

Assessment of the Relationships Between Leaf Characteristics with Air Pollutants: A Case Study on Oriental Plane (*Platanus orientalis* L.) and Caucasian Hackberry (*Celtis caucasica* Willd.)

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Abstract. Background: Plants are sensitive to air pollution by altering their vital processes such as growth or photosynthesis. Leaf characteristics reflect the adaptive mechanism of plants to their environment. This mechanism is demonstrated through changes in anatomical, morphological, and physiological characteristics relative to environmental changes. Methods: Samples were taken from 2 species of *Platanus orientalis* L. and *Celtis caucasica* Willd. in 10 urban forests of Tehran, Iran. In each study area, 50 leaves were collected from different directions of the canopy of each tree, and their area was measured by a leaf area meter instrument in a laboratory. Leaf moisture and specific leaf area (SLA) were also calculated. The data of air pollutants were obtained from the nearest pollution measurement stations to each study location. Results: The average percentage of moisture for *P. orientalis* and *C. caucasica* was calculated as 49.6% and 41.9%, respectively. The averages of SLA were estimated 9.2 and 6.5 cm²/g, respectively. The average leaf area was 36 and 6.04 cm², respectively. The correlation between quantitative variables of leaf (leaf area and SLA) and air pollutant appeared in both study species, only there was a significant negative relationship between leaf area and O₃. This relationship was stronger in *C. caucasica* ($R^2 = -0.78$). Conclusion: The results of this research showed that both species showed similar behavior against air pollutants, but *C. caucasica* showed more reaction.

Keywords. Plant Reaction; Unhealthy Air; Urban Trees.

INTRODUCTION

Urban forests have a significant value due to their shared relationship with humans and their diverse ecological and environmental functions such as landscape beauty, reduction of pollution and land surface temperature, climate adjustment, oxygen production, atmospheric carbon deposition, and ambient air conditioning (Schwaab et al. 2021; Habtamu and Elias 2022). Today, with the increase of greenhouse gases and the occurrence of global warming, there is no doubt that trees, shrubs, and green spaces as sources of carbon dioxide absorption and control of the earth's temperature play an important role in improving living conditions and improving quantitative and qualitative aspects. Parks and green spaces provide a variety of health benefits by promoting physical

activity, connection to nature, and opportunities for community engagement (Vos et al. 2013; Gunawardena et al. 2017). Nowadays, the need to preserve, maintain, and develop urban forests has become more noticeable and grown in importance to the people and authorities.

Air pollution is a prominent environmental issue in cities due to its harmful effects (Gheshlaghpoor et al. 2022). Tehran, the capital of Iran, with a population of 9.7 million, is ranked among the world's most polluted cities (Dadkhah-Aghdash et al. 2022). Vehicles are responsible for producing more than 80% of the gaseous pollutants and over 60% of air-suspended particles, including personal cars, motorcycles, heavy-duty and light delivery trucks, municipal and private sector buses, and minibuses. Personal cars contribute

the most, accounting for about 38% of gaseous pollutants and approximately 14% of air-suspended particles (TAQCC 2019). Over the years, population growth, road transportation, vehicular traffic, and industrial activities have led to an increase in gaseous and particulate pollutants, resulting in only 2 days of good air quality in Tehran during 2022. Tehran's air quality monitoring network comprises 35 stations, of which 21 are monitored by the Tehran Regional Municipalities and 14 are monitored by the Department of Environment. Most of these stations are equipped with analyzers to measure the concentration of CO, SO₂, NO_x, O₃, PM_{2.5}, and PM₁₀, which are the main air pollutants in Tehran.

The number of parks in Tehran has increased from 75 in 2017 to 2,355 in 2023, and afforestation around Tehran currently covers an area of more than 45,000 hectares. The average per capita green space in Tehran is 16.7 m², varying from 2.64 to 62 m² in different regions. There are 113 deciduous and 83 evergreen tree and shrub species in Tehran. Iran is located in a dry region of the earth, and Tehran faces crises such as population growth, climate change, and various air pollutants (Taheri et al. 2019), making green spaces essential for the city.

The purification of the city's air is an important role played by plants (Jeanjean 2015; Slamet et al. 2018). Urban trees, although helpful in mitigating air pollution, are themselves vulnerable to high levels of ambient air pollution (Larcher 2003). The primary route through which air pollution affects plants is the uptake of pollutants through stomata in the leaves (Abeyratne and Ileperuma 2006). When stomata are open, pollutants can easily diffuse into the leaf tissue and cause damage. However, if pollutant levels are excessively high, injury can still occur even when stomata are closed. For instance, plants growing along busy roads in Khartoum, Sudan, demonstrated an increase in stomata and epidermal cells due to vehicle emissions (Achille et al. 2015). Therefore, stomatal aperture regulation by various factors is crucial in determining the extent of damage that plants will incur. The modification of stomatal frequency and size is an important mechanism for plants to control the absorption of pollutants in response to environmental stress (Gostin 2009).

Air pollutants can cause a range of damage to sensitive plant species, including leaf damage, stomatal closure, premature aging, photosynthetic effects, membrane

permeability impairment, and loss of growth and yield (Tiwari et al. 2006). The effects of air pollutants on plants are multifaceted and depend on various factors, such as exposure duration, pollutant concentration, species, age, and interactions with other environmental factors including other pollutants (Abeyratne and Ileperuma 2006). Most plants experience physiological changes before showing visible damage to leaves when exposed to airborne pollutants (Liu and Ding 2008). Plants that are frequently exposed to environmental pollutants absorb, accumulate, and integrate these pollutants into their systems, and depending on their sensitivity level, they may show visible changes, including alterations in biochemical processes or accumulation of certain metabolites (Agbaire and Esiefarfenrhe 2009). Visible injury to plants can take the form of collapse of leaf tissue with necrotic patterns, yellowing or other color changes, or alterations in growth or premature loss of foliage, depending on the type of pollutant, its concentration, the species, physiological conditions, and age of the plant (Bell and Treshow 2002).

There are various indicators used to demonstrate pollution stress in plants. Research indicates that leaf characteristics reflect a plant's mechanisms to its surroundings through changes in anatomical, morphological, and physiological characteristics in response to environmental changes (Ling et al. 2011). Air pollution stress leads to stomatal closure, which reduces the availability of CO₂ in leaves. Exposure to air pollutants, such as O₃ and NO_x, affects the metabolic function of leaves and interferes with the net carbon fixation by the plant canopy, which is measured by the net photosynthetic rate, a commonly used indicator of increased air pollutant impacts on tree growth (Joshi and Swami 2007; Woo et al. 2007). Air pollution stress triggers the formation of active oxygen species in plant cells, which results in oxidative stress, affecting the biochemical processes of plants and decreasing their tolerance to other stress factors (Rai et al. 2011). Air pollutants first deposited on soil, such as heavy metals, affect the functioning of roots and interfere with soil resource capture by the plant, leading to reductions in resource capture (production of carbohydrates through photosynthesis, mineral nutrient uptake, and water uptake from the soil), affecting plant growth through changes in resource allocation to various plant structures (Weber et al. 2002). In polluted urban areas, plant species' branches and leaves accumulate significant amounts of chemical elements, acting as accumulation reagents.

Pollution reduces the levels of chlorophyll a, chlorophyll b, carotenoids, ascorbic acid, relative leaf water content, and the contamination tolerance index (Chukwu and Adams 2016). One of the most common impacts of air pollution is the gradual disappearance of chlorophyll, leading to the yellowing of leaves and a consequent decrease in the capacity for photosynthesis (Joshi and Swami 2007). Chlorophyll is the primary photoreceptor in photosynthesis, the light-driven process in which carbon dioxide is “fixed” to yield carbohydrates and oxygen. When plants are exposed to environmental pollution above the normal physiologically acceptable range, photosynthesis gets inactivated. The pollutants cause severe damage to leaves of *Joannesia princeps* Vell. (Euphorbiaceae), a native species of the Atlantic Forest in Minas Gerais, Brazil (da Silva et al. 2023). Results of a study on the particulate matter (PM) deposition on *Quercus ilex* L. leaves in 4 districts of the City of Terni (Italy) for 3 periods of the year showed that variations in PM deposition were correlated with distance to main roads and downwind position relative to the industrial area (Sgrigna et al. 2015).

Reductions in leaf area and leaf number may be a defense mechanism to limit the level of exposure to airborne contamination (Jochner et al. 2015). Reduction in leaf area due to air pollution can affect the plant's ability to photosynthesize and its ability to adapt to the stress of air pollution (Tiwari et al. 2006). The reduction of leaf area in leaves of *Albizia lebbek* (L.) Benth. was reported under the stress of air pollution (Seyyednejad et al. 2009). The leaf area of plants that had the furthest distance from the source of contamination was higher than those close to the source of contamination (Chukwu and Adams 2016). The study conducted in Quetta, Pakistan aimed to investigate the impact of air pollution on the morphological characteristics of the leaves of 13 common plant species. The findings of the study indicated that, when compared with their counterparts from non-polluted sites, all plant species in polluted areas displayed a significant reduction ($p < 0.05$) in leaf length, width, area, and petiole length (Leghari and Zaidi 2013).

The primary objective of this research was to examine the effect of air pollutants in Tehran on leaf area and specific leaf area (SLA) (which is associated with leaf area and leaf humidity) and explore the relationship between them. While some previous studies have investigated the leaf area and SLA of several

woody species in Iran (e.g., Pourhashemi et al. 2012; Panahi et al. 2013; Nowghani et al. 2016), no prior research has evaluated their relationship with air pollutants. Although some studies have investigated the relationship between air pollutants and tree leaf variables in Tehran (e.g., Rashidi et al. 2017; Abbasi et al. 2021) and other cities of Iran (e.g., Rafiee et al. 2014; Omidi et al. 2018), they were limited in scope and did not include the Caucasian hackberry (*Celtis caucasica* Willd.) as a subject of investigation. Since the climate of Tehran is arid and semi-arid and *C. caucasica* is a species adapted to such conditions, it is always used as one of the important species for planting in Tehran's urban green spaces. The present study aimed to fill this gap by examining a broader range of urban forests and a new species.

MATERIALS AND METHODS

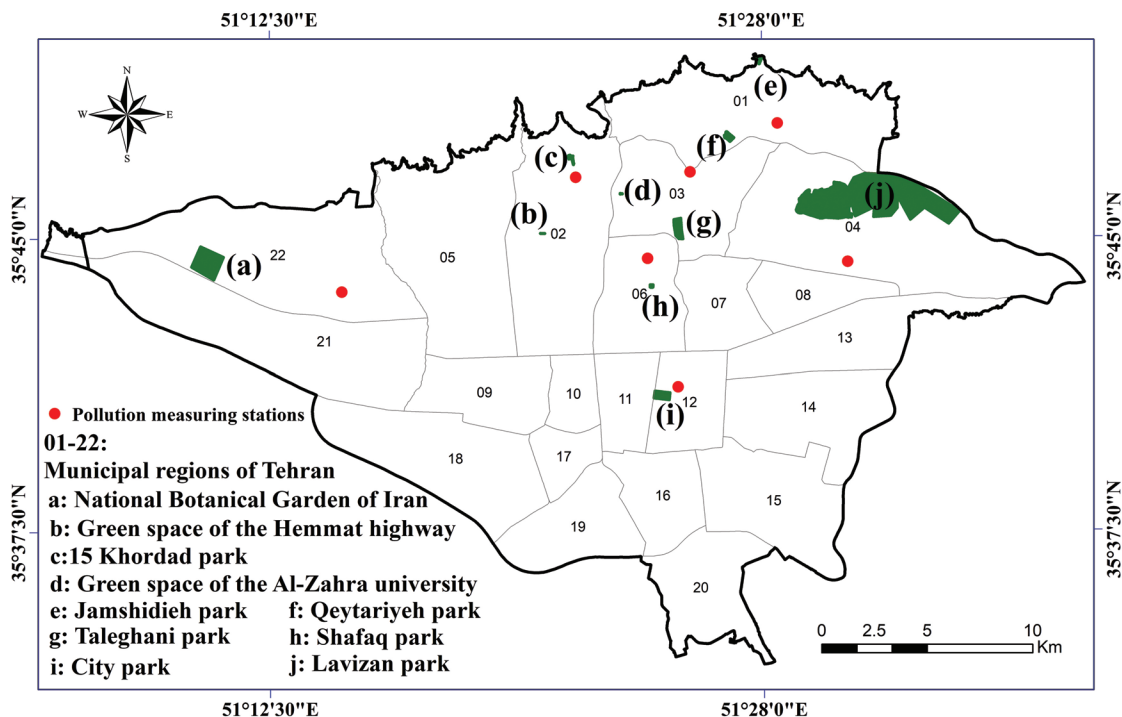
Study Areas

This study was carried out on *P. orientalis* and *C. caucasica*, 2 main species of Tehran urban forests, in 10 urban forests (Table 1, Figures 1 and 2). Tehran, with an area of 740 km², is located at 51°17' to 51°33'E and 35°36' to 35°42'N. According to the synoptic station of Mehrabad airport, Tehran has a dry and cold climate, with an average annual temperature of 17.2 °C. The range of temperature is 43 °C in July and at least -15 °C in December. The average annual rainfall is 230.5 mm with the maximum in March (9.99 mm) and minimum in September (1.1 mm). The number of freezing days is 48 days throughout the year, the maximum of which is 18 days in January. The lowest and highest relative humidity values are between 25% and 26% in June and January, respectively.

The study urban forests were selected in such a way that they (1) have both species in the desired diameter at breast height (DBH), (2) have a variety of pollution levels, and (3) have the shortest distance to the pollution measuring station of that region. The information of the closest air pollution measuring stations (7 stations) to each study urban forest was used to investigate the relationship between leaf morphological variables and pollutants. The location of the pollution measuring stations are presented in Figure 1. In this study, 4 pollutants (CO, NO₂, SO₂, and O₃) were used.

Table 1. Characteristics of study green spaces.

Urban forest	Region	Area (ha)	Geographical coordinates
Qeytariyeh Park	1	12.3	35°47'36"N, and 51°26'56.4"E
Jamshidieh Park	1	6.9	35°49'36.2"N, and 51°27'94.5"E
Green space of Hemmat Highway	2	No information	35°45'2.6"N, and 51°21'7"E
15 Khordad Park	2	1.1	35°39'57.1"N, and 51°20'12.1"E
Taleghani Park	3	23	35°45'19.5"N, and 51°25'20.6"E
Green space of Al-Zahra University	3	10	35°46'6.7"N, and 51°23'33.2"E
Lavizan Park	4	827.6	35°46'8.6"N, and 51°30'34.8"E
Shafaq Park	6	1.7	35°43'47.2"N, and 51°24'30.3"E
City Park	12	24.9	35°40'59.5"N, and 51°24'50.6"E
National Botanical Garden of Iran	22	147	35°44'21.4"N, and 51°10'26.4"E

**Figure 1. The location of urban forests and pollution measuring stations used in the study.**

Method of Data Collection

In each urban forest, 50 mature leaves of each species were collected from the tree crown (totaling 500 leaves for each species). The selected trees were healthy, had symmetric crowns and sufficient freshness, and did not have pests or dryness. The sample trees in our study had a DBH of 15 to 25 cm.

Regarding *P. orientalis*, the highest average DBH value was observed in Lavizan Park (23.7 cm), while the lowest was observed in 15 Khordad Park (21.2 cm). Concerning *C. caucasica*, the highest average DBH value was observed in City Park (22.1 cm), while the lowest was observed in the National Botanical Garden of Iran (18.3 cm). The height of *P. orientalis* trees

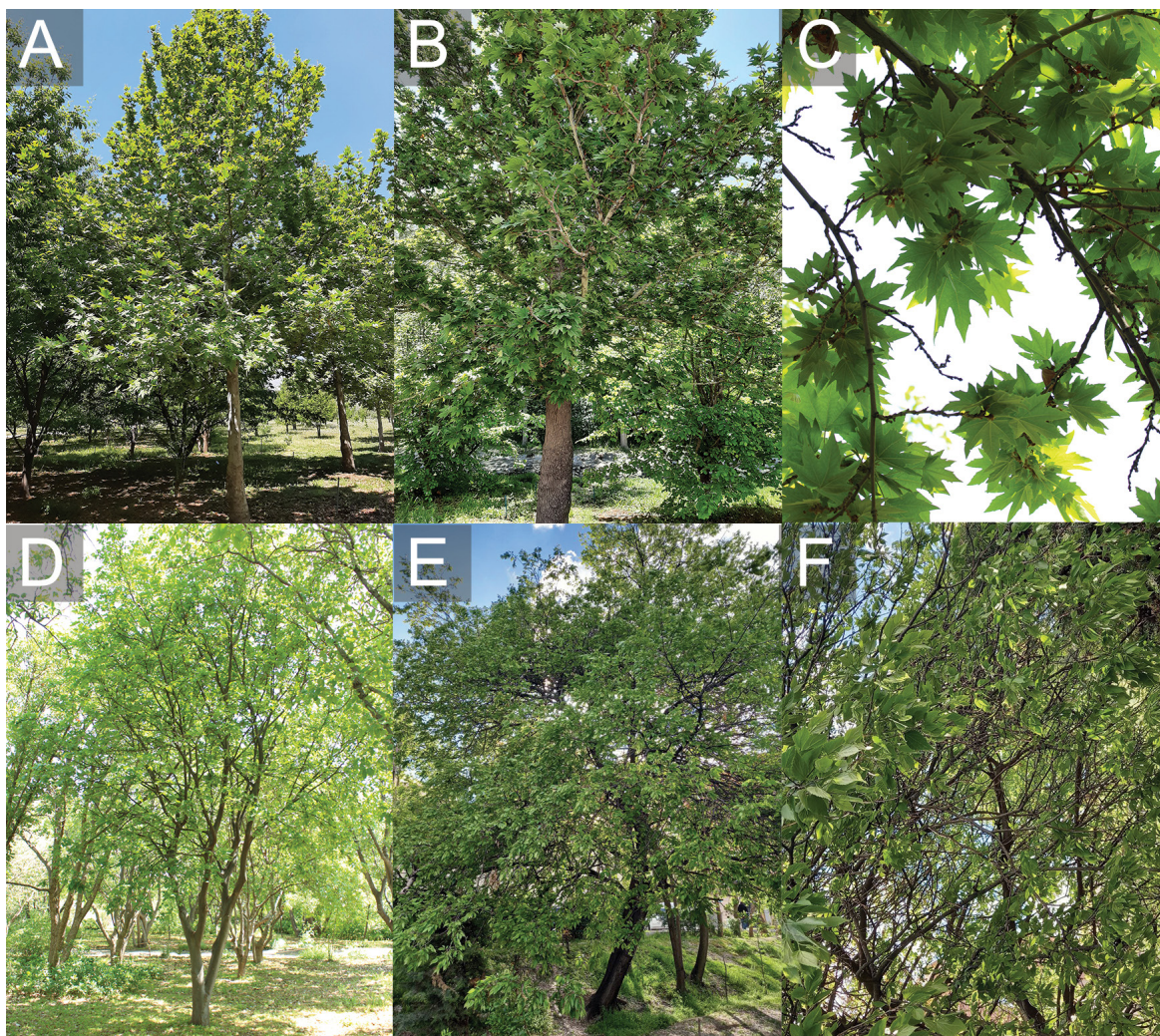


Figure 2. Study areas and species. (A) *Platanus orientalis* in the National Botanical Garden of Iran; (B) *P. orientalis* in the green space of Al-Zahra University; (C) leaf of *P. orientalis* in Jamshidieh Park; (D) *Celtis caucasica* in Lavizan Park; (E) *C. caucasica* in Qeytariyh Park; (F) leaf of *C. caucasica* in City Park.

ranged from 8 to 10 m, while *C. caucasica* trees were a little shorter, ranging from 6 to 8 m. Regarding the average height, the lowest and highest values for *P. orientalis* were observed in Lavizan Park (9.6 m) and the green space of Al-Zahra University (8.3 m), respectively. For *C. caucasica*, the lowest and highest values were observed in City Park (7.7 m) and the green space of Al-Zahra University (6.4 m), respectively. The crown diameter (CW) of *P. orientalis* trees ranged from 5 to 7 m, while the CW of *C. caucasica* trees was a little less, ranging from 4 to 6 m. The highest average CW value for *P. orientalis* was observed in City Park (5.9 m), while the lowest was observed

in the green space of Hemmat Highway (5.3 m). For *C. caucasica*, the highest average CW value was observed in Qeytariyh Park (5.2 m), while the lowest was observed in the green space of Al-Zahra University (4.4 m).

Sampling of trees was done at the beginning of September when the leaves of the trees were fully matured. Fresh leaves were collected from different directions of the crown of the trees and immediately transferred to the laboratory. The leaves were weighed using a digital scale with a sensitivity of 1 mg and their surface was measured by a leaf area meter model (CRLA1-Baher Kimia Rahavard, Tehran, Iran) with an

accuracy of 0.01 cm². They were placed inside the oven at a temperature of 65 °C for 48 hours. Then they were placed in a desiccator for 30 to 45 minutes to dry and be weighed again (dry weight). The percentage of leaf moisture was calculated by Equation 1 (Jin et al. 2017).

$$\text{Water content (\%)} = \frac{(W_f - W_d)}{W_f} \times 100 \quad (\text{Equation 1})$$

Where: Fresh weight (W_f), dry weight (W_d). Also, using the above data, the specific leaf area (SLA), that is the ratio between leaf area to dry weight in terms of cm²/g was calculated (Kardel et al. 2010).

Data Analysis

The normality of the data was tested by Shapiro-Wilk test. Due to the non-normality of the data, to compare the mean values of leaf variables among study green spaces and pollutants among study stations, the non-parametric Kruskal-Wallis and Duncan test with a 0.05 significance level was used. Also, the correlation between leaf variables and pollutants was investigated by Pearson correlation coefficient. Statistical calculations were performed in Excel and SPSS software.

RESULTS AND DISCUSSION

Regarding the pollutants, it was determined that the Pasdaran station in region 3 was the most polluted station and the region 22 municipality station was the least polluted. Of course, this was not true for a limited number of pollutants. The highest amount of CO (55.4 ppm) was related to the Pasdaran station (region 3) and the lowest (16 ppm) was related to the municipality station of region 2. The highest and lowest O₃ amount

belonged to Aqdasiyeh station (90.1 ppm) in region 1 and the University of Science and Technology station (37.5 ppm) in region 4. The highest amount of NO₂ was observed in Imam Khomeini station (89.7 ppm) in region 12 and the lowest in the region 22 municipality station (36.6 ppm). Lastly, the highest and lowest levels of SO₂ belong to the Pasdaran (28.5 ppm) and Aqdasiyeh stations (10.35 ppm) in region 1 (Table 2).

It was found that the mean of all 4 pollutants (SO₂, NO₂, O₃, and CO) among the 7 stations were significantly different at 0.05 significance level (Table 2). The grouping of pollutants showed that in the case of SO₂, the Pasdaran station with the highest amount arranged in a separate group (a), while Aqdasiyeh and the municipality of region 2, which had the lowest amounts, arranged in a group (f). Regarding NO₂, the Imam Khomeini station with the highest value was in a separate group (a), and 2 stations (Aqdasiyeh and the municipality of region 22) with the lowest values arranged in a group (d). In terms of O₃, Aqdasiyeh and the University of Science and Technology were placed in separate groups (a and d) with the highest and lowest values, respectively. In the case of CO pollutant, Pasdaran was in group (a) with the highest amount and the municipality of region 2 was in group (d) with the lowest amount.

Descriptive statistics of leaf quantitative variables of *P. orientalis* and *C. caucasica* are presented in Table 3. As can be seen, the highest value of leaf moisture of *P. orientalis* (58%) was related to green space of Hemmat Highway, while the lowest amount (41%) was related to Jamshidieh Park. In the case of *C. caucasica*, the highest and lowest values of leaf moisture belonged to 15 Khordad Park (51%) and Qeytariyeh

Table 2. Descriptive statistics (mean ± SD) of pollutant variables in the study stations.

Station	Related green space (Based on Figure 1)	SO ₂ (ppm)	NO ₂ (ppm)	O ₃ (ppm)	CO (ppm)
Aqdasiyeh	e, f	10.35 ± 1.5 f	67.7 ± 11.3 d	90.1 ± 11.2 a	18.8 ± 5.1 e
Municipality of region 2	b, c	11.20 ± 1.6 f	27 ± 4.5 c	72.2 ± 10.1 b	18.7 ± 5.9 e
Pasdaran	d, g	28.49 ± 3.9 a	83.8 ± 13.2 b	70.7 ± 16.5 b	55.4 ± 9.5 a
University of Science and Technology	j	20.14 ± 4.3 c	69.9 ± 4.3 cd	37.5 ± 8.3 d	36.1 ± 7.6 c
Geophysics (Amirabad)	h	19.44 ± 4.2 d	73.7 ± 10.6 c	74.7 ± 11.6 b	28.6 ± 5.1 d
Imam Khomeini	i	26.3 ± 5.1 b	89.7 ± 12.1 a	49.9 ± 8.9 c	45.1 ± 10.1 b
Municipality of region 22	a	13.1 ± 2.2 e	36.6 ± 6.2 d	68.4/ ± 9.5 b	16 ± 6.4 f

Means followed by the same letter in the same column are not significantly different at $p < 0.05$ according to Duncan test.

Table 3. Descriptive statistics (mean \pm SD) of leaf quantitative variables of study species in the study areas (SLA = specific leaf area).

Urban forest	<i>P. orientalis</i>			<i>C. caucasica</i>		
	Moisture content (%)	Leaf area (cm ²)	SLA (cm ² /g)	Moisture content (%)	Leaf area (cm ²)	SLA (cm ² /g)
Qeytariyeh Park	47 \pm 5.9 a	25.9 \pm 2.5 a	8.31 \pm 0.8 bc	33 \pm 4.4 a	3.6 \pm 0.2 a	3.31 \pm 0.3 a
Jamshidieh Park	41 \pm 5.1 a	21.2 \pm 2.2 a	7.14 \pm 0.7 a	38 \pm 4.9 a	4.1 \pm 1.1 ab	4.42 \pm 0.3 ab
Green space of Hemmat Highway	58 \pm 7.3 a	37.7 \pm 2.7 bc	8.79 \pm 1.1 bc	35 \pm 5.1 a	4.3 \pm 0.1 ab	5.53 \pm 0.4 ab
15 Khordad Park	51 \pm 5.3 a	36.9 \pm 3.5 bc	8.05 \pm 1.4 b	51 \pm 6.0 a	6.2 \pm 0.8 b	4.31 \pm 0.2 ab
Taleghani Park	53 \pm 6.6 a	38.6 \pm 4.5 bc	8.87 \pm 1.3 bc	44 \pm 5.4 a	5.9 \pm 0.3 b	5.58 \pm 0.3 ab
Green space of Al-Zahra University	42 \pm 6.7 a	30.8 \pm 4.1 b	9.65 \pm 1.1 c	36 \pm 3.7 a	6.7 \pm 0.9 bc	6.72 \pm 0.5 b
Lavizan Park	48 \pm 5.8 a	51.9 \pm 1.3 d	12.42 \pm 1.3 d	40 \pm 4.6 a	7.6 \pm 0.7 cd	8.0 \pm 0.6 bc
Shafaq Park	48 \pm 4.9 a	33.2 \pm 2.2 b	8.67 \pm 0.7 bc	50 \pm 6.2 a	5.6 \pm 0.6 b	8.3 \pm 0.6 bc
City Park	57 \pm 7.1 a	44.5 \pm 2.8 c	10.61 \pm 1.2 cd	46 \pm 5.4 a	8.9 \pm 0.8 d	9.69 \pm 0.9 c
National Botanical Garden of Iran	51 \pm 6.8 a	39.1 \pm 1.8 bc	9.24 \pm 0.9 c	50 \pm 6.9 a	7.5 \pm 0.3 cd	9.23 \pm 0.7 c

Means followed by the same letter in the same column are not significantly different at $p < 0.05$ according to Duncan test.

Park (33%), respectively. The average percentage of leaf moisture for *P. orientalis* and *C. caucasica* was estimated 49.6% and 41.9%, respectively. In general, the average moisture percent of *C. caucasica* in the study areas was estimated to be less than *P. orientalis*.

Leaf water content is one of the most common physiological parameters limiting efficiency of photosynthesis and biomass productivity in plants (Jin et al. 2017). The plants exposed to pollution, significantly increase the water content of the root, stem, and leaf components (Kammerbauer and Dick 2000). High water content in the plant will help maintain a physiological balance of the plant under stress conditions such as exposure to air pollution when transpiration is usually high and may lead to drying (Singh et al. 1995). The effect of air pollutants on the increase of leaf moisture has been proven in different research. For example, the amount of relative water content of *Lactuca sativa* var. *longifolia* leaves that were exposed to exhaust gases for 30 days increased by 10.15% compared to the control plants (Kohan et al. 2021). Considering the higher amounts of air pollutants in region 1, it seems that the higher moisture content of the leaves of the 2 study species in the urban forests of this region is a physiological mechanism for exposure to pollutants.

The highest value of leaf area of *P. orientalis* (51.9 cm²) was related to Lavizan Park, while the lowest value (20.97 cm²) was related to Jamshidieh Park. In the case of *C. caucasica*, the highest and lowest values of leaf area belonged to City Park (8.86 cm²) and Qeytariyeh Park (3.6 cm²), respectively. The average of leaf area in *P. orientalis* and *C. caucasica* in all study areas was 36 and 6.04 cm², respectively. In general, the average area of *P. orientalis* leaves in the study was estimated to be about 6 times that of *C. caucasica*. *Platanus orientalis* produces very broad clawed leaves, while the *C. caucasica* has relatively small single leaves. Results indicate a very large difference in leaf area variables between the 2 species. In other studies in Iran, the leaf area range of *P. orientalis* is reported from 8.19 to 240 cm² (Maddah 2016; Khosropour et al. 2018; Abbasi et al. 2021). In the only research conducted on the leaf area of *C. caucasica* in Iran, the range of this variable is estimated from 19.9 to 31.5 in natural forests of Fars and Kohgiluyeh and Boyer-Ahmad provinces (Jafaripur et al. 2016). The difference in the amount of leaf area between our study and the above studies is the big difference in age of sample trees.

Some studies have emphasized the significant reduction of leaf area in plants grown in polluted

urban areas. For example, 5 studied plant species—*Azadirachta indica* A. juss., *Calotropis procera* (Ait.) R. Br., *Catharanthus roseus* (L.) G. Don, *Nerium oleander* L., and *Tabernaemontana divaricata* L.—reportedly had decreased leaf area in the polluted area when compared with the non-polluted area (India) (Madhumonisa and Saradha 2021). Rashidi et al. (2017) reported that with increasing SO₂, the leaf area decreases on *Fraxinus rotundifolia* Mill. in different areas of Tehran. The leaf area of *Cinnamomum camphora* (L.) Nees & Eberm., *Lawsonia inermis* L. and *Bougainvillea spectabilis* Willd. was decreased significantly in the industrial zone compared with the control area (Saudi Arabia) (Shaheen et al. 2016). Areington et al. (2015) showed that the leaf area of plants that had the closest distances to pollutants had a significant decrease compared to plants located farther away.

Leaf surface is influenced by multiple factors, such as light competition (crown light exposure), varying conditions across different sites, and soil factors (e.g., soil type, nutrient availability, and plant-soil nutrient interactions). The spatial distribution and morphological variations of foliage within tree crowns reflect the tree's adaptation to different microenvironments within crowns and stands. These factors significantly impact light use efficiency, carbon assimilation, and photosynthetic capacity of the entire tree (Wang et al. 2019). Foliar morphology, quantity, and spatial distribution play crucial roles in crown structure and tree growth as they strongly influence the interception and penetration of light within the crown (Alcorn et al. 2013). Accurate quantification of leaf morphology, quantity, and spatial distribution within crowns is thus vital for enhancing forest productivity (Čermák et al. 2008; Koester et al. 2014). Numerous studies have demonstrated the influence of soil parameters on leaf traits, particularly leaf area and SLA. For instance, Khanom et al. (2008) observed that *Stevia rebaudiana* (Bert.) grown in noncalcareous soil exhibited a maximum leaf area of 1401 cm², whereas in calcareous soil, the minimum leaf area was 754 cm². Ordoñez et al. (2009) established associations between leaf traits (SLA, leaf nitrogen concentration, leaf phosphorus concentration, and leaf nitrogen-to-phosphorus ratio) and soil fertility on a global scale using data from 474 species across 99 sites (809 records in total). However, since this study did not comprehensively explore the factors influencing leaf

surfaces, such as soil and crown conditions, it is recommended that future studies address these aspects.

Regarding the SLA of *P. orientalis*, the highest and lowest values were related to Lavizan Park (12.42 cm²/g) and Jamshidieh Park (7.14 cm²/g), respectively. In the case of *C. caucasica*, City Park with an average of 9.69 cm²/g and Qeytariyeh Park with an average of 3.31 cm²/g had the highest and lowest amount, respectively. The average of SLA in all study areas were estimated 9.2 and 6.5 cm²/g for *P. orientalis* and *C. caucasica*, respectively. According to the equation of SLA, in 2 leaves with the same dry weight, the large the leaf area, the lower the SLA. In the case of the present study, although the area of *P. orientalis* leaves was about 6 times of the area of *C. caucasica* leaves, this ratio was not observed in the SLA. The SLA of *P. orientalis* leaves was slightly higher than *C. caucasica*. The range of SLA of *P. orientalis* are reported between 122 and 194 cm²/g in other research in Iran (Rafiee et al. 2014; Khosropour et al. 2018; Rashidi and Jalili 2018; Abbasi et al. 2021). In the only research conducted on the SLA of *C. caucasica* in Iran, the average of this variable is estimated to be 103.5 cm²/g in an urban forest of Sanandaj City (Pourhashemi et al. 2012).

In the present study, although there was no significant relationship between SLA and air pollutants, the SLA values were lower in more polluted areas than in less polluted areas. So, it can be said that in most cases, with the increase of pollutants, the SLA of 2 study species has decreased. Rashidi et al. (2017) also achieved similar results in the study of air pollution stress on *F. rotundifolia* in Tehran parks. Gratani et al. (2000) also showed a 25% increase in SLA values in areas with high pollution compared to the control area in Italy. Balasooriya et al. (2009) on *Traxacum officinale* Weber showed that a large amount of SLA in a less polluted location could indicate the sensitivity of this characteristic to the type of management such as pruning method. They noted that tree shading could explain the large amount of leaf area in a less polluted area, and that this reaction could be due to the plant's response to less light and the presence of shade. In some studies, the results have been contradictory. For example, for *Melia azedarach* L. in Argentina (Pignata et al. 1999) and *Ligustrum lucidum* W. T. Ation (Carreras et al. 1996) and *P. orientalis* in Iran (Rafiee et al. 2014), increases in SLA were observed in areas with more pollution. Wuytack et al.

(2011) mentioned that although their data analysis suggests a relationship between SLA and NO_x/O₃ concentration, the absence of a straightforward relationship between SLA and air pollution still questions the usefulness of this bio-indicator for monitoring air pollution.

The results of the Kruskal-Wallis test showed that, in the case of *P. orientalis*, there was no significant difference in the humidity percent among the study areas ($p > 0.05$), but the difference of the 2 variables of leaf area and SLA were significant ($p < 0.01$). The grouping of the mean of the SLA for the *P. orientalis* is shown in Table 3. As shown, the Jamshidieh Park was in a separate group (a) with the lowest values. Lavizan Park was also placed in a separate group (d) with the highest value. Also, in terms of leaf area variable, 4 groups were divided, so that Jamshidieh and Qeytariyeh Parks with the lowest values arranged in group a, and Lavizan Park with highest value arranged in group d.

In the case of *C. caucasica*, there was no significant difference in the humidity percent among the study areas ($p > 0.05$), but the difference between the 2 variables of SLA ($p < 0.01$) and leaf area ($p < 0.01$) were significant. Based on the grouping of the mean values of the SLA (Table 3), most of the study areas arranged in same group. Qeytariyeh Park with the lowest value arranged in group a, and City Park and National Botanical Garden of Iran with highest value arranged in group c. Also, 4 groups were separated for leaf area variable, so that Qeytariyeh Park with the lowest value were in group a, and City Park with the highest value were in group d. The other study areas were also in intermediate positions.

The correlation between quantitative variables of leaf (leaf area and SLA) and air pollutants appeared in both of *P. orientalis* and *C. caucasica*, only there was a significant negative relationship between leaf area and O₃ (Table 4). This relationship was stronger in *C. caucasica* ($R^2 = -0.78$). In other cases, no significant relationship was observed between quantitative variables of leaf and pollutants.

Ozone has been found to cause significant damage to plants worldwide, including crops and natural ecosystems (Grulke and Heath 2020). During the growing season, O₃ can harm sensitive vegetation, with over 90% of vegetation damage resulting from tropospheric O₃ alone. This damage can lead to reductions in crop yield and forest production ranging from 0% to 30% (Adams et al. 1989). Sufficient O₃ can reduce photosynthesis in sensitive plants (Watanabe et al. 2018), which is the process that plants use to convert sunlight into energy for growth, and slow down plant growth, increase the risk of disease and damage from insects and other pollutants, and harm plants through severe weather. For example, Hoshika et al. (2013) demonstrated that O₃-induced stomatal closure in Siebold's beech (*Fagus crenata* Blume) during early summer reduced O₃ influx and allowed the maximum photosynthetic capacity to be reached, but was not sufficient in older leaves to protect the photosynthetic system. Certain plants may show visible signs of injury when exposed to O₃ under specific conditions, including changes in pigmentation or bronzing, chlorosis, premature senescence after chronic exposure to low O₃ concentrations, and flecking and stippling after acute exposure to high O₃ levels. The deleterious effects of O₃ on individual plants can consequently

Table 4. Pearson correlation coefficient between leaf area (cm²) and amount of O₃ (ppm) in the study species and study areas.

Species	Urban forest									
	Qeytariyeh Park	Jamshidieh Park	Green space of Hemmat Highway	15 Khordad Park	Taleghani Park	Green space of Al-Zahra University	Lavizan Park	Shafaq Park	City Park	National Botanical Garden of Iran
<i>P. orientalis</i>	-0.71 *	-0.70 *	-0.60 *	-0.66 *	-0.70 *	-0.67 *	-0.71 *	-0.65 *	-0.70 *	-0.61 *
<i>C. caucasica</i>	-0.73 *	-0.71 *	-0.66 *	-0.68 *	-0.71 *	-0.70 *	-0.78 *	-0.74 *	-0.74 *	-0.71 *

*Significant at $p < 0.05$

result in negative impacts on ecosystems, such as alterations in the specific composition of plants existing in a forest, modifications in habitat quality, and changes in water and nutrient cycles. The specific reaction of a particular specimen to O₃ injury is reliant on its capacity to offset such injury. Dose-response relationships, therefore, differ based on the plant species, crop cultivar, developmental stage, and external environmental factors, such as water availability and temperature that influence the opening and closing of stomata (Mauzerall and Wang 2001). Given that the external environmental factors, including temperature, soil, and irrigation conditions, as well as the age of the 2 study species, were identical in each region of our investigation, it appears that the discrepancy in the impact of O₃ on the leaf area of the 2 species can be attributed to species-specific factors.

In urban areas, ozone (O₃) primarily arises from intricate photochemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides (NO_x) (Thielmann et al. 2001; Mazzuca et al. 2016). VOCs assist in the oxidation of primary NO emissions from various sources, leading to the formation of NO₂, while also competing with ozone to react with NO and thus preserving the existing ozone levels (Mazzuca et al. 2016). In the past, carbon monoxide (CO) represented the primary air pollutant in Tehran. However, due to recent advancements in fuel quality for automobiles, particulate matter, specifically PM_{2.5}, has become the dominant air pollutant on most days when air quality in Tehran is considered unhealthy. Nevertheless, over the past few years, O₃ has emerged as a major air pollutant during spring and summer, particularly on hot and sunny days. As a result, in the current year, Tehran has experienced unhealthy air conditions for a total of 9 days since the beginning of spring, with 7 of those days attributed to O₃ pollution. This number is expected to increase with rising temperatures in the summer. The surge in carbureted motorcycles emitting hydrocarbons constitutes the primary factor behind the recent increase in O₃ levels in Tehran's air.

In our investigation, it was observed that O₃ had a more deleterious impact on the leaf surface of *C. caucasica*. Certain scholars have underscored the harmful effect of O₃ on leaf morphological indicators. For instance, Dermody et al. (2006) demonstrated that the heightened O₃ expedited senescence, thereby reducing LAI by 40% towards the end of the growing

season in *Glycine max* (L.) Merr. (Soybean). No significant effect on photosynthesis was observed. The primary effect of heightened O₃ on leaf area index (LAI) was found to be through modification of the senescence rate. Reduction in plant leaf area with increasing O₃ concentration was noted in soybeans (Oikawa and Ainsworth 2016). A meta-analysis conducted by Emberson (2020), which involved 263 peer-reviewed articles, investigated the impact of heightened O₃ (an average of 64 ppb) on northern temperate and boreal trees and found an 11% reduction in tree biomass in comparison with those grown in ambient O₃ (Wittig et al. 2009). Moreover, significant declines in root: shoot ratio, leaf area, Rubisco, chlorophyll content, transpiration rates, tree height, and stem diameter were also detected.

CONCLUSION

In general, the results of this research emphasize that air pollutants affect the morphology of tree leaves. The type and amount of its effect depends on various factors such as species, type, amount of pollutants, and environmental conditions. Both study species are widely used in the green spaces of Tehran metropolis, but the use of *P. orientalis* is more common. The morphology of the 2 study species and the morphology of their leaves are very different. In general, *P. orientalis* mature trees are seen as tall trees with wide crowns in urban forests, but *C. caucasica* is shorter and produces a small crown. Leaves of *P. orientalis* are big and wide, while *C. caucasica* has small leaves. Based on the results of this research, the morphological differences of leaves greatly affect their quantitative variables. Also, the 2 study trees have shown a negative reaction to O₃, and the reaction of *C. caucasica* was more severe. It seems that the increase in the amount of O₃ in the air of Tehran in recent years has caused this pollutant to have a greater effect on the tree leaf morphology. It is suggested that in future studies, the impact of air pollutant on other tree species in Tehran urban forests is also evaluated in order to reach a suitable summary about how trees react to air pollutants. The answer to this question can be of great help to city managers in choosing suitable tree species for planting in different green spaces of Tehran.

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Conflicts of Interest:

The authors reported no conflicts of interest.