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Assessment of Air Pollution Tolerance Index (APTI) and Physiological Response of Selected Urban Tree Species in Jaipur City, India

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ABSTRACT

Air pollution poses a critical challenge in industrial and urban areas, severely affecting both environmental quality and plant health. The present study evaluated the *Air Pollution Tolerance Index (APTI)* and associated physiological responses of seven urban tree species—*Azadirachta indica, Acacia nilotica, Ziziphus mauritiana, Prosopis cineraria, Polyalthia longifolia, Alstonia scholaris,* and *Ficus religiosa*—in the Vishwakarma Industrial Area (VKIA), Jaipur, India. Leaf samples were collected during winter (December 2023–February 2024) and summer (April–June 2024) to analyze four key biochemical parameters: ascorbic acid, total chlorophyll, leaf extract pH, and relative water content, following standard protocols (Arnon, 1949; APHA, 2017; Weatherley, 1950). APTI values were computed to determine species-specific and seasonal tolerance variation. Results revealed that *A. indica* (APTI = 13.5 winter, 12.6 summer) and *F. religiosa* (12.9 winter, 12.0 summer) were the most tolerant species, while *A. scholaris* (9.8 winter, 9.3 summer) was the most sensitive. Higher APTI in winter indicated favorable physiological conditions for tolerance, attributed to greater hydration and antioxidant activity. Correlation analysis showed strong positive associations of APTI with ascorbic acid and relative water content. The findings identify *A. indica* and *F. religiosa* as suitable candidates for greenbelt development in polluted industrial zones of semi-arid cities like Jaipur.

Keywords: Air Pollution Tolerance Index (APTI); Biochemical parameters; Urban tree species; Jaipur; Industrial pollution.

1. Introduction

Air pollution is currently one of the biggest environmental problems in most nations across the world, primarily in the developing world, where the increased pandemic growth of urbanization and industrialization has been escalating day by day, faster than pollution control structures. The high levels of various air pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and carbon monoxide (CO) in the majority of the Indian cities, such as Delhi, Mumbai, and Jaipur, lead to environmental pollution and severe health effects on the populations. With time, respiratory diseases, oxidative stress, and reduction in productivity of plants and people are some of the effects of prolonged exposure to these air pollutants (Parveen et al., 2021). In this regard, urban plants and predominantly trees can be used as a biological sink, which is crucial in alleviating pollution through interception, absorption, and assimilation of pollutants and through enhancement of microclimate and carbon sequestration. However, the tolerance differs with species based on their morphological, anatomical, and biochemical characteristics (Nadgórska et al., 2017).

The Air Pollution Tolerance Index consists of four physiological indicators, they are ascorbic acid content, total chlorophyll, leaf extract pH, and RWC; thus, they are used to estimate the adaptation or vulnerability of a plant to air pollutants, researchers apply this biochemical marker. APTI has become an easy but very effective method of finding tolerant species that can be used in urban and industrial greenbelt creation and finding sensitive species that can be taken as bioindicators of stress caused by pollution. Besides this, APTI is supplemented by the Anticipated Performance Index that incorporates ecological, morphological, and

socioeconomic features in the classification of species based on overall performance in a polluted environment. API, 2018: APTI, and API are effective designs of greenbelt and urban forest planning.
APTI and API have been proven as significant ecological indices in different studies in the tropical and subtropical areas. Kaur and Nagpal (2017) were able to establish that the association of these indices could result in the systematic selection of plant species that carry a high load of pollutants and the highest aesthetic and ecological value in cities. Rajakaruna and Masakorala (2019) evaluated the native and ornamental plants in Matara, Sri Lanka. They reported that evergreen plants that had dense foliage and high chlorophyll contents had superior APTI and API values. Bandara and Dissanayake (2021) reported that roadside trees were the appropriate tree species in the area that can survive a humid climate in the tropics. In addition, they proposed that the cover canopy and the surface of leaves are two attributes that significantly influence the interception of trees on pollutants.
It is in the recent scientific literature that the various biochemical mechanisms of APTI paved the way. One of the most effective antioxidants that plant tissues can offer is ascorbic acid, which protects the tissues against the formation of ROS. Reduction in chlorophyll content is one of the expressions of destabilization of the photosynthetic apparatus under the impact of pollutants. pH of leaf extract is the aspect of the activity of proteins extracted by the enzyme's accumulative nature of the metabolism. RWC illustrates the amount of water that is present in the plant tissue and its capability to maintain physiological balance. The above mechanisms were reviewed by Enitan et al. (2022) and who concluded that APTI and API played an important role in developing nature-based solutions to the air pollution issues of urban areas, especially in the developing areas of the world, where they could not do the instrumental monitoring regularly. These conclusions were highly supported by Rai (2020), who indicated that the species with high APTI value not only can withstand the loading of particulate matter but also are active participants in the dust retention and pollutant absorption process, hence their multifunctional role in eco-control strategies.
In South Asia, the APTI-based testing has been seriously affected by different research on the regional levels. Bala et al. (2022) found the most tolerant species in the roadside of the northern part of India and proposed these species for the sustainable urban greenbelt development. Similarly, Lekshmi et al. (2023) researched 12 tree species in Jhansi, Uttar Pradesh, and reported notable seasonal variations in APTI values, which were greater in the winter than in the summer, and hence, demonstrated that temperature and moisture stress regulate biochemical changes. In the study by Patil et al. (2023), the roadside vegetation of Ratnagiri City was analyzed, and evergreen species with thick cuticle and high antioxidant capacity were the best in reducing the impact of particulate and gaseous pollution.
These experiments are supported by the results of the studies made in other urban centres, which have been compared. Sen et al. (2017) compared the ecophysiological characteristics of the various species and assumed that the APTI of *F. religiosa* and *A. indica* was high, and therefore, the two species were the most suitable for planting in pollution-contaminated areas. Similarly, Balasubramanian et al. (2018) and Kaur and Nagpal (2017) claimed that they are the most dominant plants in industries because they have an evergreen canopy and contain high levels of ascorbic acid. Another point that was highlighted by Bandara and Dissanayake (2021), the background of the climate affects APTI significantly since the trees in the moist regions do not respond in the same way as the ones in the semi-arid regions, like Rajasthan. It implies that tolerance level tests must be at a local level in order they provide a true image of a plant.
Generally speaking, more recent research underlines that, along with the experiments aimed at industrial and vehicular pollution, the concept of APTI can be applied to research the topic of heavy metal bioaccumulation and the restoration of the ecosystem. Nadgórska-Socha et al. (2017) implied that the plant species with a more significant APTI are less prone to accumulating the level of heavy metals, thereby implying the relationship between biochemical tolerance and detoxification. Similar studies by Bala et al. (2022) and Patil et al. (2023) also concluded that not only the species with high APTI make the city more resilient to the pollution process, but also, as a result of the soil stabilization process, urban areas can also become more resistant to changes. These results indicate that the application of APTI and API as important aspects in ecological sound landscape planning is necessary, particularly in the highly urbanized regions.
Although very little research on the local level has been conducted in semi-arid regions like Jaipur, where the temperatures are extreme, rainfall is scarce, and particulates are high, and where the result in a complex situation of vegetation stress. Vishwakarma Industrial Area (VKIA) of Jaipur is an ideal location to conduct such research due to the high population of small and medium-sized textile, metal, and chemical industries, among others, emitting enormous quantities of pollutants. The APTI of the most prevalent urban tree species in the area can be quite informative regarding the ability to adapt and ecological preference to greenbelt making.
The study conducted by the exploration of the Air pollution tolerance index (APTI) and other physiological reactions of the tree species chosen in Jaipur, India, was in a position to determine the APTI values and inter-species differences in the circumstances of industrial pollution. It also analysed the seasonal variations in key biochemical parameters-ascorbic acid, total chlorophyll, leaf extract pH, and relative water content and identified the stress-resistant and stress-sensitive plant species that can be used to establish a greenbelt and also the biomonitoring of air quality in semi-arid regions. The research, through the intertwining of both biochemical and ecological knowledge, is a scientific basis for choosing pollution-resistant trees in order to

enhance the quality of the environment and make the urban forest system sustainable in industrial regions such as the Vishwakarma Industrial Area (VKIA), Jaipur.

2. Materials and Methods

2.1 Study Area

The study is based on Vishwakarma Industrial Area (VKIA), Jaipur City, Rajasthan, India. The most industrially active area is VKIA, the density of which is rather close to the small and medium-scale industries. Metal fabrication, textiles, chemical processing, and mechanical workshops are the primary activities of these industries. The emissions of these industries are SPM, NO_x, SO_2, and VOCs that, under a constant process, lead to worsening of the air quality.

Climatically speaking, Jaipur is a semi-arid area, and it has a clear seasonal variation. The dry and cold winter takes place between December and February. The dispersion capability of the atmosphere during this period is relatively low, making it possible to experience the accumulation of pollutants near the surface. On the contrary, the summer season, between April and June, is hot and dry with an increased speed of wind that favors the dispersion, yet at the same time leads to physiological stress to the plants due to dehydration and high evapotranspiration rates. Such contradictory conditions created a suitable environment in which the seasonal changes in the Air Pollution Tolerance Index (APTI) and resultant physiological adjustments that transpired in the chosen tree species were to be measured.

2.2 Selected Plant Species

Seven species of urban trees have been researched on APTIs. They were chosen, depending on the kind of trees that are there, their canopy covers, and how significant they are to the ecology of the city. Deciduous trees and evergreen trees were both thought to have taken into consideration the differences in physiological response to stress pollution. They were considered the seven most prevalent tree species that represent both evergreen and deciduous species, which are represented in Table 1.

Table 1: List of selected urban tree species used for Air Pollution Tolerance Index (APTI) analysis in Vishwakarma Industrial Area (VKIA), Jaipur, India

S. No	Scientific Name	Common Name	Family	Habit	Leaf Type
1	*Azadirachta indica*	Neem	Meliaceae	Tree	Evergreen
2	*Acacia nilotica*	Babul	Fabaceae	Tree	Deciduous
3	*Ziziphus mauritiana*	Ber	Rhamnaceae	Tree	Deciduous
4	*Prosopis cineraria*	Khejri	Fabaceae	Tree	Deciduous
5	*Polyalthia longifolia*	Ashoka	Annonaceae	Tree	Evergreen
6	*Alstonia scholaris*	Saptaparni	Apocynaceae	Tree	Evergreen
7	*Ficus religiosa*	Peepal	Moraceae	Tree	Semi-evergreen

The selection of these species was due to the fact that they are overrepresented in the green cover of the region, and they are of different physiological and morphological features that determine their ability to absorb or signal air pollution stress.

2.3 Sampling Design

The sampling was performed in two seasons, i.e., the cold (December 2023-February 2024) and the warm (April-June 2024) one. In the VKIA, mature and healthy trees without any damage or pest infestation were selected for sampling.

Three trees of each species were sampled, and three leaves of each mature tree were sampled as replicas of the first place to ensure that all three were exposed to equal environmental conditions. All the cases involved picking of the leaves at 2 to 3 m above the ground with the assistance of a canopy facing south to provide uniformity in exposure to sunlight and physiological processes.

The leaves were then gently rinsed with distilled water immediately after the collection in order to wash off dust and other forms of particulate matter that were on the surface without rupturing the epidermal layer. Drying of the material was done through filter paper and subjected to biochemical analyses immediately not to prevent the breakdown of the labile compounds, like ascorbic acid and chlorophyll.

2.4 Measured Parameters

The study focused on the first four biochemical and physiological indicators, which are commonly known to be highly sensitive blowers of stress induced by air pollution and primary determinants of APTI. Standard procedures were used to measure four important biochemical and physiological parameters, including ascorbic acid, total chlorophyll, the pH of leaf extract, and relative water content, as provided in Table 2.

Table 2: Biochemical and physiological parameters used for the assessment of Air Pollution Tolerance Index (APTI), with their analytical methods.

Parameter	Symbol	Unit	Method	Reference
Ascorbic Acid	A	mg g^{-1} FW	Titration with 2,6-dichlorophenol-indophenol	Arnon (1949)
Total Chlorophyll	T	mg g^{-1} FW	80% acetone extraction and spectrophotometric estimation	Arnon (1949)
Leaf Extract pH	P	—	1:10 leaf extract in distilled water using pH meter	APHA (2017)
Relative Water Content	R	%	Gravimetric method	Weatherley (1950)

All of the parameters represent a different feature of plant physiology when it experiences a form of pollution:
• **Ascorbic Acid (A):** acts as an antioxidant, protecting chloroplasts from oxidative damage.
• **Total Chlorophyll (T):** indicates photosynthetic efficiency and pigment stability under pollutant exposure.
• **Leaf Extract pH (P):** determines the buffering capacity of the leaf against acidic pollutants.
• **Relative Water Content (R):** represents the hydration status of the leaf, influencing its metabolic activity and tolerance potential.

2.5 Experimental Procedures
Estimation of Ascorbic Acid (A)
An equivalent of one gram of fresh leaf tissue was ground with 10 mL of 4% oxalic acid, and the mixture was filtered using a muslin cloth. Standard solution of 2,6-dichlorophenol-indophenol (DCPIP) was added to the resulting filtrate until the end point of the reaction, which was the appearance of a permanent pink color. The concentration of ascorbic acid was determined by the values of titration and noted in mg g^{-1} FW.

Determination of Total Chlorophyll (T)
0.5 g leaf extracted in 10 mL of 80% acetone. The mixture was then centrifuged to get a clear liquid as well as solid components. A spectrophotometer was used to measure the absorbance of the clear extract at 645nm and 663nm. The total chlorophyll was determined and put in the formula designed by Arnon and transformed into mg g^{-1} FW.

Measurement of Leaf Extract pH (P)
Fresh leaves were ground in distilled water at a ratio of 1:10 (w/v). A digital pH meter that was calibrated was used to measure the pH of the extract. Each measurement was at room temperature and repeated three times.

Determination of Relative Water Content (R)
The fresh weight (FW) of each leaf sample was taken immediately, and the sample was immersed in distilled water to achieve full turgidity of the sample (4 hours). The turgid weight (TW) was measured and oven-dried at 80°C for 24 hours to give the dry weight (DW). The RWC was calculated using the formula:

$$RWC = \frac{(FW-DW)}{(TW-DW)} \times 100 \quad (1)$$

2.6 Calculation of Air Pollution Tolerance Index (APTI)
The Air Pollution Tolerance Index (APTI) for each species was determined using the formula:

$$APTI = \frac{A(T+P)+R}{10} \quad (2)$$

where,
A = Ascorbic acid (mg g^{-1} FW)
T = Total chlorophyll (mg g^{-1} FW)
P = Leaf extract pH
R = Relative water content (%)
This equation represents the biochemical and physiological behaviors of the plants in terms of quantifying the level of tolerance of the plants to pollution in the atmosphere. The higher the APTI values, the more the species can be considered as resistant and adaptable to the polluted environments, and the lower they are, the more sensitive the plants are and the more the possibility that they could be used as a proxy indicator of bioindicators.

3. Results

3.1 Overview
The findings of the current research indicate the seasonal variation of the quality of the Air Pollution Tolerance Index (APTI) of seven tree species of the urban surface of Vishwakarma Industrial Area (VKIA), Jaipur. The survey was conducted in two seasons of radical differences, i.e., winter (December 2023 to February 2024) and summer (April 2024 to June 2024), to determine how the biochemical and physiological processes in the vegetation are affected by variations in weather (temperature, humidity, and air pollution). The variables

considered in the calculation of APTI were ascorbic acid (AA), total chlorophyll (TChl), leaf extract pH (LpH), and relative water content (RWC). All these are cellular indicators of the physiological system of the plant which is experiencing stress as a result of pollution. The grouping of these indicators in the APTI equation is a numerical measure of tolerance or air pollutant sensitivity. The finding indicated significant changes in the values of APTI between the species under investigation and also between the two seasons, which implies that environmental factors have a highly powerful impact on the physiological flexibility of urban trees.

3.2 Seasonal Variation in APTI Values

3.2.1 Winter Season (December 2023–February 2024)

The APTI of the seven species being studied was found to be between 9.8 and 13.5 during the winter season. Neem (*A. indica*) recorded the highest APTI value of 13.5, and consequently, Peepal (*F. religiosa*) and Khejri (*P. cineraria*) had the second and third highest APTI values of 12.9 and 12.3, respectively. These trees were proclaimed to be tolerant of air pollution. Whereas, Saptaparni (*A. scholaris*) had the least APTI value of 9.8, which negatively makes the plant more vulnerable to atmospheric pollutants. The elevated APTI values in *A. indica* and *F. religiosa* were also correlated with the high content of ascorbic acid and relative content of water, which suggests that the plants may have physiological functions maintaining cellular homeostasis and protecting photosynthetic pigments against the stress of pollution. Table 3 provides detailed biochemical and physiological characteristics measured for each of the species during the winter.

Table 3: Biochemical and physiological parameters of selected tree species during winter (Dec 2023–Feb 2024) at Vishwakarma Industrial Area (VKIA), Jaipur

Species	Ascorbic Acid (mg/g)	Total Chlorophyll (mg/g)	Leaf pH	RWC (%)	APTI
Azadirachta indica	8.2	2.5	6.8	78	13.5
Acacia nilotica	6.5	2.1	6.5	70	11.5
Ziziphus mauritiana	5.8	1.9	6.4	65	10.2
Prosopis cineraria	7.0	2.3	6.7	72	12.3
Polyalthia longifolia	6.2	2.0	6.6	68	11.0
Alstonia scholaris	5.5	1.8	6.3	64	9.8
Ficus religiosa	7.5	2.4	6.8	75	12.9

Interestingly, as Figure 1 shows, *A. indica* and *F. religiosa* recorded higher values of tolerance compared with other species at all seasons. The increased value during winter can be explained by the increased antioxidant activities as well as by the stability of pigments at low temperature, hence, reducing chlorophyll degradation and oxidative damage. *A. scholaris*, on the other hand, exhibited relatively low APTI, which implies that it is sensitive to particulate and gaseous pollutants.

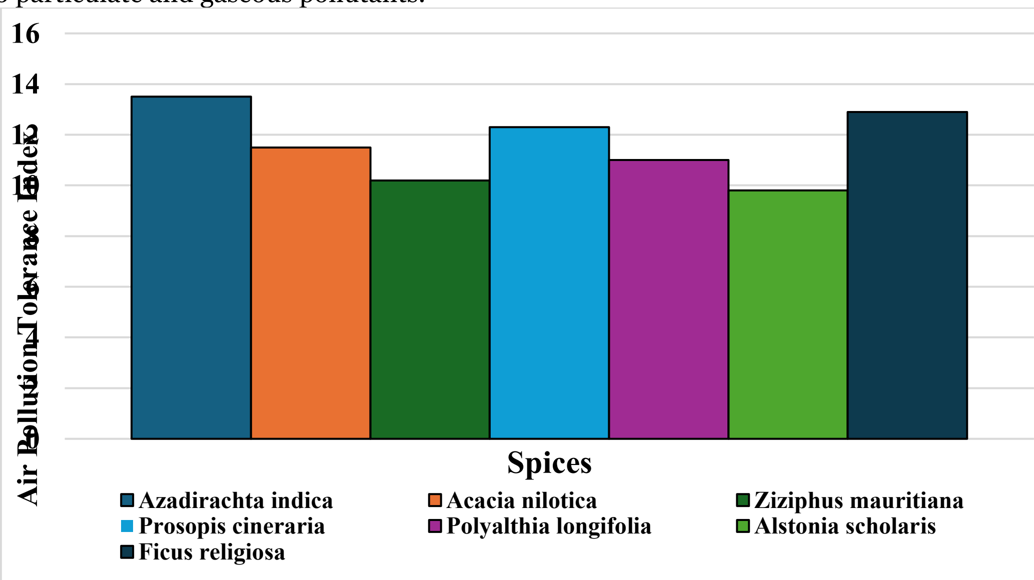

Figure 1: Comparative APTI values of tree species during winter season at VKIA, Jaipur

3.2.2 Summer Season (April–June 2024)

All the species had a decline in values of APTI in summer that ranged between 9.3 and 12.6. This reduction was principally attributed to an increase in ambient temperatures and a decrease in relative humidity, which led to physiological water stress and a decrease in biochemical stability. But once again, *A. indica* was the most tolerant, characterized with APTI 12.6, followed by *F. religiosa* (12.0) and *P. cineraria* (11.8), and *A. scholaris* was the lowest valued at 9.3, which was the most sensitive of the study samples. The measurements of parameters of all species in summer are summarized in Table 4.

Table 4: Biochemical and physiological parameters of selected tree species during summer (Apr–Jun 2024) at Vishwakarma Industrial Area (VKIA), Jaipur

Species	Ascorbic Acid (mg/g)	Total Chlorophyll (mg/g)	Leaf pH	RWC (%)	APTI
Azadirachta indica	7.8	2.3	6.7	74	12.6
Acacia nilotica	6.1	2.0	6.5	68	11.0
Ziziphus mauritiana	5.5	1.8	6.3	62	9.9
Prosopis cineraria	6.7	2.1	6.6	70	11.8
Polyalthia longifolia	5.9	1.9	6.5	65	10.7
Alstonia scholaris	5.2	1.7	6.2	60	9.3
Ficus religiosa	7.1	2.2	6.7	72	12.0

Figure 2 demonstrates a downward movement of the APTI in the summer season, and it is observed that environmental stressors such as high temperature and low humidity adversely impact the physiological performance of plants. Nevertheless, *A. indica* and *F. religiosa* remained exceedingly high in terms of tolerance, further confirming that they are adaptive to extremes of climate and also exposure to pollutants.

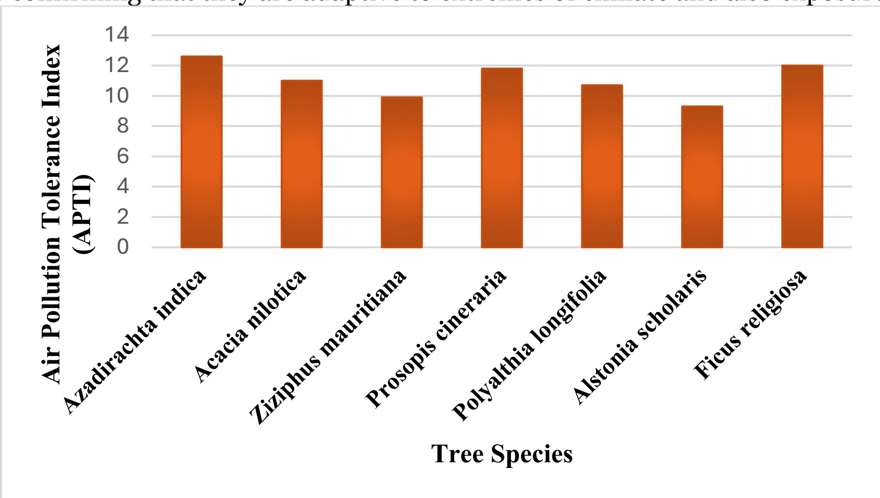

Figure 2: Comparative APTI values of tree species during summer season at VKIA, Jaipur

3.3 Comparative Seasonal Analysis

The comparative analysis of the winter-to-summer period revealed that all the species were found to have a slightly higher value of APTI in winter. These seasonal variations can thus imply that the environmental conditions favouring biochemical stability in plants are moderate climate, increased humidity, and reduced sunlight intensity. The average weight of APTI of all the species was 11.9 during winter, and the weight reduced to 11.0 during summer. This decline was greater in those species that are more physiologically vulnerable to heat and moisture stress and include *Z. mauritiana* and *A. scholaris*.

Figure 3 illustrates this seasonal change in the values of APTI of all the species. The differences noted in the two seasons indicate that the plants are likely to be more tolerant during the colder seasons of the year, when the accumulation of air pollutants is less rapid and the water retention is of high quality.

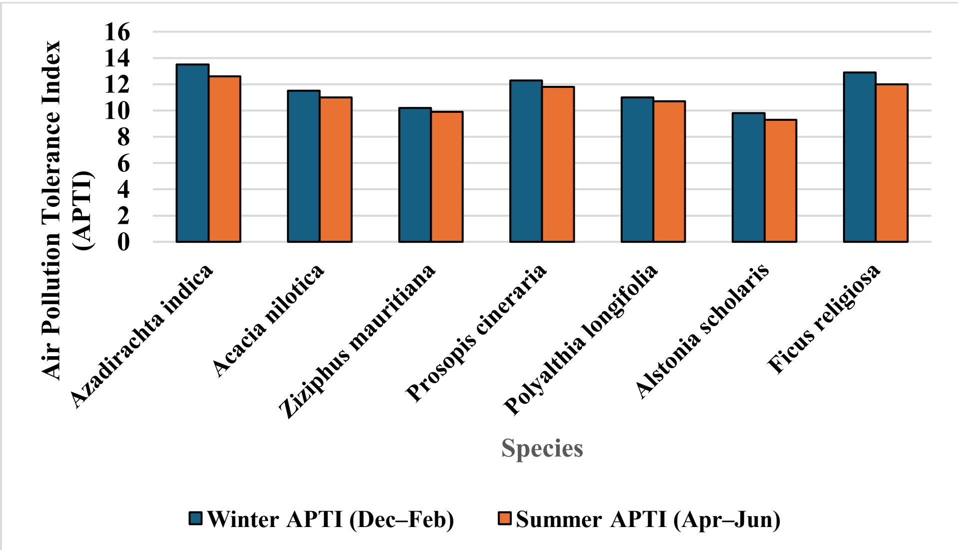

Figure 3: Seasonal comparison of mean APTI values for seven tree species in VKIA, Jaipur

3.4 Inter-Specific Differences in Biochemical Attributes

There have been significant interspecific variations found in biochemical parameters among the species studied. The concentration of ascorbic acid was also found to be highest in *A. indica* (8.2 mg/g in winter), and it is a manifestation of the robust antioxidant defense system in it. In line with this, the large values of ascorbic acid and relative water content in *F. religiosa* and *P. cineraria* were the primary causes of their having a greater APTI. The total chlorophyll content of these species was also higher, and this is a clear indication of their capacity to carry on with photosynthesis in the presence of the pollutant. The pH of all the species in the leaf was near to neutral (6.2 to 6.8), and which means that there is a good buffering capacity in resisting the acid-producing pollutants.

Conversely, the *A. scholaris* and *Z. mauritiana* formed low amounts of ascorbic acid, chlorophyll, and relative water content and, therefore, they are the ones that possessed low APTI score.

3.5 Ranking of Tree Species Based on APTI

The species were grouped into three categories, i.e., tolerant, moderately tolerant, and sensitive, based on their average APTI values of two seasons. *A. indica* and *F. religiosa* were the two plant species that showed the highest tolerance, having a mean APTI of more than 12.5, which demonstrated stable physiological performance and APTI less change from one season to another. *P. cineraria, A. nilotica*, and *P. longifolia* were referred to as species of moderate tolerance with APTI ranging from 10 to 12, whereas *Z. mauritiana* and *A. scholaris* have been identified as sensitive species due to their values of less than 10.

Table 5: Classification of species based on average Air Pollution Tolerance Index (APTI) across two seasons.

Category	Species	Mean APTI (Winter + Summer)
Tolerant	*Azadirachta indica, Ficus religiosa*	>12.5
Moderately Tolerant	*Prosopis cineraria, Acacia nilotica, Polyalthia longifolia*	10–12
Sensitive	*Ziziphus mauritiana, Alstonia scholaris*	<10

This classification provides an ecological framework for selecting appropriate species for greenbelt development in industrial areas and for identifying suitable bioindicators of air quality.

3.6 Correlation Between Physiological Parameters and APTI

The positive correlation between the ascorbic acid content and relative water content and APTI implies that both the former aspects are very instrumental in the embodiment of air pollution tolerance. The species that had a high antioxidant capacity and had the capacity to hold back water also had a higher resistance to oxidative and dehydration stress. The overall chlorophyll content was positively related in a moderate way, and it indicates that photosynthetic stability is among the factors sustaining adaptation in the long term when subjected to pollutant exposure. Although the direct relationship between the leaf pH was not as close, it was acting as a stabilizing factor in the maintenance of acid-base balance in the leaf tissue.

The tolerance plant observations at the cellular level are certainly comprised of the integrated actions of various biochemical and physiological variables, and not just one variable. This means that *A. Indica* and *F. religiosa* may be employed to provide the dependable pollution-resistant species that may be used in urban green cover, and *A. scholaris* and *Z. mauritiana* are the bio-indicators that may be used to implement the first stage of a warning system in the monitoring.

Data sets of primary evidence showed that not only were the most tolerant species *A. indica* and *F. religiosa,* capable of surviving in a polluted environment, but they could also efficiently clean the city air. The level of tolerance of *P. cineraria* and *A. nilotica* was moderate and can therefore be utilized in mixed plantations in moderately polluted regions. *A. scholaris* and *Z. mauritiana,* on the other hand, were highly sensitive and thus were christened as the biomonitors, which are useful in detecting the pollution stress. The influence of seasonality was also clear, as winter resulted in an increase in APTI values because of the fact that water relations were better, and there was less physiological stress. The current research is therefore a reliable source of information to use in choosing plant species to design a greenbelt and also to determine the impact of air pollution on urban vegetation.

4. Discussion

Modification of APTI and the corresponding biochemical parameters of the urban trees used in VKIA Jaipur showed significant interspecific and seasonal variation, which clearly demonstrates how various trees survive under air pollution pressure. The most resistant ones, according to the findings, were *A. indica* and *F. religiosa*, followed by *P. cineraria,* which was tolerant, and *A. scholaris* and *Z. mauritiana*, which were the most sensitive. Such data allow concluding that the tolerance of plants to pollution of the atmosphere is determined by their biochemical stability, water balance, and antioxidant potential.

These APTI values of *A. indica* and *F. religiosa* agree with the high ascorbic acid values and RWC of both species, and these parameters are hugely significant in terms of alleviation of oxidative stress. Ascorbic acid is a highly significant antioxidant constituent that controls the enzyme activity and provides the chloroplasts with

protection against free radicals caused by pollutants. Banerjee et al. (2021) provided such a relation and discovered that the stability of ascorbic acid and chlorophyll is the primary factor for primary plant endurance in a polluted environment. These two species have a high RWC, which points to a high level of cell hydration and metabolic efficiency, except that photosynthetic activity has been maintained under the stress trend that Nayak et al. (2018) depict in Haridwar City.
Conversely, the low APTI of the species of *A. scholaris* and *Z. mauritiana* represents a weak biochemical protection and vulnerability of the plants to atmospheric pollutants. Such species exhibited low levels of chlorophyll and ascorbic acid, which is indicative of low buffering capacity of antioxidants. This finding is consistent with the corresponding finding of Balasubramanian et al. (2018) across Coimbatore, at which the species with low ascorbic acid and pigment deterioration despite a greater burden of particles of material were determined as being sensitive to pollution. Therefore, the various APTIs across the species mean that tolerance is a multifactorial physiological process, which requires the interplay of the antioxidants, photosynthetic efficiency, and water relations.
The seasonal analysis revealed that the APTI values of all the plant species were higher in winter compared to summer. This could be attributed to the fact that they experience less evapotranspiration and have higher leaf moisture during the colder seasons. It is known that temperature and humidity gradients affect biochemical resilience, where high thermal stress during summer leaves chlorophyll and RWC at low. Accordingly, biochemical stability is preferred in winter, greater temperatures in summer lead to more oxidative stress and water loss, and reduced tolerance indices.
The current range of APTI (9.3-13.5) is well consistent with the previous regional and international research. The same range of tolerance (8.9-14.2) was documented by Nayak et al. (2018) in Haridwar who recorded the *A. indica* species was the most tolerant to pollution. Equally, Sen et al. (2017) and Kaur and Nagpal (2017) also indicated that species with a greater concentration of ascorbic acid and chlorophyll invariably recorded higher APTI values, demonstrating that these physiological indicators are critical in this respect.
Recent research also confirms the categorization of the two groups of species that were tolerant and sensitive, which were found in this research. It is observed that *F. religiosa* and *A. indica* exhibited high APTI and API in polluted highways in Himachal Pradesh, and the *A. scholaris* and *P. longifolia* were comparatively sensitive. These parallels are also consistent with the research that identified that pollution-tolerant species possess adaptive biochemical mechanisms controlling chlorophyll stability, lipid stability, and osmotic balance under stress, whilst species with thin cuticles and low antioxidant concentration, exemplified by *Z. mauritiana,* exhibited early chlorosis and cellular damage and therefore validated their relevance as biomonitors. In addition, Husen (2021) pointed out that thick lamina and dense stomata are some of the morpho-anatomical characteristics that increase resistance to pollutants; in the current study, *A. indica* and *F. religiosa* have these characteristics.
The discovery of the tolerant and sensitive species is enormously used in urban planning, afforestation, as well as greenbelt development. Industrial and roadside areas that are highly polluted, such as *A. indica, F. religiosa,* and *P. cineraria*, are found to be tolerant to the forces of air pollution, and they also help in the absorption of particulates and sequestration of carbon. These results are complementary to those of Pandey et al. (2015), who have suggested that the APTI, in combination with the Anticipated Performance Index- API, has an effective ecological basis in the choice of multipurpose urban species. In addition to that, they will be tolerant to various amounts of pollution in combination with other moderately tolerant like *A. nilotica* and *P. longifolia* in the mixed-planted sites so as to enhance the heterogeneity of the urban ecosystems, which can still endure various amounts of pollution. Physiological alterations in sensitive species such as *A. scholaris* and *Z. mauritiana* may be used as an indicator of air quality, and their reaction to which may serve as a preliminary warning of pollutant stress. This is why their response with low RWC, as well as with low chlorophyll content, can be utilized to provide early warning of the pollutant stress.

In this case the paper illuminates the problem of seasonal variation in APTI by virtue of the aspect of seasonality, which the study is the management and local context. The schedules of planting and maintenance plans must be conscious of the biochemical performance, which is seasonally influenced by climatic stress. The previous studies have proposed that the persistent observation of the physiological indices of plants in different seasons is required to maintain the energy of the green infrastructure in the shifting climatic conditions.
The existing findings are in line with the thought that trees could not be taken as lifeless objects that take in air pollutants as a passive sink, but as living organisms that are also able to undergo physiological alterations that reduce the extent of the pollution impact. The identified species having a high level of tolerance can be a great source of oxygen, local climate enhancement, and overall air pollution cleansing. This is because the use of pollution-tolerant species within urban ecosystems directly pertains towards the reduction of climate change through an improved system of carbon storage and a high pollution absorbing ability. The study aligns with the overall idea of plants-pollution interactions and also provides a regional outlook, which is imperative to the development of environmental policies within the urban center. The application of APTI-based assessments in the urban planning schemes will result in the most efficient utilization of the tree resources in the afforestation and urban reforestation programs, which will guarantee the environmental resilience and ecological stability with time.

5. Conclusions

This study critically looked at the Air pollution Tolerance Index (APTI) and biochemical alterations associated with the air pollution tolerance index in seven urban tree species in the Vishwakarma Industrial Area (VKIA), Jaipur. Using the four key physiological parameters in the study, namely the content of ascorbic acid, total chlorophyll, the pH of the extract of the leaves, and the relative water content of the leaf under the two drastically different seasons, the study has provided a profound understanding of the tolerance of the various species and their adaptability to the seasons under the air pollution caused by the industry. Both *A. indica* and *F. religiosa* had displayed maximum APTI scores by determining their highest antioxidant power and effective management of water in winter and in summer hence, demonstrating their best resistance properties to air pollutants. In addition, desert acacia was found to be reasonably tolerant to the pollution, whereas the *A. scholaris* and *Z. mauritiana* were found to be the most susceptible to the pollution and hence the most appropriate species to be used as biomonitoring species. It was observed that the seasons were compared and the APTI values were more significant in winter, supposedly because of reduced evapotranspiration and better hydration. The role of climatic factors in the physiological performance is enormous. The primary conclusion, drawn in the work, is that the various biochemical specifications of a species define the degree of its tolerance to air pollution, which consequently defines how urban vegetation may play a role in solving air pollution issues. The next urban forestry practices in the Jaipur air-polluted environment have a scientific reason in the presence of tolerant species such as *A. indica* and *F. religiosa*. Those species can significantly enhance the quality of the air and reduce the load of pollutants as well as help the ecological stability in the rapidly developing regions such as Jaipur.

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