11.57±0.66[b]	8.25±0.27[c]
Azadirachta indica	5.35±0.28[bc]	4.86±1.92[c]	6.00±1.09[a]	18.07±4.26[c]	-	-	4.57±0.85[a]	5.26±0.22[b]
Citrus maxima	4.58±0.05[abc]	4.41±0.48[bc]	3.24±0.89[a]	4.82±0.89[ab]	-	-	3.97±0.11[a]	4.45±0.31[ab]
Ficus benghalensis	1.77±0.25[a]	3.70±0.75[abc]	15.72±1.78[a]	13.42±1.64[ab]	-	-	3.57±0.04[a]	2.49±0.39[ab]
Ficus religiosa	4.99±0.81[bc]	2.22±0.04[ab]	5.99±0.19[a]	11.16±1.40[abc]	-	-	4.30±1.85[a]	2.07±0.01[a]
Mangifera indica	5.13±0.06[bc]	4.17±0.27[bc]	4.00±0.35[a]	1.19±0.30[ab]	4.82±0.92[ab]	3.59±1.02[a]	4.42±0.67[a]	1.87±0.29[a]
Neolamarckia cadamba	4.04±0.55[abc]	3.18±0.11[abc]	4.89±0.47[a]	2.72±0.64[ab]	3.19±0.21[a]	3.74±0.08[a]	4.48±0.24[a]	3.15±0.40[ab]
Nephelium litchi	3.65±0.07[abc]	1.80±0.17[a]	6.67±1.98[a]	3.04±0.95[ab]	-	-	6.56±0.13[b]	2.12±0.09[a]
Psidium guajava	6.17±1.10[cd]	2.63±0.12[abc]	4.96±0.54[a]	3.82±0.25[ab]	5.98±1.17[b]	2.36±0.23[a]	4.99±0.13[a]	1.63±0.04[a]
Syzygium cumini	8.56±2.20[d]	3.09±0.14[abc]	8.56±2.20[a]	3.16±0.25[ab]	-	-	4.66±0.09[a]	3.43±0.09[ab]
Saraca asoca	5.23±0.07[bc]	3.16±0.82[abc]	-	-	4.50±0.07[ab]	2.10±0.70[a]	5.01±0.64[a]	2.08±0.23[a]
Tectona grandis	2.44±0.51[ab]	1.42±0.39[a]	2.86±1.52[a]	1.91±0.17[a]	-	-	1.69±0.07[a]	1.66±0.31[a]
F-value	3.55	2.56	0.42	2.60	2.29	1.73	1.30	4.26
p-value	*0.00*	*0.02*	*0.92*	*0.03*	*0.15*	*0.23*	*0.27*	*0.00*

Note: Data are expressed as Mean± S.E and statistical analysis using one way ANOVA for obtaining F and *p* value. Significance mean value among different plant species are indicated by different letters. (Duncan multiple test, $p \leq 0.05$, n=12 to 36)

Table 11: Total Chlorophyll of different plant species at different study areas during two seasons

Plant species	Industrial		Roadside		Residential		Campus area	
	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter	Monsoon
Artocarpus heterophyllus	1.37±0.06[f]	1.16±0.12[ab]	1.37±0.05[c]	1.08±0.04[b]	-	-	1.54±0.16[b]	2.19±0.11[ab]
Azadirachta indica	0.73±0.07[cd]	0.98±0.00[a]	0.73±0.07[b]	1.68±0.20[c]	-	-	0.82±0.07[a]	1.96±0.43[ab]
Citrus maxima	0.56±0.03[bc]	1.00±0.10[a]	0.64±0.03[b]	1.23±0.14[b]	-	-	0.73±0.06[a]	2.77±0.81[b]
Ficus benghalensis	0.30±0.04[ab]	1.49±0.03[bcd]	0.62±0.13[b]	1.10±0.04[b]	-	-	0.73±0.04[a]	2.06±0.43[ab]
Ficus religiosa	0.60±0.06[bc]	1.37±0.11[abc]	1.47±0.09[c]	1.06±0.01[b]	-	-	2.24±0.27[c]	1.49±0.08[a]
Mangifera indica	1.97±0.03[g]	1.88±0.015[d]	1.49±0.10[c]	1.76±0.08[c]	1.70±0.08[b]	1.63±0.18[a]	2.17±0.07[b]	2.36±0.06[ab]
Neolamarckia cadamba	1.03±0.04[de]	1.85±0.08[d]	1.84±0.03[d]	1.35±0.10[b]	0.55±0.03[a]	2.01±0.43[a]	1.91±0.02[bc]	2.37±0.40[ab]
Nephelium litchi	0.75±0.04[cd]	1.83±0.03[d]	1.22±0.04[c]	1.29±0.00[b]	-	-	1.85±0.05[bc]	2.07±0.02[ab]
Psidium guajava	1.85±0.08[g]	1.86±0.24[d]	1.33±0.09[c]	0.63±0.05[a]	1.35±0.23[b]	1.31±0.08[a]	2.19±0.07[c]	2.78±0.14[b]
Syzygium cumini	1.30±0.27[ef]	1.24±0.16[ab]	1.30±0.27[c]	0.72±0.05[a]	-	-	1.53±0.32[b]	1.36±0.15[a]
Saraca asoca	2.48±0.14[h]	1.73±0.13[cd]	-	-	0.79±0.08[a]	1.74±0.22[a]	3.08±0.43[d]	2.44±0.09[ab]
Tectona grandis	0.13±0.12[a]	1.27±0.18[ab]	0.17±0.00[a]	1.15±0.02[b]	-	-	0.48±0.04[a]	1.56±0.13[a]
F-value	50.32	7.57	20.38	14.13	15.14	1.18	17.63	4.26
p-value	*0.00*	0.00	*0.00*	0.00	*0.00*	*0.37*	*0.00*	*0.00*

Note: Data are expressed as Mean± S.E and statistical analysis using one way ANOVA for obtaining F and *p* value. Significance mean value among different plant species are indicated by different letters. (Duncan multiple test, $p \leq 0.05$, (n=12 to 36))

in less polluted areas. However, certain species like *Saraca asoca, Mangifera indica* and *Psidium guajava* showed higher amount of total chlorophyll during the winter season (Table 11). In contrast, *Tectona grandis* had the lowest levels, showing high sensitivity to pollution. During winter, total chlorophyll content ranged from 0.13 mg/g in *Tectona grandis* (industrial area) to 3.08±0.43 mg/g in *Saraca asoca* (less polluted area). In monsoon, the values range from 0.72 mg/g in *Syzygium cumini* (roadside area) to 2.78mg/g in *Psidium guajava* (less polluted area).

Total chlorophyll content in the leaves *Mangifera indica, Artocarpus heterophyllus, Azadirachta indica, Ficus benghalensis* and *Neolamarckia cadamba* showed relatively lower reductions in polluted areas during the winter season (Figure 10). Conversely, *Syzygium cumini, Ficus religiosa, Azadirachta indica, Neolamarckia cadamba* exhibited less reduction in total chlorophyll content during the monsoon season.

Discussion

Dust load

Dust load in industrial areas was comparatively higher during the winter seasons, primarily due to the presence of industries, brick kilns and factories. Elevated levels of particulate matter were found

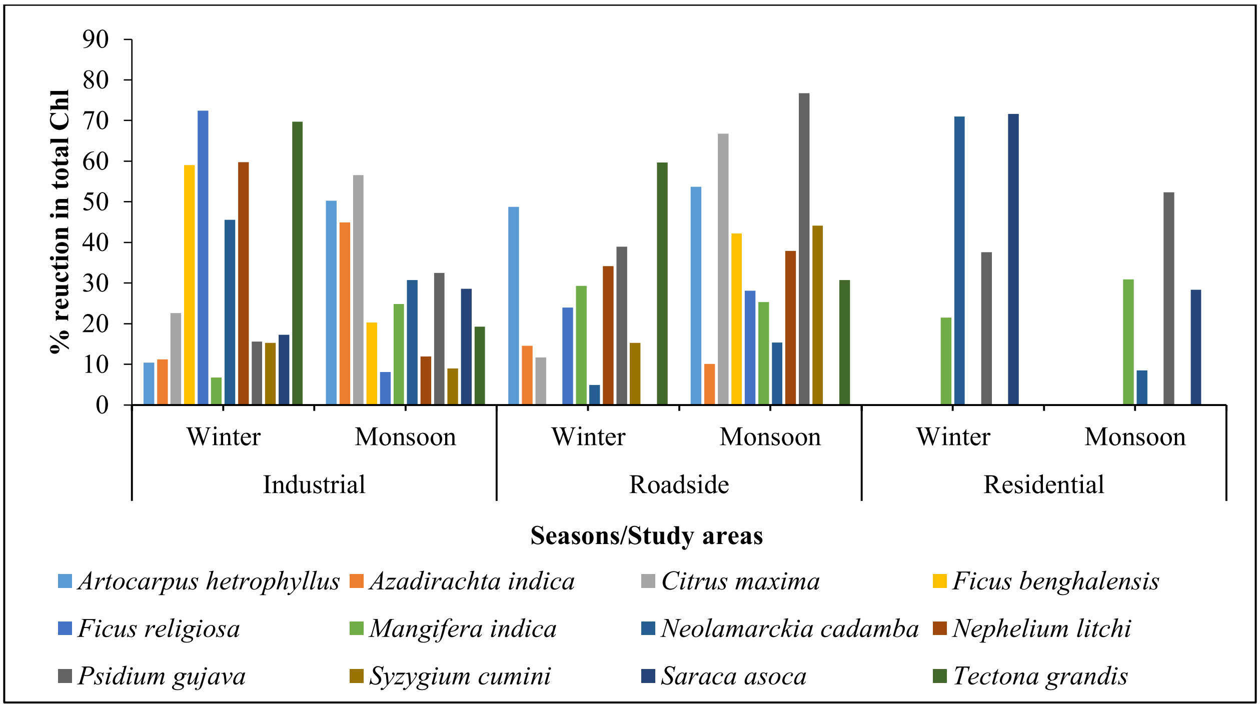


Figure 10: Percentage reduction in total chlorophyll content of different plant species in two seasons

in these areas compared to others. Dust load pollution is higher in winter than in the monsoon due to lack of precipitation, low wind speed and low temperature, which trap pollutants near the surface. Dry soil and increased human activities, vehicle movement and biomass burning further contribute to dust accumulation. In contrast, during the monsoon season, rainfall washes away dust particles, while strong wind disperses the pollutants and dense vegetation helps trap airborne particles thereby reducing atmospheric dust pollution (Linden et al., 2023). Similar findings were also reported by Chaturvedi et al. (2013) in industrial areas. Roadside and residential areas were reported as moderately polluted due to construction of roads and traffic congestion. The dust-holding capacity of the plants depends on various morphological traits and environmental conditions (Prusty et al., 2005). Plants growing near busy roads, and polluted areas like industries are highly affected by dust (Gostin, 2009; Leghari & Zaidi, 2013). This study found that high dust load was found in leaves with thick, rough, and hairy surfaces whereas low dust was accumulated on smoother and smaller leaf surface areas, consistent with the findings of Javanmard et al. (2019).

In the present study, *Tectona grandis* from industrial areas - with rough surfaces, large surface area, and short petiole, accumulated more dust whereas species like *Saraca asoca* with smoother, flatter and smaller surface areas accumulated less dust. Dust deposition was more on *Ficus benghalensis* and *Artocarpus heterophyllus* compared to other species, likely due to their coriaceous and waxy leaf structures. Similar findings were also reported by Rai & Panda (2014).

Dust accumulation can significantly obstruct stomatal pores, impeding the plant's ability to perform gaseous exchange efficiently (Sawidis et al., 2012). This obstruction reduces CO_2, uptake, leading to a decline in photosynthetic activity and energy production, which are vital for plant growth and metabolism. The findings of this study indicate that leaf physiological process appear to be significantly impacted by dust pollution than morphological traits. Physiological stress induced by dust pollution could lower chlorophyll content, decrease enzyme activity, and disrupt overall plant metabolism, as the dust layers block light penetration, which reduces photosynthetic activities (Swaidis et al., 2012).

Reduction on leaf morphology

Leaf area reduction was more pronounced in industrial areas during the winter season followed by roadside and residential areas. Similarly, leaf length and width were mostly reduced in polluted areas in monsoon seasons compared to less polluted controlled sites. These findings are consistent with those of Hamal & Chettri (2017) and Hamal (2023), who reported a reduction in leaf area and SLA in the polluted area as compared to that of a controlled less polluted area. Several studies have reported the effect of dust on plant morphological traits across different seasons in different plant species (Leghari & Zaidi, 2013; Rai & Panda, 2014; Lu et al., 2018).

A reduction in SLA near polluted areas during winter season was also reported by Prasai (2021). Notably, *Ficus religiosa* and *Nephelium litchi* could be utilized for pollution control, as they exhibited a significant reduction in SLA indicating their strong dust trapping ability and adaptive leaf morphology (Singh & Kaushik, 2022). A reduction in leaf area, leaf length, and leaf width, in polluted areas than the non-polluted areas has been reported, which is consistent with the findings of the present study. The reduction in the leaf area, leaf length and leaf width might be due to the reduction of gaseous exchanges for photosynthesis and productivity of the leaf as the pollutants can block stomatal openings (Bhatti & Iqbal, 1988; Jahan & Iqbal, 1992; Leghari & Zaidi, 2013).

Leaf area reduction is the result of air pollution that can block a plant's ability to undergo photosynthesis effectively and reduce its resilience in coping with the strains posed by air pollutant stressors (Tiwari et al., 2006). Plants growing in polluted areas showed lower SLA (Yang et al., 2023). Plants species thriving in environments with limited amounts of nutrients, shortage of water and light, exhibited lower SLA values (Cornelissen et al., 1996). The inverse relationship between dust load and SLA near polluted sites found from this study corresponds with the findings of Hamal (2023). Furthermore, prolonged exposure to pollutants leads to reductions in leaf area, SLA, leaf length, and width (Meerabai et al., 2012)

Chlorophyll content

In this study, variation in chlorophyll-a and chlorophyll-b was observed across different plant species, likely driven by seasonal changes, dust accumulation, and leaf morphological traits. Seasonal changes primarily control chlorophyll variations, while dust load and leaf morphology act as modifying factors influencing their impact (Prajapati & Tripathi, 2008). In winter, dust accumulation due to minimal precipitation and low wind speed obstructed sunlight, thereby reducing photosynthesis and contributing to chlorophyll degradation. The monsoon rains helped to wash away dust, allowing for improved light absorption and a subsequent increase in chlorophyll content. Leaf traits also influenced the extent of dust accumulation, with plants having rough or hairy leaves tending to trap more dust, leading to greater chlorophyll loss. The chlorophyll-a to chlorophyll-b ratio was generally higher in winter, especially in less polluted areas. The study showed that chlorophyll-a was more affected than chlorophyll-b, which resembled the findings of Giri et al. (2013) and Talebzadeh & Valeo (2022). Chlorophyll-a and -b reduction was highest during the monsoon. *Mangifera indica* and *Neolamarckia cadamba* showed minimal reduction in chlorophyll-a during winter, while *Ficus benghalensis*, *Ficus religiosa*, *Mangifera indica*, *Neolamarckia cadamba*, and *Syzygium cumini* were less affected by dust in monsoon. Chlorophyll-b reduction was lowest in *Artocarpus heterophyllus* and *Citrus maxima* in winter, while *Syzygium cumini* and *Mangifera indica* exhibited better retention during the monsoon season. The photosynthetic pigments undergo several photochemical reactions like oxidation, reduction, and pheophytinisation to overcome stress due to which the chlorophyll content decreases in polluted areas (Tripathi & Gautam, 2007). The reduction of chlorophyll content in plants growing in polluted areas might also be due to the adverse effects of industrial and vehicular emissions on plant physiology (Dhyani et al., 2019). The reduction in chlorophyll contents might also be due to the uptake of heavy metals like Cu, Zn, and Pb through the leaf surfaces. Decreased chlorophyll (a:b) ratio with increasing pollution, also reported by Chettri et al. (1998), might be due to a decrease in chlorophyll-a and an increase in chlorophyll-b concentrations. This shift might occur because chlorophyll-b is synthesized from chlorophyll-a through the oxidation of the methyl group on ring II to an aldehyde (Bidwell, 1979).

Conclusion

Air pollutants significantly affect both the morphological and physiological characteristics of the tree leaves growing around industrial and roadside areas, particularly during the winter season, compared to those in residential and campus areas. Leaves with rough texture, large areas and complex structures, such as those of *Tectona grandis* showed higher dust accumulation than the leaves with smooth and smaller areas like those of *Nephelium litchi* and *Psidium guajava*. Plant leaf morphological characters were significantly reduced across the industrial, roadside and residential areas in comparison to that of campus areas during the winter than the monsoon seasons However, synthesis of chlorophyll-a was more significantly affected by dust pollution than chlorophyll-b, as evidenced by a higher chlorophyll a:b ratio in less polluted areas, particularly during winter indicating their resilience to seasonal variations and environmental stressors. Plant species like *Artocarpus heterophyllus, Citrus maxima, Ficus* *benghalensis, Ficus religiosa, Mangifera indica, Neolamarckia cadamba, Nephelium litchi* and *Psidium guajava* showed minimal reductions in both morphological traits and chlorophyll content. These species, therefore, exhibit potential for use in urban greening and pollution mitigation strategies due to their relative tolerance to environmental pollutants.

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Author's contribution statement

U. Shrestha: Sample collection, laboratory analysis, original draft writing, and formal analysis. **S. Rijal, A. Shrestha, P. Adhikari:** Sample collection and laboratory analysis. **M. K. Chettri**: Material collection, data curation and validation. **B. D. Acharya, M. R. Paudel:** Material collection and supervision. **A. Devkota:** Material collection, conceptualization, laboratory analysis, Writing-review and editing, and supervision

Data availability

The data used in the study are accessible upon request to the corresponding author.

Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this paper.

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