



Spatio-Temporal and Statistical Evaluation of Air Pollution Tolerance and Metal Accumulation in Plant Leaves and Foliar Dust in Rajasthan, India

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This study evaluated the air pollution tolerance index (APTI) and metal accumulation index (MAI) to assess the tolerance, sensitivity and metal accumulation potential of plant leaves towards air pollution. The study was conducted on 12 roadside plant species across 4 sampling sites during 4 seasonal variations. Three sites, namely RIICO Industrial Area Mansarovar (MS), heavy-traffic Ajmeri Gate (AG), and commercial/residential Chandpole (CP), were located in Jaipur city, while Banasthali (BT) served as the rural reference site. Metal pollution was analysed to determine the capacity of plants and associated dust particles to accumulate metals. The highest metal concentrations (mg/kg) exceeded the WHO (1996) permissible limits for Cd (49.68, 37.72), Cr (45.90, 39.39), Cu (197.21, 171.21), Fe (1460.09, 1206.09), Hg (417.55, 365.54), Pb (217.55, 177.34) and Zn (200.06, 187.98) in dust foliage and leaf samples. Winter, pre- and post-monsoon seasons showed enhanced APTI and MAI, while monsoon showed moderated to reduced values in most species. *Ficus benghalensis* (31.22, 79.02), *Ficus religiosa* (32.25, 78.69) and *Cassia fistula* (29.13, 76.13) exhibited the highest APTI and MAI across sites, demonstrated high potential as phytomonitoring species and bioaccumulators of air pollutants, thereby supporting their suitability for greenbelt development to improve air quality. In contrast, *Dalbergia sissoo* (6.40, 38.27), *Senna siamea* (7.24, 36.97) and *Vachellia nilotica* (8.97, 37.03) had lowest APTI and MAI. Site-specific trends revealed that MS, followed by AG and CP, were more polluted environments compared to BT. This study emphasised that phytomonitoring can play a significant role in mitigating air pollution and improving the urban environment.

Keywords: Phytomonitoring, Air pollution tolerance index, Metal pollution, Metal accumulation index, Foliar dust deposition.

INTRODUCTION

Air quality has deteriorated alarmingly over the past three to four decades due to rapid urban population growth, large-scale industrial expansion and increasing vehicular emissions worldwide [1]. These anthropogenic sources release hazardous airborne pollutants including particulate matter (PM), carbon residues, sulphur dioxide (SO₂), volatile organic compounds (VOCs) and nitrogen oxides (NO_x). Elevated concentrations of these air pollutants facilitate the accumulation of metals in atmosphere [2]. Metals such as Pb, Cu, Cd, Cr, Zn, Hg and As, which are often associated with air pollutants, pose serious environmental and human health risks worldwide [3,4]. The rising concentrations of these persistent and toxic metals have increased the global economic and health burden, making air pollution a critical national and international environmental

challenge. Consequently, evaluation of effective strategies to mitigate air pollution has attracted increasing global attention.

Phytomonitoring has emerged as an effective, low-cost, eco-friendly approach for evaluating air quality by studying the physiological and biochemical responses of plants [5]. Plants serve as natural filters and bioindicators, capable of absorbing airborne pollutants through their foliar surfaces, thus contributing to urban air purification *via* phylloremediation [6]. This makes plant-based monitoring highly suitable for regions where conventional monitoring infrastructure is limited or expensive. Thus, an appropriate method is required when choosing suitable roadside trees for greenbelt development [7]. Air Pollution Tolerance Index (APTI), based on four biochemical parameters, including leaf extract pH, total chlorophyll content (TCC), relative water content (RWC) and ascorbic acid content (AAC), is widely applied to assess species-specific tolerance [8-11].

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APTI is extremely helpful for identifying tolerant plants and understanding their physiological and biochemical responses to air pollution [12]. Plants are categorised into sensitive and tolerant categories based on their APTI values [11]. These biochemical indicators reflect the ability of plants to withstand oxidative stress, maintain moisture balance and ensure cellular protection under polluted conditions, making APTI an effective preliminary screening tool for greenbelt planning.

Numerous plants can serve as effective biomonitors for assessing airborne metal accumulation [13,14]. Leaves serve as natural filters due to their wide surface area and distinct micro- and macrostructural characteristics, which enhance their capacity to absorb and accumulate metal-bound airborne pollutants [15-18]. Consequently, increasing attention has been directed toward the capacity of plants to remove noxious metals from air pollutants, especially in suburban and urban environments [18]. Planting trees along roadsides is a key strategy for mitigating noxious metals in urban air pollution [19]. Anthropogenic activities, primarily through vehicular and industrial emissions, led to metal accumulations in foliar dust and plant leaves [16,20-22] and severely affected plant growth and human health [23-26]. Therefore, it is important to identify plants that can accumulate multi-metal combinations [27]. To evaluate the metal accumulation capacity of plants, the metal accumulation index (MAI) has been proposed [28,29]. MAI values are often site-specific and vary among species [30], providing important insight into the role of urban vegetation in pollution monitoring. When applied together, APTI and MAI offer a comprehensive assessment of plant tolerance and metal bioaccumulation behaviour, thereby serving as an effective tool for environmental risk assessment.

Jaipur city, the historic "Pink City" of India located in the semi-arid region of Rajasthan state, has experienced significant deterioration in ambient air quality due to rapid urbanisation, increasing vehicular traffic and industrial emissions, resulting in elevated levels of air pollutants and associated metals at roadside locations [31-37]. These increased pollutants and associated metals have detrimental effects on urban flora and human health [38,39]. Despite the documented pollution levels, limited studies have evaluated the combined plant tolerance and metal accumulation potential of species growing in polluted urban areas of Jaipur and the rural region of Banasthali in Rajasthan, highlighting a significant research gap. Furthermore, there is a paucity of research concerning the tolerance and metal accumulation of plant species in Jaipur city (highly polluted) and Banasthali (rural area) sites of Rajasthan, India. Regarding sustainability of the environment, the objectives of the current investigation are: (i) To ascertain APTI method to interpret and understand air pollution tolerance capacities of 12 selected plants; (ii) To appraise eight metal concentrations (As, Cd, Cr, Cu, Fe, Hg, Pb and Zn) to calculate metal accumulation in foliar dust and plant leaves present along roadsides in polluted regions of Jaipur city and compare with rural area of Banasthali across four seasonal variations. These objectives determine plant tolerance levels, evaluate toxicity of foliar dust metals and their accumulation in plants and identify efficient species for greenbelt development in tropical metropolitan regions. This examination will be important and helpful for policymakers and urban planners

to make educated decisions, suggesting appropriate and relevant tree species for maintaining the sustainability of urban green areas and minimizing the detrimental consequences of air pollution to improve air quality.

EXPERIMENTAL

Location and geographical area: For present study, monitoring stations, codes, categories and their geographical coordinates were chosen for phytomonitoring across study sites namely site-1: RIICO industrial zone, Mansarovar (MS) (26°50'2.763" N, 75°46'33.3" E), site-2: residential/commercial zone, Chandpole (CP) (26°55'10.252" N, 75°49'1.876" E), site-3: heavy traffic zone, Ajmeri gate (AG) (26°55'0.077" N, 75°49'0.551" E) and site-4: rural area of Banasthali (BT) (26°21'42.695" N, 75°55'50.049" E) of Rajasthan state. A map of study area is shown in Fig. 1. According to Central Pollution Control Board (CPCB), industrial areas like Mansarovar, developed by Rajasthan State Industrial Development and Investment Corporation (RIICO), promote industrialisation in Jaipur city. The residential and commercial area in Chandpole is historic in Jaipur, characterised by combined residential housing, markets and commercial establishments. Urban traffic-dense area in Ajmeri Gate is prominent entry point into Jaipur's walled city, characterised by congestion. The rural/agricultural zone (Banasthali) is known for its educational institutions and surrounding rural landscapes, characterised by agricultural activities, lower population density and minimal industrial development.

Plant species selection: The species were *Alstonia scholaris* (PS1), *Azadirachta indica* (PS2), *Bougainvillea spectabilis* (PS3), *Cassia fistula* (PS4), *Cordia dichotoma* (PS5), *Dalbergia sissoo* (PS6), *Ficus benghalensis* (PS7), *Ficus religiosa* (PS8), *Polyalthia longifolia* (PS9), *Pongamia pinnata* (PS10), *Senna siamea* (PS11) and *Vachellia nilotica* (PS12). These species were selected for their availability, abundance and widespread occurrence at each site. Leaf samples were collected during four distinct seasons viz. pre-monsoon (S1), monsoon (S2), post-monsoon (S3) and winter (S4). Selected sites provided a diverse representation of plant responses to varying pollution levels across seasons, enabling the assessment of biochemical parameters and metal accumulation. All species were present across study sites to maintain consistency in comparative analysis.

Sample collection: To account for the spatio-temporal variability, leaf samples from 12 plant species were collected across four sampling sites during each season. Approximately 30-50 healthy, fully mature leaves were harvested from ~10 year old trees at a height of 1.5-2.0 m above ground level during early morning hours. Leaves showing signs of disease, pest infestation or physical damage were excluded. The collected leaves were pooled in sterile plastic bags and transported to the laboratory. Samples were initially washed with deionized water followed by distilled water to remove adhered dust particles and surface contaminants. The combined washings (~300 mL) were filtered and preserved for analysis of dust-bound metals. Leaf samples were stored in labelled polythene bags at 4 °C under dark conditions to minimize analyte degradation and moisture loss prior to biochemical and metal analyses.

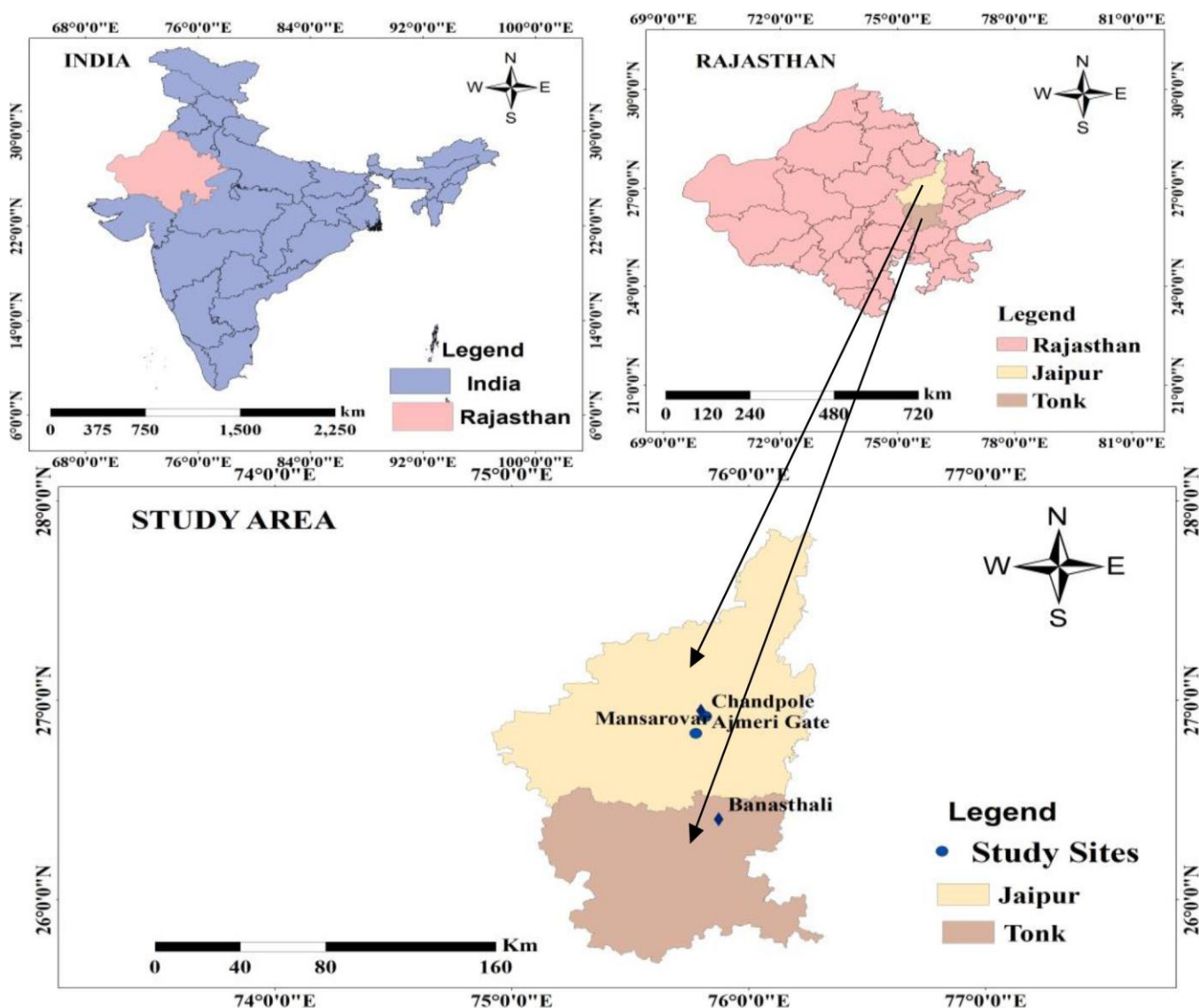


Fig. 1. Location map of the study area showing the selected sampling sites in Jaipur and Tonk districts, Rajasthan, India

Dust and leaf samples preparation and digestion for metal analysis: Washed foliar dust and leaf samples were oven-dried and separately powdered using a mortar and pestle. Approximately 0.5 g of each dried sample was used for metal analysis [15,18]. The samples were digested in quartz tubes using aqua regia following the U.S. EPA Method 3050B for acid-extractable metals. Digestion was carried out at 80 °C for 15 min under controlled heating conditions to ensure efficient metal extraction while minimizing volatilization losses and sample splattering. After digestion, the solutions were filtered through Whatman No. 42 filter paper and diluted to 25 mL with double-distilled water.

The aqua regia digestion procedure provides pseudo-total metal concentrations, which is suitable for foliar dust and leaf matrices where metals mainly occur in adsorbed and biologically accumulated forms. The prepared samples were analysed by atomic absorption spectroscopy (AAS) to determine metal concentrations in foliar dust and leaf tissues [40]. The reliability of the digestion method has been validated in similar environmental studies [15,18].

Analytical procedure

Relative water content (RWC): The RWC of leaves was determined based on a method by Sen & Bhandari [41]. This parameter was calculated using following formula:

$$\text{RWC} = \frac{\text{Fresh weight (FW)} - \text{Dry weight (DW)}}{\text{Turgid weight (TW)} - \text{Dry weight (DW)}} \times 100 \quad (1)$$

Total chlorophyll content (TCC): Approximately 0.5 g of crushed leaf sample was processed and centrifuged at 3000 rpm for 15 min. The absorbance of the resulting supernatant was measured at 645 and 663 nm using a UV-visible spectrophotometer (Thermo-Scientific Evolution 201), corresponding to the characteristic absorption maxima of chlorophyll b and chlorophyll a, respectively [42]. TCC was calculated using formula:

$$\text{Chlorophyll a} \left(\frac{\text{mg}}{\text{g FW}} \right) = \frac{[12.7(A_{663}) - 2.69(A_{645})] \times V}{1000W} \quad (2)$$

$$\text{Chlorophyll b} \left(\frac{\text{mg}}{\text{g FW}} \right) = \frac{[22.9(A_{645}) - 4.68(A_{663})] \times V}{1000W} \quad (3)$$

From eqns. 2 and 3:

$$\text{TCC} \left(\frac{\text{mg}}{\text{g}} \text{FW} \right) = 20.2(A_{645}) + 8.02(A_{663}) \times \frac{V}{1000 \times W} \quad (4)$$

where A_{645} = absorbance at 645 nm; A_{663} = absorbance at 663 nm; V = total volume of extract; W = weight of leaf material in grams.

pH of leaf extract: The pH of the leaf extract was measured using a digital pH meter (pH 700 model, EUTECH Instruments). After centrifugation of the crushed leaf samples, the pH of the obtained supernatant was directly recorded.

Ascorbic acid content (AAC): The AAC of leaf samples was determined using a modified colorimetric 2,6-dichlorophenol indophenol method [43]. Approximately 0.5 g of leaf tissue was extracted with 4% oxalic acid and centrifuged at 6000 rpm for 10 min. An aliquot of 5 mL supernatant was mixed with 10 mL of 4% oxalic acid and titrated against the dye solution until the appearance of a persistent light pink colour. The following equation was used to calculate AAC.

$$\text{AAC} \left(\frac{\text{mg}}{\text{g}} \text{FW} \right) = \frac{0.5(\text{mg}) \times V_2(\text{mL}) \times 30(\text{mL})}{V_1(\text{mL}) \times 5(\text{mL}) \times \text{Weight of sample (g)}} \quad (5)$$

where V_1 volume of the dye titrated against the working standard; V_2 volume of dye titrated against the sample.

Air pollution tolerance index (APTI): The APTI was calculated using the formula proposed by Singh & Rao [44]. APTI combines multiple biochemical parameters to assess the tolerance capacity of plants against air pollution stress [10,11,45]. The following formula was used to compute APTI:

$$\text{APTI} = \frac{A(T+P)+R}{10} \quad (6)$$

where A: ascorbic acid content of leaf sample (mg/g) FW; T: total chlorophyll content (mg/g) FW; P: pH of leaf extract; and R: relative water content (%) of foliage samples. Green plants as ≤ 12 = sensitive; 13-16 = intermediate; 17-20 = moderately tolerant; > 20 = tolerant against air pollution [11].

Metal analysis of foliar dust and plants: Foliar dust and tree leaves accumulate various elements simultaneously. The prepared solutions were analysed using AAS (Thermo Scientific iCE 3000 Series). Metals like arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), lead (Pb) and zinc (Zn) were examined. Quality assurance (QA) and quality control (QC) were maintained by analyzing standard samples (without foliar dust and leaves) and metal samples (for each sample) measured simultaneously [40]. The AAS was operated under element-specific conditions optimised to ensure the maximum sensitivity and analytical accuracy. Each metal was measured at its characteristic resonance wavelength with appropriate hollow cathode lamp currents (3-10 mA) and slit widths (0.2-0.5 nm) selected to enhance spectral resolution. All measurements were performed using an air-acetylene flame and the AAS operated in absorbance mode. These standardised operational settings ensured precise atomisation, improved signal stability and reliable quantification across the studied elements. Five replicate measurements were performed for standard samples. Calibration curves were prepared using standard solutions of known concentrations [40,46]. Metal concentrations were measured based on

these calibration curves and expressed in $\mu\text{g g}^{-1}$. Absorbance was measured at respective wavelengths for each sample. All samples were analysed in triplicate to ensure accuracy and the standard deviation (SD) of replicate results was used to measure precision [47].

MAI was calculated to provide an integrated measure of total metal load in plants. MAI values were determined for each plant across seasons using formula [29]:

$$\text{MAI} = \frac{1}{N} \sum_{j=1}^N I_j \quad (7)$$

where N = Total number of metals analysed, I_j = the sub-index for variable j , I_j = division of mean concentration value (x) of each metal on their standard deviation (Δx) as follows:

$$I_j = \frac{x}{\Delta x} \quad (8)$$

Standard reference values for metal concentrations in plants: Standard reference values for metals in plant tissues were adopted from previously published literature to assess the level of contamination in the present study. These reference ranges represent the typical physiological concentrations of metals that are normally found in plants [48,49]. The normal concentration ranges for essential and non-essential metals such as Cu, Zn, Pb, Hg, Fe, Cd and Cr were considered as baseline values for comparison. Copper (Cu) is generally found within the range of 5-20 mg/kg, while zinc (Zn) typically varies between 20-100 mg/kg in plant tissues. Lead (Pb), a non-essential and toxic metal, is usually present in lower concentrations ranging from 1-10 mg/kg. Mercury (Hg), being highly toxic, occurs at trace levels, typically below 0.1 mg/kg. Iron (Fe), an essential micronutrient, is present in relatively higher concentrations, ranging from 50-250 mg/kg. Cadmium (Cd), a highly toxic metal, is found in very low concentrations, usually between 0.05-0.2 mg/kg, whereas chromium (Cr) is typically present in the range of 0.1-1 mg/kg. These standard reference values were used as baseline thresholds to assess metal accumulation and environmental contamination in foliar samples.

Data analysis and pollution indices

Quality assurance and quality control (QA/QC): Strict quality assurance and quality control (QA/QC) procedures were followed throughout sampling, sample preparation and analysis to ensure data reliability. Field blanks and replicate samples were processed identically to evaluate contamination and analytical precision. The limits of detection (LOD) and limits of quantification (LOQ) were calculated as three times the standard deviation of blank samples. Only values exceeding the LOD and LOQ were considered for further analysis. Instrument calibration was performed using standard reference materials and recovery studies were conducted to verify analytical accuracy, with recoveries maintained within acceptable limits ($100 \pm 15\%$).

Enrichment factor (EF): The EF was calculated to assess the degree of anthropogenic influence on metal concentrations in the samples. Iron (Fe) was used as reference element due to its natural abundance and relatively stable geochemical behaviour. The EF was computed using following equation:

$$EF = \frac{(C_m/C_{Fe})_{\text{sample}}}{(C_m/C_{Fe})_{\text{background}}} \quad (10)$$

where C_m represents the concentration of the target metal in sample, C_{Fe} is the concentration of Fe in sample and the denominator represents their respective background concentrations.

The EF classification proposed by Sutherland [50] was used to interpret the results: $EF < 2$ indicates minimal enrichment, 2-5 moderate enrichment, 5-20 significant enrichment, 20-40 very high enrichment and $EF > 40$ extremely high enrichment.

Geoaccumulation index (I_{geo}): The geoaccumulation index (I_{geo}), originally proposed by Müller [51], was applied to evaluate the contamination level of heavy metals by comparing present concentrations with pre-industrial background values. The I_{geo} was calculated as:

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n} \right) \quad (11)$$

where C_n is the measured concentration of metal in sample and B_n is the geochemical background concentration of element. The factor 1.5 accounts for possible variations in background values due to lithogenic effects.

The I_{geo} scale consists of seven classes ranging from unpolluted ($I_{geo} \leq 0$) to extremely polluted ($I_{geo} > 5$).

Contamination factor (CF): The CF, introduced by Hakanson [52], was used to determine the level of contamination of individual metals. It is defined as:

$$CF = \frac{C_{\text{metal}}}{C_{\text{background}}} \quad (12)$$

where C_{metal} is the concentration of metal in sample and $C_{\text{background}}$ is its background concentration.

Based on CF values, the contamination levels are classified as: $CF < 1$ (low contamination), 1-3 (moderate contamination), 3-6 (considerable contamination) and > 6 (very high contamination).

Ecological risk assessment: The potential ecological risk index (RI), proposed by Hakanson [52], was used to evaluate the ecological risk posed by heavy metals. The CF was used to calculate the ecological risk factor (E_r^i) for each metal:

$$E_r^i = T_r^i \times CF \quad (13)$$

$$RI = \sum E_r^i \quad (14)$$

where T_r^i is the toxic response factor of metal. Standard toxic response factors were adopted from previous studies (*e.g.*, Cd = 30, Pb = 5, Cu = 5, Zn = 1, Cr = 2, Fe = 1, Hg = 40). The ecological risk levels were classified as: low risk ($RI < 150$), moderate risk (150-300), considerable risk (300-600) and very high risk ($RI > 600$).

Statistical analysis: Statistical analyses were performed using Microsoft Excel 2007. The impact of variations in independent variables, *viz.* RWC, pH, TCC and AA, on dependent variable APTI was assessed through linear regression (R^2) analysis. Pearson's correlation coefficient (r) was computed to determine the strength of relationship among variables. OriginPro and Python were used to generate graphical visualisations of seasonal and site-specific variations in data-

sets. Principal component analysis (PCA), a multivariate statistical method, was applied to identify possible sources of trace elements in plant leaves and foliar dust.

RESULTS AND DISCUSSION

Relative water content (RWC) is an important physiological parameter reflecting the balance between water uptake and water loss in plants and is widely considered an indicator of plant tolerance under environmental stress conditions [53-55]. In the present study, RWC exhibited considerable seasonal and species-wise variation (Table-1). RWC values ranged from 41.21% to 90.94% during S1, decreased to 25.03-69.93% during S2, recovered to 42.56-83.87% during S3, and varied between 50.03% and 85.10% during S4. The highest RWC was observed in PS9 (90.94%), whereas the lowest value was recorded in PS5 (25.03%). The comparatively higher RWC observed in tolerant species suggests a greater capacity to maintain cellular hydration and physiological stability under polluted environmental conditions. Maintenance of higher water content is known to support metabolic activity, stomatal regulation and pollutant dilution within plant tissues, thereby enhancing tolerance against atmospheric stress [53-55]. In contrast, reduced RWC may indicate increased membrane permeability and impaired water balance caused by air pollutants, which can limit nutrient transport and accelerate senescence processes [56].

Seasonal reductions in RWC during S2 may be associated with changes in atmospheric conditions and rainfall mediated alterations in pollutant dynamics, while the recovery observed during S3 and S4 indicates adaptive physiological adjustment in certain species. Species exhibiting consistently higher RWC values across polluted sites demonstrated improved adaptability to urban pollution stress, supporting their potential suitability for urban plantation and greenbelt development.

pH of leaf extract: Leaf extract pH is an important biochemical parameter associated with enzymatic activity, metabolic regulation, and plant tolerance to air pollution [55,57]. In the present study, leaf pH ranged from 4.32 to 9.08 during S1, 3.14 to 8.19 during S2, 4.69 to 8.43 during S3 and 4.37 to 8.52 during S4 (Table-1). The highest pH was recorded in PS7 (9.08), while the lowest was observed in PS12 (3.14).

Higher or alkaline leaf pH in tolerant species indicates better pollutant neutralization capacity, enhanced enzymatic activity and increased ascorbic acid synthesis, thereby contributing to higher APTI values [56-59]. In contrast, acidic pH in sensitive species may result from the absorption of gaseous pollutants such as CO_2 , NO_x and SO_2 , which form acidic compounds within leaf tissues and adversely affect enzymatic and photosynthetic processes [58]. The comparatively higher pH values observed at polluted sites suggest adaptive biochemical responses under atmospheric stress conditions.

Total chlorophyll content (TCC): Total chlorophyll content (TCC) is an important indicator of photosynthetic efficiency and plant tolerance under polluted conditions [55]. In the present study, TCC varied considerably across seasons and species (Table-1). TCC ranged from 0.06 to 1.13 mg/g FW during S1, 0.08 to 1.36 mg/g FW during S2, 0.16 to 1.72 mg/g FW during S3, and 0.27 to 1.70 mg/g FW during S4.

TABLE-1
AIR POLLUTION TOLERANCE INDEX (APTI) OF PERENNIAL PLANT LEAVES IN FOUR SITES OF RAJASTHAN RECORDED IN FOUR SEASONS

Sites	RWC (%)				pH				TCC (mg/g)				AAC (mg/g)				APTI				
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	
PS1	MS	83.89	38.29	70.06	52.80	6.96	6.52	7.19	8.21	0.80	0.23	1.23	1.48	15.44	10.32	16.05	25.63	20.37	10.80	20.51	27.56
	CP	53.04	31.63	57.37	78.59	7.43	5.43	5.76	7.77	0.26	0.26	0.85	0.72	12.84	9.77	17.35	21.77	15.18	8.72	17.21	26.33
	AG	71.58	55.78	63.91	71.20	6.57	4.38	6.65	7.07	0.50	0.45	1.10	0.99	20.14	10.74	16.05	15.07	21.39	10.77	18.82	19.26
	BT	46.21	29.39	42.98	50.03	6.23	5.18	6.18	6.40	0.24	0.16	0.34	0.31	16.65	10.88	19.95	16.14	15.39	8.75	17.31	15.84
PS2	MS	76.38	53.94	71.63	60.96	7.99	6.57	7.78	7.81	0.68	0.20	1.72	1.42	19.16	17.91	22.23	20.14	24.26	17.52	26.06	22.68
	CP	54.55	47.09	83.60	83.27	7.67	4.38	7.27	7.61	0.34	0.80	1.11	0.46	23.12	10.70	18.42	19.16	23.97	10.25	23.80	23.80
	AG	66.26	25.60	69.78	64.33	7.18	3.28	7.19	6.95	0.74	0.51	0.80	0.79	20.37	10.32	18.56	18.51	22.77	8.54	21.81	20.77
	BT	51.98	30.73	55.64	60.20	6.88	5.11	6.37	6.68	0.31	0.23	0.27	0.39	19.58	12.42	21.77	11.86	19.27	9.70	20.01	14.40
PS3	MS	74.95	49.49	70.77	83.04	7.17	6.21	7.92	7.22	0.72	0.19	1.31	1.70	15.44	9.39	17.49	18.19	19.68	10.96	23.21	24.54
	CP	60.88	44.08	64.96	63.28	7.15	5.79	7.43	6.25	0.32	0.37	0.50	0.47	14.98	9.21	18.56	18.37	17.27	10.08	19.10	18.68
	AG	74.64	49.69	68.57	64.28	7.82	4.19	7.25	6.74	0.36	0.19	0.89	0.85	18.46	13.35	14.98	14.98	22.57	10.82	19.05	17.79
	BT	54.28	38.92	47.16	53.31	7.25	5.28	6.69	8.01	0.23	0.16	0.34	0.27	16.05	9.81	16.23	16.60	17.44	9.23	16.13	19.09
PS4	MS	80.99	62.63	78.62	64.45	7.48	7.91	8.43	7.83	0.55	0.36	0.25	1.41	19.44	18.51	20.65	27.53	23.70	21.58	25.79	29.13
	CP	53.89	32.33	76.66	77.49	6.28	5.85	6.86	6.74	0.59	1.05	1.07	0.67	17.67	12.46	21.30	22.23	17.53	11.84	24.57	24.22
	AG	69.55	55.20	64.23	77.71	7.12	5.67	6.25	6.57	0.70	1.02	0.88	0.84	24.74	16.93	20.37	23.16	26.31	16.85	20.96	24.94
	BT	41.21	48.52	51.21	60.04	7.07	6.15	7.25	7.89	0.41	0.34	0.47	0.37	23.81	13.44	20.32	19.30	21.94	13.58	20.82	20.02
PS5	MS	90.75	30.25	54.21	65.79	8.44	7.47	7.71	7.38	1.13	0.31	1.18	1.65	18.37	16.51	22.23	22.19	26.65	15.87	25.18	26.62
	CP	56.67	54.35	64.80	85.10	6.11	6.17	6.22	6.28	0.62	0.87	0.78	0.72	16.05	14.46	19.86	20.79	16.46	15.62	20.38	23.06
	AG	64.31	54.92	40.89	64.09	7.24	6.78	6.77	5.48	0.68	1.36	1.05	0.98	22.56	13.53	19.12	22.28	24.29	16.50	19.04	20.81
	BT	64.25	25.03	57.71	73.15	7.14	5.67	7.62	7.82	0.19	0.41	0.38	0.43	18.37	11.91	22.23	12.93	19.90	9.74	23.56	16.69
PS6	MS	71.39	62.48	75.68	70.94	7.06	6.97	6.18	8.05	0.44	0.08	1.52	1.26	12.51	10.65	11.12	18.56	16.53	13.85	16.13	24.37
	CP	56.56	25.64	81.09	77.71	7.21	5.47	5.66	5.69	0.18	1.11	0.43	0.19	10.23	10.93	16.51	10.14	13.22	8.66	18.16	13.74
	AG	56.74	48.92	79.45	74.65	7.05	5.18	7.64	7.43	0.16	0.26	0.39	0.80	14.93	11.02	10.98	18.32	16.44	10.89	16.76	22.55
	BT	34.36	26.70	46.60	56.95	6.78	3.51	6.59	7.11	0.23	0.09	0.27	0.33	10.56	10.37	14.79	18.37	10.84	6.40	14.81	19.36
PS7	MS	85.95	58.83	74.49	76.78	8.21	7.37	8.38	8.52	1.13	0.56	1.50	1.23	23.86	18.42	24.05	21.26	28.49	20.48	31.22	27.56
	CP	65.44	69.93	66.99	70.55	8.14	6.83	8.12	7.76	0.83	0.82	0.92	1.11	21.72	14.70	23.67	22.19	26.03	16.61	28.11	26.73
	AG	75.68	43.65	76.95	60.72	9.08	6.19	7.86	7.94	0.78	0.99	1.22	0.62	21.16	14.84	22.74	25.02	28.44	15.03	28.35	27.49
	BT	67.33	40.41	56.92	61.23	7.73	6.75	7.28	7.13	0.91	0.27	0.22	0.63	16.37	14.46	25.07	14.70	20.88	14.60	24.50	17.53
PS8	MS	83.87	68.07	70.71	75.11	8.67	8.19	8.18	8.32	1.11	0.60	1.61	1.69	24.56	19.44	25.72	23.02	29.96	23.90	32.25	29.80
	CP	68.34	57.52	73.16	79.14	7.58	6.97	7.39	8.28	0.99	1.01	1.02	1.25	23.21	16.42	26.60	23.81	26.73	18.86	29.68	28.23
	AG	76.37	46.37	83.87	84.90	8.34	6.78	7.96	7.89	0.89	1.22	1.43	0.94	23.67	17.53	23.77	25.63	29.48	18.67	30.72	29.08
	BT	69.36	53.83	59.60	72.64	7.34	6.82	7.86	7.06	0.40	0.21	0.41	0.64	18.37	16.60	27.72	16.51	21.16	17.06	27.78	20.97
PS9	MS	90.94	65.13	76.40	70.73	7.87	7.17	7.53	8.04	0.81	0.31	1.19	1.08	19.81	18.05	22.05	21.49	24.32	20.01	24.68	22.36
	CP	42.40	69.93	71.08	74.01	7.65	5.97	8.42	7.25	0.30	0.16	0.37	0.78	17.25	13.95	19.30	21.07	17.96	15.54	20.98	24.33
	AG	89.01	53.83	62.61	67.92	7.17	6.29	7.30	6.95	0.61	0.47	0.31	0.51	15.30	11.67	17.63	19.72	20.81	13.27	19.68	21.51
	BT	61.53	33.82	52.53	62.09	6.56	6.19	6.29	7.13	0.37	0.23	0.45	0.91	15.30	17.49	22.28	19.21	16.76	14.60	20.27	19.73
PS10	MS	72.64	48.10	58.63	60.28	7.27	6.32	7.59	5.18	0.83	0.23	1.30	1.08	16.70	16.05	21.72	22.23	20.79	15.31	25.18	19.95
	CP	59.37	43.73	52.77	66.12	6.19	6.26	7.37	6.18	0.21	0.34	0.34	0.30	19.16	12.88	18.23	19.39	18.20	12.87	19.33	19.19
	AG	76.69	58.46	80.17	69.27	5.38	6.29	6.33	6.18	0.38	0.70	1.11	0.66	19.44	9.81	18.37	20.37	18.87	12.70	21.68	20.85
	BT	47.87	49.63	57.57	51.23	6.57	5.24	6.69	7.19	0.25	0.30	0.40	0.82	18.51	11.02	19.16	15.02	17.42	11.07	19.34	17.15
PS11	MS	60.13	56.02	70.33	56.62	7.77	5.57	6.06	6.35	0.73	0.13	0.70	1.32	11.67	9.16	16.05	15.30	15.93	10.82	17.88	17.39
	CP	66.32	63.36	76.91	71.30	5.92	4.75	4.70	5.91	0.13	0.38	0.25	0.35	14.37	9.21	19.39	21.63	15.33	11.06	17.28	20.66
	AG	50.21	48.45	61.47	71.53	5.23	4.32	4.69	4.98	0.27	0.19	0.31	0.48	14.46	10.32	20.37	21.25	12.98	9.51	16.33	18.77
	BT	52.89	38.59	42.56	60.22	4.32	3.47	5.25	4.37	0.06	0.22	0.16	0.63	10.09	9.16	17.63	7.39	9.71	7.24	13.80	9.72
PS12	MS	77.38	56.61	60.60	59.98	7.11	6.16	6.18	5.58	0.61	0.27	1.09	0.99	13.12	8.60	11.39	14.93	17.87	11.19	14.35	15.81
	CP	55.53	58.83	67.78	58.18	7.45	3.14	5.43	5.29	0.19	0.20	0.35	0.28	9.25	10.65	11.07	19.30	12.63	9.44	13.17	16.58
	AG	55.78	31.21	61.04	70.13	6.23	5.44	5.29	5.48	0.38	0.29	0.80	0.41	11.21	13.39	20.14	18.65	12.99	10.79	18.37	17.99
	BT	42.15	36.56	45.43	52.06	6.17	4.28	6.78	7.15	0.17	0.42	0.27	0.31	12.60	11.30	20.23	10.28	12.21	8.97	18.81	11.85

S1 = Pre-monsoon; S2 = Monsoon; S3 = Post-monsoon; S4 = Winter; MS = Mansarovar; CP = Chandpole; AG = Ajmeri gate; BT = Banashali; RWC = Relative water content; TCC = Total chlorophyll content; AAC = Ascorbic acid content; PS1 = *Alstonia scholaris*; PS2 = *Azadirachta indica*; PS3 = *Bougainvillea spectabilis*; PS4 = *Cassia fistula*; PS5 = *Cordia dichotoma*; PS6 = *Dalbergia sissoo*; PS7 = *Ficus benghalensis*; PS8 = *Ficus religiosa*; PS9 = *Polyalthia longifolia*; PS10 = *Pongamia pinnata*; PS11 = *Senna siamea*; PS12 = *Vachellia nilotica*; ≤12 = Sensitive; 13-16 = Intermediate; 17-20 = Moderately Tolerant; > 20 = Tolerant [11].

The highest TCC was observed in PS2 (1.72 mg/g FW), whereas the lowest value was recorded in PS11 (0.06 mg/g FW).

Species maintaining higher TCC under polluted conditions are considered more tolerant due to their ability to sustain photosynthetic activity, biomass production and growth [55]. Variations in TCC are influenced by species characteristics, leaf maturity, pollution intensity and environmental conditions such as temperature, light intensity and drought [30,54,60]. Elevated concentrations of PM, NO_x and SO_x can enter leaf tissues through stomata and induce chlorophyll degradation by replacing Mg²⁺ ions in chlorophyll molecules, leading to pheophytin formation and increased chlorophyllase activity [22,42,54]. Consequently, sensitive species exhibited lower TCC values, indicating greater damage to the photosynthetic apparatus under pollution stress.

Ascorbic acid content (AAC): In the present study, AAC varied significantly among seasons and species (Table-1). AAC ranged from 9.25 to 24.74 mg/g FW during S1, 8.60 to 19.44 mg/g FW during S2, 11.07 to 27.72 mg/g FW during S3, and 7.39 to 27.53 mg/g FW during S4. The highest AAC was recorded in PS8 (27.72 mg/g FW), whereas the lowest value was observed in PS11 (7.39 mg/g FW). Species exhibiting higher AAC under polluted conditions were comparatively more tolerant, indicating the protective role of ascorbic acid against atmospheric stress [54,61,62]. AAC functions as a low molecular weight antioxidant that protects cellular membranes, maintains metabolic activity, and scavenges reactive oxygen species (ROS) generated under pollution stress [12,63]. Increased levels of pollutants and associated abiotic stress conditions enhance ROS production, thereby stimulating AAC synthesis as part of the antioxidant defence mechanism [64]. Consequently, tolerant species maintained higher AAC levels,

whereas sensitive species showed comparatively lower antioxidant capacity under polluted environments.

Air pollution tolerance index (APTI)

Interpretation of APTI: The air pollution tolerance index (APTI) integrates important biochemical parameters including RWC, leaf pH, TCC and AAC to evaluate plant tolerance or sensitivity toward atmospheric pollution stress [11]. Based on the classification proposed by Singh *et al.* [11], the investigated species were categorized as tolerant (APTI > 20), intermediate to moderately tolerant (APTI 13-20) and sensitive (APTI ≤ 12). Distinct seasonal and site-wise variations in APTI were observed among the studied plant species (Fig. 2).

Species-wise, PS8, PS7, PS4 and PS2 consistently recorded higher APTI values across most seasons and polluted sites indicating greater tolerance to air pollution stress [10,22,57,62,65,66]. Their elevated tolerance may be associated with higher AAC, stable chlorophyll content, alkaline leaf pH and improved water retention capacity under polluted conditions. These species maintained relatively high APTI values particularly during S1 and S3, corresponding to elevated vehicular movement, industrial activity and dust deposition. Therefore, these species may be considered suitable candidates for plantation in urban-industrial regions and high-traffic corridors. In contrast, PS1, PS3, PS5, PS9 and PS10 exhibited intermediate to moderate tolerance with noticeable seasonal fluctuations, whereas PS6, PS11 and PS12 consistently showed lower APTI values, indicating higher sensitivity to pollution stress. The comparatively lower biochemical stability in these sensitive species supports their potential use as bioindicators of environmental pollution [11,22,44,57,67].

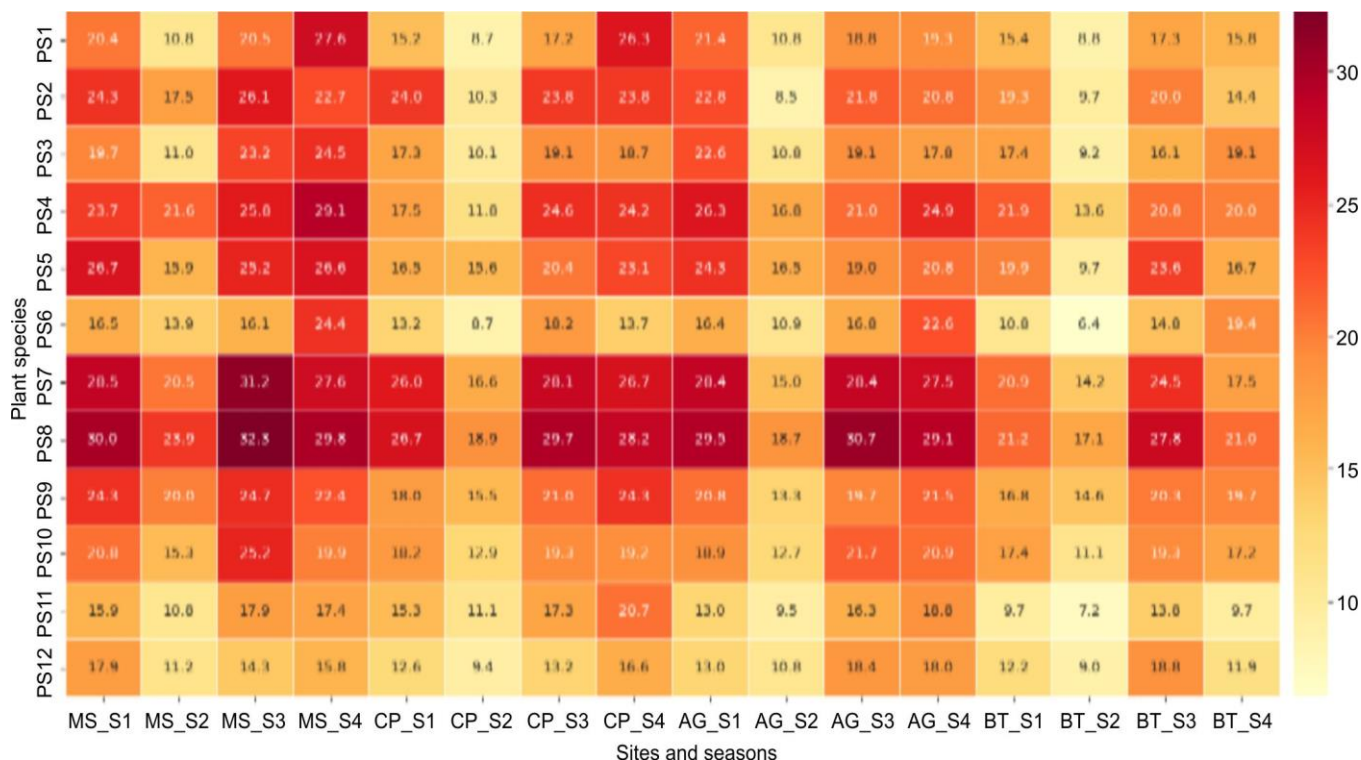


Fig. 2. Heatmap of spatio-temporal variations in APTI of plants in four seasons and sites

Seasonally, higher APTI values during S1 and S3 were associated with increased dust load, vehicular emissions and industrial activities, which stimulated adaptive biochemical responses in tolerant species. Moderate to high APTI values observed during S4 may be attributed to atmospheric inversion conditions favouring pollutant accumulation within plant tissues, particularly in PS7 and PS8. Conversely, reduced APTI values during S2 likely resulted from rainfall-induced pollutant washout, temporarily lowering atmospheric pollution stress across sites (Fig. 2). Site-wise, plants growing at MS and AG recorded comparatively higher APTI values than those at CP and BT indicating that prolonged exposure to polluted environments promotes physiological acclimatization and selection of tolerant species [68,69]. Lower APTI values at BT reflected comparatively lower pollution pressure at the rural control site.

Statistical analysis

Linear regression: relationship between biochemical parameters and APTI: Linear regression analysis presented positive effect of RWC ($R^2 = 0.440$, $R^2 = 0.367$, $R^2 = 0.165$ and $R^2 = 0.249$), pH ($R^2 = 0.532$, $R^2 = 0.687$, $R^2 = 0.549$ and $R^2 = 0.422$), TCC ($R^2 = 0.614$, $R^2 = 0.178$, $R^2 = 0.248$ and $R^2 = 0.377$) and AAC ($R^2 = 0.777$, $R^2 = 0.784$, $R^2 = 0.645$ and $R^2 = 0.766$) on APTI in S1, S2, S3 and S4 (Fig. 3a-p).

Pearson’s correlation coefficient: Pearson’s correlation coefficient (r) analysis (Table-2) demonstrated significant inter-relationships among biochemical parameters, gaseous pollutants and APTI values. Significant positive correlations ($p < 0.05$) were observed between leaf pH and RWC, as well as between RWC and TCC, indicating improved water balance and chlorophyll stability under polluted conditions. A strong positive

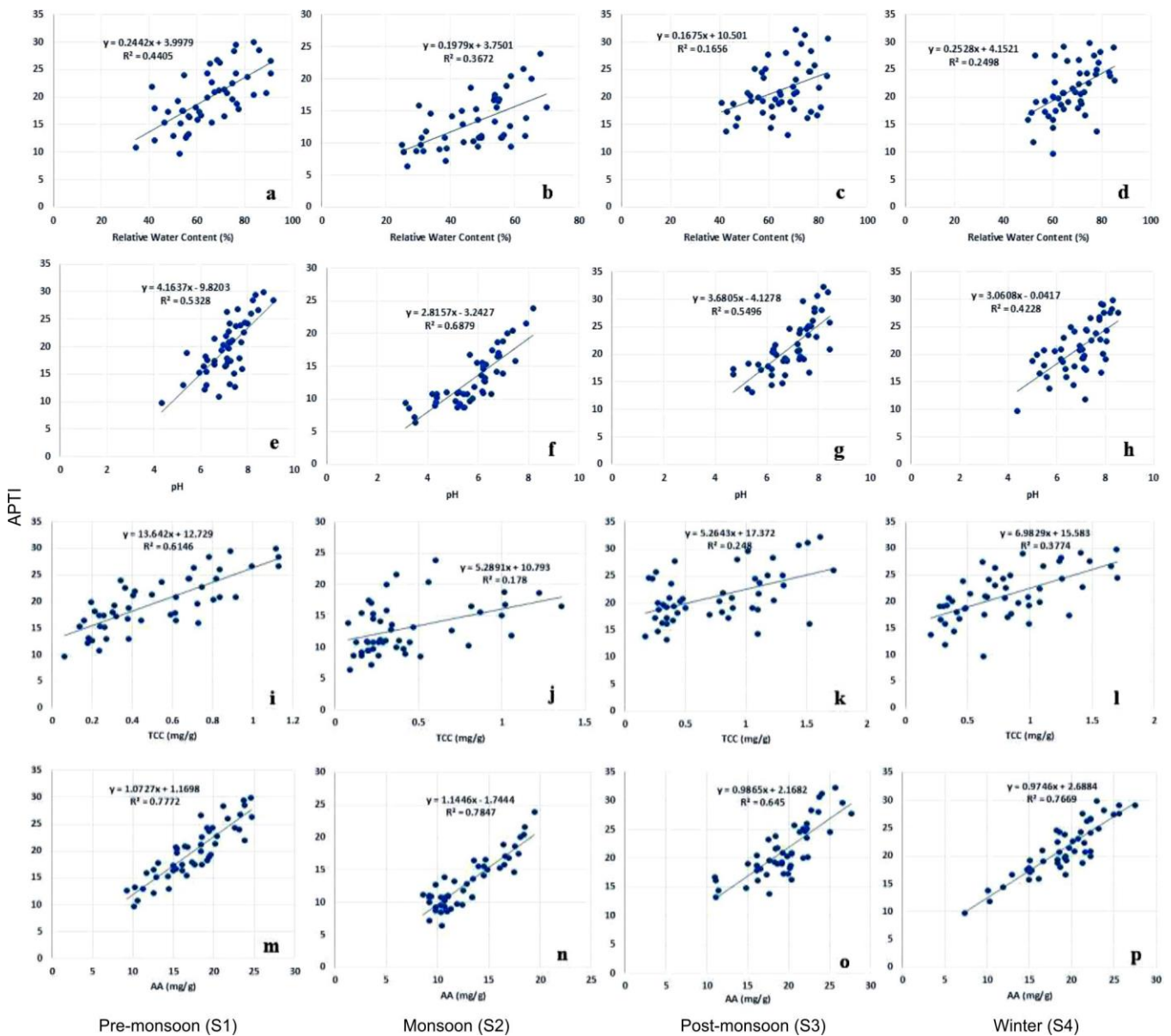


Fig. 3. Linear regression analysis of individual variables (biochemical parameters) with APTI values. a, b, c, d RWC (%) vs. APTI for S1, S2, S3, S4. e, f, g, h pH vs. APTI for S1, S2, S3, S4. i, j, k, l TCC (mg/g) vs. APTI for S1, S2, S3, S4. m, n, o, p AAC (mg/g) vs. APTI for S1, S2, S3, S4

TABLE-2
PEARSON'S CORRELATION COEFFICIENT (r) MATRICES AMONG BIOCHEMICAL PARAMETERS

Plants	Pearson correlation in S1 season				Pearson correlation in S2 season				Pearson correlation in S3 season				Pearson correlation in S4 season						
	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
PS1	pH	0.175			pH	-0.506			pH	0.680			pH	0.234					
	TCC	0.973	0.116		TCC	0.942	-0.619		TCC	0.996	0.642		TCC	-0.024	0.817				
	AA	0.279	-0.724	0.192	AA	0.326	-0.419	0.096	AA	-0.974	-0.566	-0.989	AA	-0.097	0.901	0.651			
	APTI	0.893	-0.137	0.810	0.669	APTI	0.790	0.104	0.597	0.246	APTI	0.831	0.964	0.792	-0.716	APTI	0.289	0.984	0.704
PS2	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.640			pH	0.737			pH	0.690			pH	0.409					
	TCC	0.885	0.323		TCC	0.018	-0.639		TCC	0.637	0.971		TCC	-0.418	0.614				
	AA	-0.502	0.157	-0.436	AA	0.680	0.935	-0.698	AA	-0.616	-0.062	0.118	AA	0.381	0.826	0.636			
PS3	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.640			pH	-0.119			pH	0.883			pH	-0.236					
	TCC	0.885	0.323		TCC	-0.022	0.304		TCC	0.798	0.841		TCC	0.972	-0.074				
	AA	-0.502	0.157	-0.436	AA	0.462	-0.932	-0.345	AA	0.152	0.462	-0.042	AA	0.423	-0.182	0.243			
PS4	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.543			pH	0.635			pH	0.367			pH	-0.982					
	TCC	0.581	-0.112		TCC	-0.542	-0.691		TCC	0.105	-0.836		TCC	0.017	0.130				
	AA	-0.179	0.448	0.036	AA	0.921	0.644	-0.262	AA	0.710	0.022	0.526	AA	0.077	0.075	0.996			
PS5	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.948			pH	0.062			pH	-0.144			pH	0.039					
	TCC	0.748	0.599		TCC	0.892	-0.013		TCC	-0.482	-0.059		TCC	-0.552	-0.024				
	AA	0.075	0.340	0.059	AA	0.067	0.865	-0.224	AA	0.359	0.871	-0.276	AA	-0.229	-0.666	0.725			
PS6	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.727			pH	0.763			pH	-0.061			pH	-0.312					
	TCC	0.540	-0.068		TCC	0.165	-0.097		TCC	0.312	-0.286		TCC	0.150	0.870				
	AA	0.409	0.101	-0.026	AA	0.159	0.406	0.688	AA	-0.252	-0.652	-0.536	AA	-0.553	0.928	0.631			
PS7	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.339			pH	0.760			pH	0.737			pH	0.738					
	TCC	0.707	-0.422		TCC	0.154	-0.524		TCC	0.944	0.900		TCC	0.985	0.679				
	AA	0.663	0.442	0.366	AA	0.770	0.770	-0.138	AA	-0.849	-0.484	-0.677	AA	0.177	0.660	0.212			
PS8	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.953			pH	0.906			pH	0.022			pH	0.388					
	TCC	0.588	0.725		TCC	-0.395	-0.221		TCC	0.739	0.444		TCC	-0.020	0.882				
	AA	0.638	0.805	0.975	AA	0.624	0.895	-0.039	AA	-0.937	-0.358	-0.793	AA	0.839	0.818	0.524			
PS9	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.148			pH	0.234			pH	0.796			pH	0.361					
	TCC	0.928	0.458		TCC	-0.098	0.306		TCC	-0.834	-0.406		TCC	0.002	0.829				
	AA	0.229	0.852	0.574	AA	-0.236	0.552	-0.462	AA	-0.064	-0.461	0.022	AA	0.863	0.779	0.466			
PS10	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	-0.231			pH	0.051			pH	-0.756			pH	-0.470					
	TCC	0.600	0.614		TCC	0.842	0.271		TCC	0.554	0.051		TCC	-0.499	-0.326				
	AA	-0.141	-0.917	-0.873	AA	-0.622	0.370	-0.759	AA	-0.247	0.597	0.623	AA	0.676	-0.963	0.177			
PS11	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.539			pH	0.777			pH	-0.032			pH	-0.125					
	TCC	0.151	0.910		TCC	0.462	-0.192		TCC	0.468	0.793		TCC	-0.855	0.494				
	AA	0.239	0.110	-0.074	AA	-0.171	-0.153	-0.179	AA	0.109	-0.962	-0.632	AA	0.764	0.495	-0.338			
PS12	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC	RWC	pH	TCC	AAC			
	pH	0.557			pH	-0.206			pH	-0.857			pH	-0.675					
	TCC	0.920	0.188		TCC	-0.660	0.124		TCC	0.310	-0.188		TCC	0.123	-0.256				
	AA	0.266	-0.446	0.539	AA	-0.825	-0.166	0.211	AA	-0.682	0.209	-0.256	AA	0.710	-0.932	-0.102			
APTI	0.940	0.392	0.933	0.558	APTI	0.080	0.854	-0.401	-0.170	APTI	-0.755	0.319	-0.170	0.987	APTI	0.881	-0.938	0.140	0.939

correlation between AAC and APTI ($r > 0.85$; $p < 0.05$) was consistently observed across seasons, whereas TCC also showed a significant positive relationship with APTI. In contrast, AAC exhibited a negative correlation with TCC under pollution stress. Among gaseous pollutants, SO_2 significantly influenced AAC and TCC, while NO_2 affected leaf pH and chlorophyll stability.

Metal concentration (mg/kg): Foliar dust analysis revealed substantial accumulation of particulate-bound heavy metals (HMs) on leaf surfaces across all studied species, sites,

and seasons, indicating the combined influence of vehicular emissions, soil resuspension and localized industrial activities (Fig. 4). The concentration of metals in foliar dust followed the order: $\text{Fe} > \text{Hg} > \text{Zn} > \text{Pb} > \text{Cu} > \text{Cr} > \text{Cd}$. Among the analyzed metals, Fe exhibited the highest concentration, reaching up to 1460 mg/kg, particularly in PS8, whereas As, Cd, and Cr were either absent or detected only at trace levels in selected samples from MS. Metal accumulation was considerably higher at industrial and high-traffic locations (MS

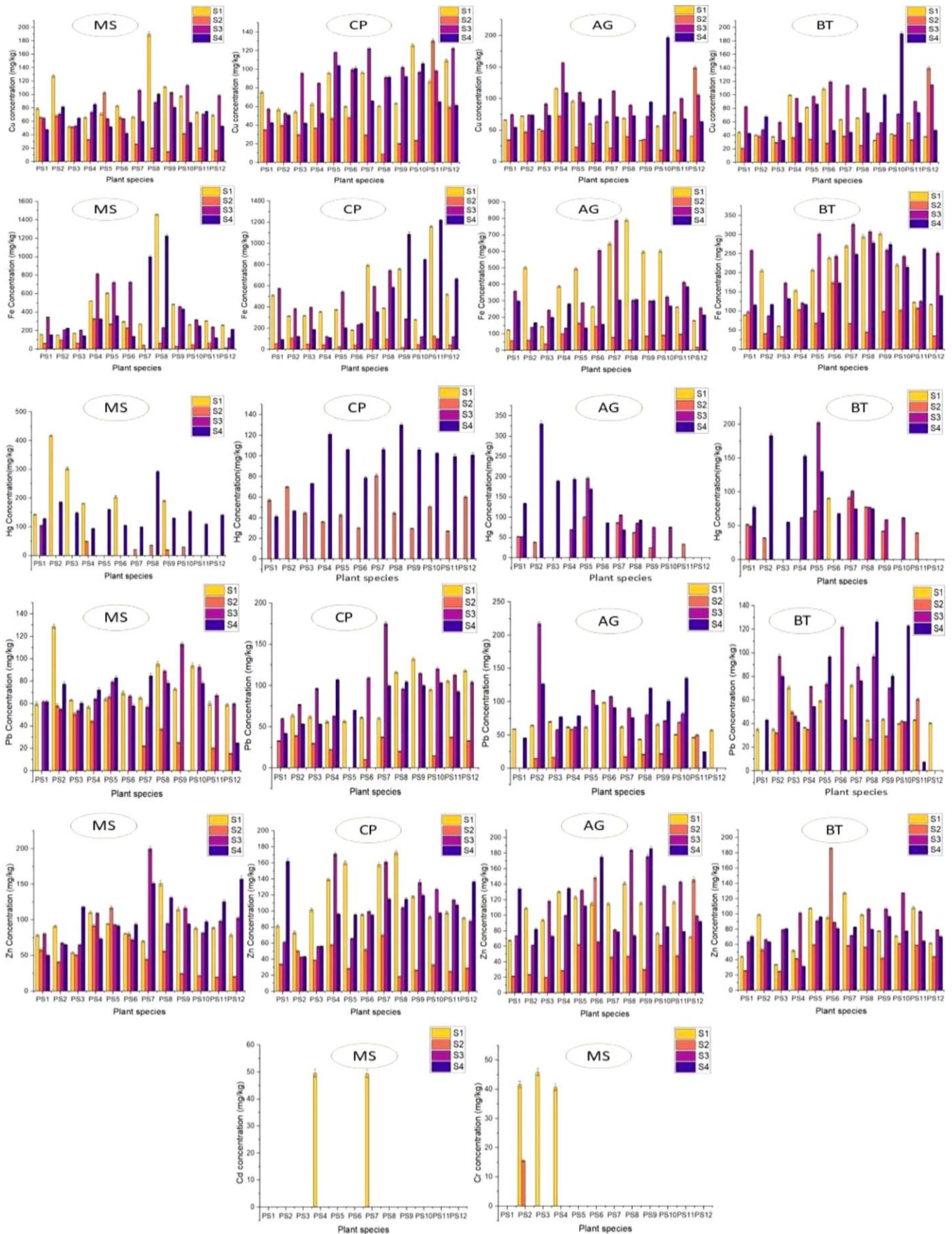


Fig. 4. Metal contents (mg/kg) association with airborne dust deposited on foliage samples

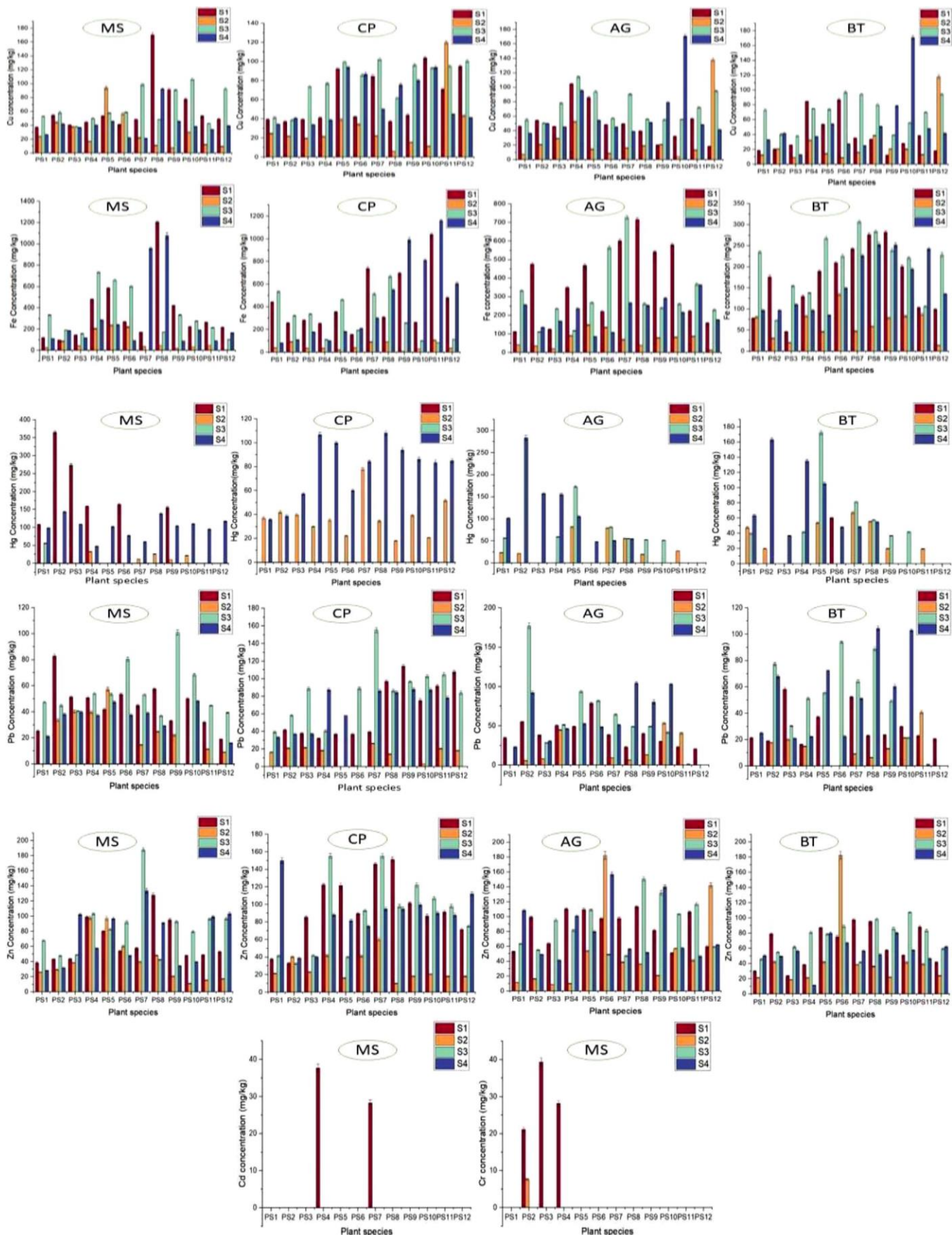


Fig. 5. Graphical representation of metal concentration (mg/kg) of perennial plants in four sites and seasons

and AG) compared with commercial-residential (CP) and rural (BT) sites. Vehicular-related metals such as Pb, Zn, Cu and Cd showed comparatively higher accumulation in traffic-intensive areas, while Cr, As and Hg displayed localized enrichment associated with industrial activities and combustion processes. Similarly, perennial plant tissues also exhibited source-dependent metal accumulation patterns (Fig. 5). Iron (Fe) remained the dominant metal in plant tissues across all sites and seasons, followed by Pb, Cu, Hg, Zn, Cr, Cd and As. The measured metal concentrations in several samples exceeded the WHO permissible limits [70].

The observed distribution patterns suggest that atmospheric deposition is the principal pathway of metal accumulation in roadside vegetation [15,16,20,21,46]. The elevated Fe content in foliar dust was mainly associated with resuspension of arid soil particles and road dust, which is characteristic of Rajasthan's semi-arid climatic conditions. Frequent vehicular movement, sparse vegetation cover and dry environmental conditions likely enhanced the redistribution and deposition of crustal particulates on leaf surfaces. Higher concentrations of Pb, Zn, Cu and Cd at traffic-dominated sites indicate contributions from exhaust emissions, brake and tire wear, lubricating oil residues, fuel combustion and other transportation-related activities [15,71,72]. In contrast, enrichment of Hg, Cr and As suggests additional inputs from industrial emissions, coal combustion, construction activities, and high-temperature processes [73-75]. The higher metal concentrations observed in foliar dust compared with plant tissues further support foliar deposition as the dominant mechanism of accumulation rather than root uptake [21,76,77]. In addition, the morphological characteristics such as trichomes, stomata and leaf surface texture may enhance particulate retention and facilitate metal uptake through foliar pathways [15,76,78]. The strong association between metal concentrations in foliar dust and leaf tissues indicates that deposited airborne particles substantially contribute to internal metal accumulation in plants, while the absence of correlation with roots and soils further emphasizes the significance of atmospheric deposition. These findings demonstrate the effectiveness of perennial roadside plant species as passive biomonitors for assessing spatial and seasonal variations in urban metal pollution [4,20,45,46,79-81].

Data analysis and pollution indices

Quality assurance (QA) and quality control (QC) validation and inclusion of limits of detection (LOD), limits of quantification (LOQ) and recovery data: QA and QC were maintained through replicate analysis, calibration with standard solutions and recovery studies. The QA and QC analysis demonstrated high analytical reliability, with %RSD values below 5% for all detected metals indicating high analytical precision. The calculated LOD and LOQ values demonstrated adequate sensitivity of the analytical method and were found to be within acceptable limits for trace metal analysis. The recovery ranged between 90-110%, ensuring good analytical accuracy.

Comparison with standard plant values: The concentrations of metals in foliar dust were compared with standard plant reference ranges to assess the extent of atmospheric

contamination. Cu, Pb, Cd and Cr concentrations exceeded normal physiological limits indicating substantial anthropogenic contributions and increasing environmental stress. Zinc showed moderate to high accumulation, whereas Hg exhibited markedly elevated levels, reflecting severe atmospheric deposition on leaf surfaces. Iron concentrations were also higher than typical plant requirements at several sites, suggesting enhanced atmospheric deposition rather than natural uptake. These findings demonstrate abnormal metal accumulation compared with standard physiological ranges reported in the literature [48,49] and highlight the suitability of plant leaves as effective bioindicators of atmospheric metal pollution (Table-3).

TABLE-3
COMPARISON OF METAL CONCENTRATIONS IN FOLIAR DUST WITH STANDARD PLANT RANGES

Metal	Observed range (mg/kg)	Normal plant range (mg/kg)	Contamination status
Cu	25-190	5-20	Highly elevated
Pb	20-130	1-10	Severely contaminated
Zn	20-200	20-100	Moderately to highly elevated
Hg	0-400	< 0.1	Extremely high contamination
Cd	0.00-40	0.1-2	Highly toxic/elevated
Cr	0.00-40	0.1-1	Moderately to highly elevated
Fe	5-1200	50-250	Elevated

Enrichment factor (EF): The EF values (> 40) revealed extremely high enrichment for all metals *i.e.*, Cu, Zn, Pb, Hg, Cr and Cd exhibited extremely high enrichment, suggesting dominant anthropogenic sources such as vehicular emissions and industrial activities. These results suggested that vehicular emissions, industrial activities, resuspended road dust, urban activities and atmospheric deposition are the primary and major sources of metal accumulation. Iron (Fe) showed validating its use as a reference element in EF calculations (Table-4).

TABLE-4
ENRICHMENT FACTOR (EF) VALUES

Metal	EF Range	Interpretation
Cu	2-15	Moderate to significant enrichment
Pb	5-25	Significant enrichment
Zn	5-25	Significant enrichment
Hg	20-200	Very high enrichment
Cd	10-100	Very high to extremely high enrichment
Cr	5-30	Moderate to significant enrichment

Geoaccumulation index (I_{geo}): The I_{geo} indicated moderate to heavy pollution levels for most metals, particularly for Hg, showed the highest pollution contamination, Pb, Cd, Cu were moderate to heavy pollution contamination, highlighting increasing environmental stress and Zn, Cr were low to moderate pollution contamination. The CF analysis revealed moderate to considerable moderate to high contamination for metals posing higher ecological risks. These findings highlight the impact of atmospheric deposition on plant systems and reinforce their role of plants as effective bioindicators of urban metal pollution (Table-5).

TABLE-5
GEOACCUMULATION INDEX (I_{geo}) VALUES

Metal	I_{geo} range	Pollution level
Cu	1-3	Moderate to heavy
Pb	1-3	Moderate to heavy
Zn	0-2	Low to moderate
Hg	2-5	Heavy to extreme
Cd	1-4	Moderate to heavy
Cr	0-2	Low to moderate

Contamination factor (CF): The results revealed that Hg exhibited extremely high contamination factor (CF) values, indicating severe contamination and strong anthropogenic influence. Lead (Pb) showed moderate to very high contamination, whereas Cu ranged from moderate to considerable contamination levels. Zinc (Zn) exhibited moderate contamination, suggesting relatively lower ecological impact compared with other metals. Cadmium (Cd) displayed considerable to very high contamination, reflecting its high mobility and toxic nature, while Cr showed low to moderate contamination levels. The elevated CF values indicate that atmospheric deposition, vehicular emissions, industrial activities and resuspended road dust are the major contributors to metal accumulation in foliar dust. These findings further confirm the suitability of plant leaves as effective bioindicators of environmental pollution (Table-6).

TABLE-6
CONTAMINATION FACTOR (CF) VALUES

Metal	CF range	Contamination level
Cu	1-6	Moderate to considerable
Pb	2-8	Moderate to very high
Zn	1-4	Moderate
Hg	10-400	Very high
Cd	3-20	Considerable to very high
Cr	1-3	Low to moderate

Ecological risk assessment: The ecological risk index (RI) assessment of metals was evaluated using the Hakanson method, incorporating CF and toxic response factors (Tr). The calculated RI values across all sites, seasons and plant species indicated considerable to very high RI. Among the studied metals, Hg contributed the most significantly to the overall RI due to its very high toxic response factor ($Tr = 40$). Cd also showed a substantial contribution ($Tr = 30$), indicating high ecological risk. Pb and Cu contributed moderately toxic response factors ($Tr = 5$), while Cr ($Tr = 2$) showed relatively lower risk. Zn exhibited relatively lower ecological risk owing to its lower toxicity coefficient ($Tr = 1$). Fe was not included in RI calculations due to its negligible toxic response factor ($Tr \approx 0$) and natural origin. Higher RI values were consistently observed at high-traffic and polluted sites, suggesting strong anthropogenic influence, particularly from vehicular emissions, industrial activities and atmospheric deposition. Seasonal variation further indicated that S3 and S4 seasons showed relatively elevated risk levels, likely due to increased particulate accumulation and reduced dispersion conditions. The RI values across sampling locations were classified as low risk ($RI < 150$), moderate risk ($150 \leq RI < 300$), considerable risk ($300 \leq RI < 600$), and very high risk ($RI \geq 600$). Most sampling sites fell within the considerable to very high

RI categories, indicating that metal accumulation in foliar dust and plant leaves may pose significant ecological and biological risks. The elevated RI values highlight the importance of continuous monitoring and implementation of mitigation strategies to manage metal pollution in urban environments (Table-7).

TABLE-7
ECOLOGICAL RISK ASSESSMENT (RI) ACROSS SITES

Location	RI range	Risk level
MS	450	Considerable
CP	620	Very high
AG	380	Considerable
BT	700	Very high

Atmospheric deposition: The elevated metal concentrations in foliar dust indicate substantial atmospheric deposition processes. High EF, CF, I_{geo} and RI values suggest that vehicular emissions, industrial activities, and resuspended road dust are the major contributors to metal accumulation on leaf surfaces. Seasonal variation further supported this trend, with higher accumulation during S3 and S4, likely due to reduced atmospheric dispersion and enhanced particulate settling. The combined application of EF, CF, I_{geo} and RI provided a comprehensive evaluation of pollution sources, contamination intensity, and ecological risks associated with atmospheric metal deposition.

Metal accumulation index (MAI): The MAI was calculated to evaluate the metal accumulation efficiency of plant species under varying environmental conditions (Fig. 6) [28]. The obtained MAI values showed clear species-wise, seasonal and site-wise variations. Among the studied species, PS7 followed by PS8, PS2, PS4, PS1 and PS9 consistently exhibited higher MAI values across most seasons and sampling sites, particularly at urban and traffic-influenced locations (MS, AG and CP). In contrast, PS6, PS11 and PS12 recorded comparatively lower MAI values throughout the study period. Seasonally, MAI values were highest during S1, declined markedly during S2, increased again during S3 and remained moderate to high during S4. Site-wise analysis demonstrated the highest MAI values at MS, followed by AG and CP, whereas the rural site BT consistently exhibited lower MAI values, indicating relatively lower atmospheric metal loads and cleaner environmental conditions (Fig. 6).

The observed variations in MAI indicate the strong influence of urbanization, traffic intensity, industrial activities, and seasonal atmospheric conditions on metal deposition and accumulation in plant leaves [28-30]. Species exhibiting high MAI values along with elevated APTI values, particularly PS7, PS8, PS2 and PS4, demonstrated comparatively greater tolerance and higher accumulation potential under polluted conditions. Their rough leaf surfaces, larger canopy structure, and enhanced particulate interception capacity may contribute to greater retention of metal-associated airborne particles. In contrast, species with lower MAI values showed comparatively limited accumulation efficiency and may respond more sensitively to changes in ambient pollution levels, supporting their role as bioindicators of environmental quality [22,29,45,82]. The higher MAI values during S1 and S3 were likely

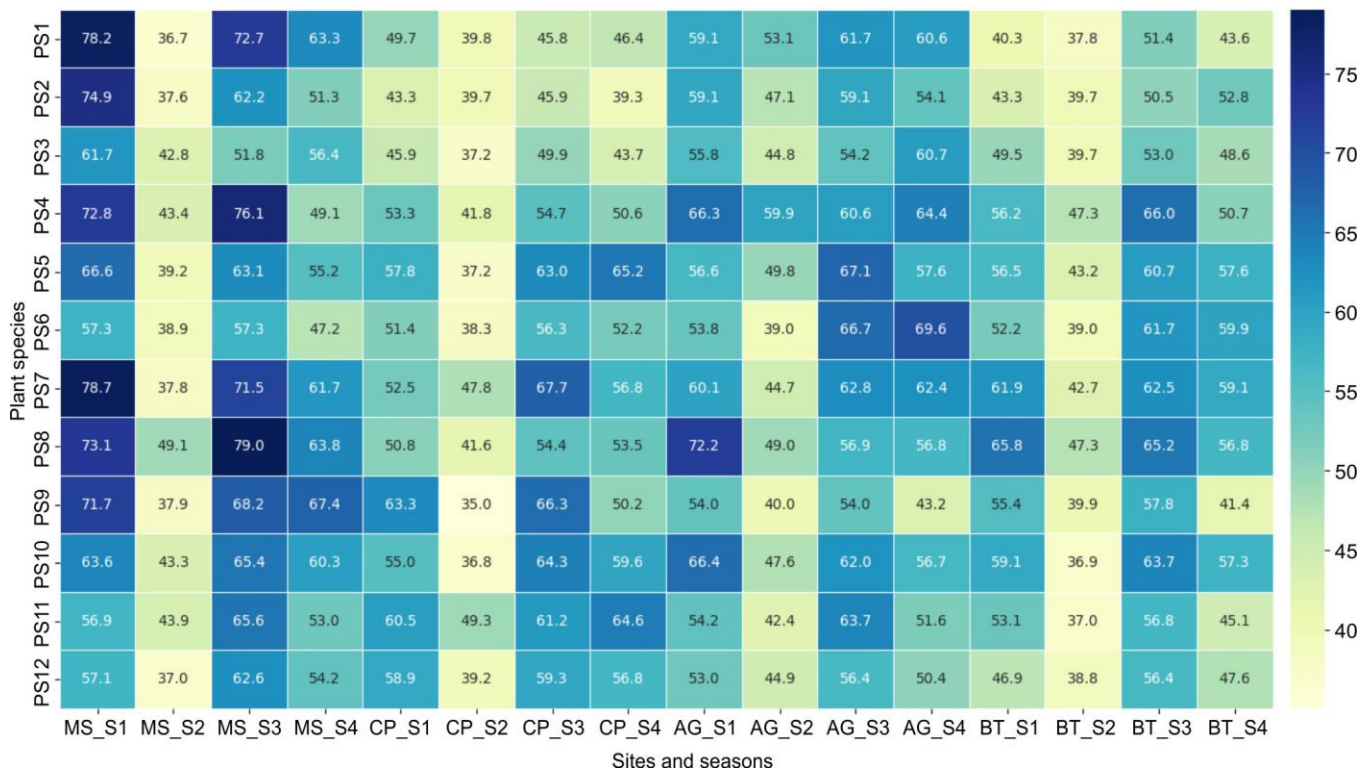


Fig. 6. Heatmap represents spatiotemporal variations of MAI in plants in four seasons and sites

associated with dry atmospheric conditions, increased dust resuspension, and enhanced particulate deposition, whereas the lower values during S2 reflected rainfall-induced wash-off and dilution effects. Moderate to high MAI values during S4 may be related to atmospheric stagnation, fog and smog conditions that promote pollutant trapping. These findings suggest that MAI effectively reflects relative metal accumulation behaviour of plant species under different environmental conditions; however, it should be interpreted cautiously, as it represents total accumulated metals and does not directly account for metal speciation, bioavailability or actual pollutant removal efficiency.

Principal component analysis (PCA): The results of PCA for foliar dust and plant tissues are presented in Tables 8 and 9, respectively. In both datasets, the first two principal components (PC1 and PC2) exhibited eigenvalues greater than unity and explained a substantial proportion of the total variance, generally ranging from approximately 40% to more than 60%, indicating that these components effectively represented the major variability in metal distribution patterns.

For foliar dust (Table-8), PC1 was predominantly associated with strong positive loadings of Cu, Fe, Zn and Pb across most sites and seasons. These metals are commonly linked with vehicular emissions, including brake and tyre wear, fuel combustion, lubricating oil residues and resuspended road dust, suggesting that traffic-related activities were the dominant contributors to atmospheric metal deposition in the study area [4,20,83-87]. Stronger associations during dry seasons further indicate the influence of enhanced dust resuspension and reduced atmospheric dispersion. PC2 showed relatively higher loadings of Hg, Cr, Pb and occasionally Zn, indicating additional contributions from industrial emissions, fossil fuel

combustion and regional atmospheric transport processes. The presence of Hg within this component suggests the influence of non-traffic-related anthropogenic sources.

Similarly, PCA results for plant tissues (Table-9) revealed that PC1 was mainly dominated by Cu, Fe, Zn and Pb, indicating that metal accumulation in plants closely reflected surrounding atmospheric conditions and deposition patterns. The similarity between foliar dust and plant tissue PCA groupings confirms that atmospheric deposition is the major pathway of metal accumulation in roadside vegetation. However, compared with foliar dust, metal associations in plant tissues showed slight variations, likely due to biological uptake, internal translocation, selective retention and physiological regulation mechanisms within plant systems. PC2 in plant tissues was characterised by relatively higher contributions of Hg, Pb and Fe, suggesting differential uptake behaviour and seasonal physiological responses under varying pollution stress conditions.

The strong association of metals within similar PCA groupings agrees with previous studies [4,20,83,87] reporting the dominant influence of vehicular and industrial emissions on urban metal variability. Metals such as Cu and Zn consistently exhibited strong loadings in both foliar dust and plant tissues, reflecting their higher mobility and easier uptake, whereas As, Cd, and Cr showed comparatively weaker or inconsistent loadings due to limited accumulation or concentrations near detection limits. Seasonal variations observed in PCA components further highlight the influence of meteorological conditions, emission intensity and plant physiological activity on metal distribution patterns. The PCA findings indicate that vehicular emissions, resuspended road dust and localized industrial activities are the principal contributors to atmospheric metal contamination in the study area. The close

TABLE-8
RESULTS OF PRINCIPAL COMPONENT ANALYSIS (PCA) FOR THE IDENTIFICATION OF METAL SOURCES IN FOLIAR DUST AROUND THE STUDY AREA DURING FOUR DIFFERENT SEASONS

	MS_S1		MS_S2		MS_S3		MS_S4		CP_S1		CP_S2		CP_S3		CP_S4	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Cu	0.54	0.20	0.50	-0.27	0.67	0.18	0.47	0.09	0.44	-0.51	0.18	0.68	0.48	0.33	0.45	0.01
Fe	0.51	-0.12	0.52	0.32	-0.40	0.58	0.59	0.08	0.60	-0.11	0.52	0.33	-0.33	0.91	0.49	0.23
Hg	-0.16	0.63	-0.06	0.62	0	0	0.55	-0.16	0	0	0.46	-0.46	0	0	0.57	-0.13
Pb	0.28	0.50	0.39	-0.15	0.28	0.77	0.24	-0.69	0.62	0.12	0.61	0.10	0.54	0.23	0.44	-0.45
Zn	0.53	-0.01	0.56	0.26	0.56	-0.19	0.24	0.69	0.25	0.84	0.32	-0.45	0.61	0.02	0.18	0.85
As	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	-0.15	-0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	-0.20	0.53	0.14	-0.58	0	0	0	0	0	0	0	0	0	0	0	0
Eigen values	2.98	2.06	2.70	1.55	1.90	1.30	2.20	1.24	1.49	1.02	2.28	1.56	1.90	0.91	2.24	1.07
Variance (%)	37.25	25.70	33.75	19.44	23.80	16.22	27.50	15.57	18.67	12.78	28.55	19.52	23.81	11.43	27.95	13.44
Cumulative (%)	37.25	62.95	33.75	53.19	23.80	40.02	27.50	43.07	18.67	31.45	28.55	48.07	23.81	35.24	27.95	41.39
	AG_S1		AG_S2		AG_S3		AG_S4		BT_S1		BT_S2		BT_S3		BT_S4	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Cu	0.45	0.46	-0.64	0.06	0.44	-0.15	0.31	0.69	0.50	-0.10	-0.20	-0.77	0.47	-0.40	0.48	0.33
Fe	0.56	-0.37	0.44	0.28	-0.23	0.02	-0.54	0.28	0.34	0.58	0.66	0.13	0.62	-0.16	0.51	-0.26
Hg	0	0	0.46	0.43	0.57	0.54	0.50	-0.53	0.56	-0.28	-0.20	0.44	0.55	0.21	-0.42	0.60
Pb	-0.28	0.73	0.14	-0.72	-0.25	0.83	0.60	0.32	-0.47	0.40	-0.23	0.44	0.27	0.27	0.37	0.67
Zn	0.63	0.33	-0.39	0.46	0.60	-0.04	0.05	0.25	0.31	0.64	0.65	-0.08	0.13	0.83	0.43	-0.05
As	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eigen values	1.85	1.09	2.00	1.41	1.46	1.15	1.81	1.44	2.36	1.51	1.92	1.40	1.99	1.04	2.23	1.38
Variance (%)	23.11	13.61	25.05	17.58	18.32	14.37	22.59	18.00	29.45	18.85	23.97	17.50	24.89	13.07	27.87	17.29
Cumulative (%)	23.11	36.72	25.05	42.63	18.32	32.69	22.59	40.59	29.45	48.30	23.97	41.47	24.89	37.96	27.87	45.16

TABLE-9
RESULTS OF PRINCIPAL COMPONENT ANALYSIS (PCA) FOR THE IDENTIFICATION OF METAL SOURCES IN PLANTS AROUND STUDY AREA DURING FOUR DIFFERENT SEASONS

	MS_S1		MS_S2		MS_S3		MS_S4		CP_S1		CP_S2		CP_S3		CP_S4	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Cu	0.50	0.20	0.47	-0.35	0.64	-0.16	0.61	-0.35	0.47	-0.10	0.07	0.74	0.55	-0.21	0.39	-0.36
Fe	0.53	0.23	0.54	0.07	-0.11	0.79	0.61	0.32	0.54	-0.43	0.48	0.42	-0.36	0.79	0.47	0.18
Hg	-0.36	0.45	0.01	0.71	-0.29	-0.03	0.32	-0.63	0	0	0.50	-0.38	0	0	0.57	-0.09
Pb	-0.07	0.58	0.44	-0.01	0.44	0.57	0.11	0.34	0.57	-0.11	0.57	0.15	0.50	0.51	0.52	-0.07
Zn	0.48	0.29	0.54	0.28	0.55	-0.12	0.36	0.51	0.39	0.89	0.44	-0.33	0.56	0.26	0.15	0.91
As	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	-0.03	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	-0.30	0.49	0.05	-0.54	0	0	0	0	0	0	0	0	0	0	0	0
Eigen values	2.99	2.14	2.88	1.48	1.89	1.33	1.84	1.50	1.76	0.88	2.32	1.45	2.10	0.96	2.21	1.02
Variance (%)	37.31	25.65	36.05	18.47	23.69	16.69	22.99	18.82	21.98	11.01	29.02	18.09	26.31	12.03	27.61	12.79
Cumulative (%)	37.31	62.96	36.05	54.53	23.69	40.38	22.99	41.81	21.98	32.99	29.02	47.12	26.31	38.33	27.61	40.40
	AG_S1		AG_S2		AG_S3		AG_S4		BT_S1		BT_S2		BT_S3		BT_S4	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Cu	0.60	-0.23	-0.65	0.07	0.02	0.72	-0.02	0.73	0.50	-0.28	-0.45	0.23	0.46	-0.37	0.49	0.38
Fe	0.21	0.82	0.45	0.34	-0.55	0.27	-0.63	0.11	0.33	0.62	0.65	0.03	0.63	-0.13	0.51	-0.23
Hg	0	0	0.47	0.39	0.31	0.60	0.68	-0.21	0.56	-0.27	-0.14	0.38	0.54	0.05	-0.48	0.56
Pb	0.45	-0.45	0.16	-0.64	-0.17	-0.19	0.36	0.63	-0.47	0.27	0.06	-0.83	0.30	0.55	0.37	0.68
Zn	0.63	0.27	-0.34	0.56	0.75	-0.11	-0.09	0.06	0.33	0.62	0.58	0.33	0.08	0.74	0.38	-0.14
As	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eigen values	1.92	1.19	1.77	1.35	1.41	1.34	1.54	1.51	2.18	1.49	1.93	1.31	1.95	1.19	2.24	1.31
Variance (%)	23.99	14.88	22.01	16.93	17.63	16.76	19.30	18.90	27.30	18.68	24.10	16.41	24.41	14.88	28.00	16.44
Cumulative (%)	23.99	38.87	22.01	38.94	17.63	34.38	19.30	38.20	27.30	45.97	24.10	40.51	24.41	39.29	28.00	44.44

correspondence between foliar dust and plant tissue patterns further demonstrates the suitability of perennial roadside vegetation as effective phytomonitors for assessing spatial and seasonal variations in urban air quality. However, as the dataset contains variables with relatively low variance and limited sample size, the PCA results should be interpreted as exploratory and indicative rather than definitive.

Conclusion

The present investigation demonstrated that roadside plant species exhibit distinct physiological and biochemical responses under varying levels of urban air pollution across Jaipur city and Banasthali regions. The seasonal and site-specific variations in APTI, MAI, foliar dust deposition and metal accumulation clearly reflected the influence of vehicular

emissions, industrial activities and atmospheric deposition on urban vegetation. Species such as *Ficus benghalensis*, *Ficus religiosa* and *Cassia fistula* showed comparatively higher tolerance and metal accumulation capacity, indicating their suitability for plantation in polluted urban and industrial environments, whereas sensitive species may serve as reliable bioindicators for early detection of environmental stress. The strong association between biochemical parameters, atmospheric metal deposition and pollution indices highlighted the adaptive capacity of certain plant species to withstand oxidative and particulate stress under contaminated conditions. Elevated concentrations of Pb, Hg, Cu, Zn and Fe in foliar dust and leaf tissues further confirmed the dominant contribution of anthropogenic sources, particularly traffic emissions, industrial activities and resuspended road dust. Multivariate statistical analyses additionally supported the role of atmospheric deposition as the principal pathway governing metal accumulation in roadside vegetation. The findings emphasize that integration of APTI and MAI offers a practical and scientifically reliable framework for identifying pollution-tolerant and metal-accumulating species suitable for phytomonitoring and greenbelt development. Plantation of tolerant species with greater particulate interception and accumulation potential may contribute to improvement of urban air quality, reduction of airborne metal load and enhancement of ecological sustainability in rapidly urbanizing regions. Continuous biomonitoring using roadside vegetation, combined with stricter emission control measures and scientifically planned urban greening strategies, is essential for mitigating atmospheric pollution and minimizing associated ecological and public health risks in Jaipur and similar metropolitan environments.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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