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Biomonitoring of Potentially Toxic Elements in the Urban Atmosphere of Tehran Metropolis Using the Lichen *Anaptychia setifera* (Mereschk.) Räsänen

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Abstract: This study investigated the bioaccumulation of PTEs in the 22 districts of the Tehran metropolis using the lichen *Anaptychia setifera* collected from Kalpoosh unpolluted area in Semnan province and exposed for 4 months in the study area using the lichen transplant technique. The concentrations of eight potentially toxic elements in the lichen were quantified using ICP-OES analysis. PCA was used to detect common sources of PTEs, and distribution maps were produced using QGIS. A statistically significant difference in the toxic elements was observed among the different stations in the Tehran metropolis. The CF index results indicate severe pollution ($CF \geq 3$) for all eight studied toxic elements in the atmosphere of the Tehran metropolis. The values of the PLI index in the monitoring stations were calculated in the range of 14–31, confirming very high pollution ($PLI \geq 2.5$) in the study area. The results showed a significant accumulation of all investigated toxic elements. Toxic elements such as Fe, Al, and Cr were primarily derived from natural geogenic sources, whereas Co, Cu, Ni, Pb, and Zn originated from anthropogenic sources, predominantly vehicular traffic, as depicted by the distribution patterns of these toxic elements, with peaks near sites with heavy traffic. Overall, the entire study area exhibited severe pollution levels.

Keywords: air pollution; bioaccumulation; contaminated factor; enrichment factor; pollution load index; toxic elements

Academic Editor: Małgorzata Rajfur

Received: 21 December 2024
Revised: 27 January 2025
Accepted: 9 February 2025
Published: 11 February 2025

Citation: Abdollahi, S.; Hassanzadeh, N.; Sohrabi, M.; Loppi, S. Biomonitoring of Potentially Toxic Elements in the Urban Atmosphere of Tehran Metropolis Using the Lichen *Anaptychia setifera* (Mereschk.) Räsänen. *Atmosphere* **2025**, *16*, 206. https://doi.org/10.3390/atmos16020206

1. Introduction

Air pollution is a major concern for public health, as it is consistently associated with adverse health outcomes and reduced life expectancy [1,2], and it has been estimated that air pollution kills roughly 7 million people worldwide each year [3]. Among the many dangerous air pollutants, potentially toxic elements (PTEs), mostly associated with atmospheric particulate matter (PM), are of particular concern due to their adverse effects on human health and the environment [4].

Currently (10 July 2014), more than half of the world's population lives in cities, and this percentage is predicted to increase to 66% by 2050 [5]. This emphasizes the need for monitoring air pollutants in urban environments [6], which is crucial for obtaining information on population exposure [7]. Usually, air pollution is monitored with stationary or mobile physico-chemical devices, which are expensive and require intensive maintenance. Consequently, the net of monitored sites is typically meager, especially in developing countries [8,9]. To circumvent this problem, monitoring pollution using living organisms (biomonitoring) has become increasingly popular [10]. Besides the low cost, the advantages of biomonitoring include the possibility of surveying several sites and obtaining information on the effects of pollutants on living organisms [11,12]. Among biomonitors of air pollution, lichens are the most widely used [13,14], thanks to their ability to accumulate PTEs owing to their nutrition based on the atmosphere, large surface-to-volume ratio, and lack of roots, stoma, and cuticles [15,16].

Numerous studies have demonstrated the successful use of lichens in assessing heavy metal pollution in mining areas [17,18], industrial zones [19,20], and urban areas [21,22].

In contemporary society, a significant number of capital cities globally encounter challenges associated with air pollution [23]. The metropolis of Tehran, one of these capitals, has encountered acute air pollution issues in recent decades, primarily attributed to accelerated population growth, migratory movements, and insufficient consideration of environmental concerns [24]. This phenomenon has reached a level wherein the transit of approximately 2 million diverse vehicles within this urban area [25] has rendered air pollution a critical issue in Tehran [26].

In a research investigation conducted by Sohrabi et al. [27], the assessment of air quality, along with the spatial distribution of toxic elements via the lichen *Ramalina sinensis*, was executed across six distinct locales within the metropolitan area of Tehran. The quantified concentrations of the toxic elements were established in the order of Ca > K > Fe > Mg > Na > Mn > Zn > Pb > Cr > Cu > Ni > Co. Principal component analysis (PCA) indicated that the primary origin of the toxic elements assimilated by the lichen is predominantly associated with vehicular emissions [27].

In a separate investigation undertaken by Khosropour et al. [28] within the metropolis of Tehran, the foliage of the *Platanus orientalis* L. tree species was employed as a biological indicator to assess the concentrations of Cd, Pb, Cr, Ni, and Zn. Specimens were procured from an urban environment and a non-urban forest park. The findings revealed that the concentrations of Cd, Pb, Ni, and Cr in the samples obtained from the urban site were markedly elevated, whereas the concentration of Zn was diminished in comparison to the samples from the forested area [28].

In a separate investigation carried out in Tehran [29], the levels of heavy metals such as Pb, Cu, Cd, Co, Ni, Cr, Hg, and Zn present in sediment particles adhering to the foliage of *Platanus orientalis*, *Ulmus minor 'Umbraculifera'*, and *Robinia pseudoacacia* specimens situated along urban roadways in Tehran were meticulously examined. The findings indicated that Pb, Cu, Cd, Co, Ni, and Zn predominantly represent the contaminants within the assessed locale. Furthermore, it was also determined that chromium and mercury significantly contribute to overall environmental pollution as well [29].

In a separate investigation, the ambient coarse particulate matter (PM), along with its temporal variations, was examined at two distinct sampling locations in central Tehran. To collect the samples, low-volume air samplers equipped with filters were employed, followed by a comprehensive analysis of the chemical constituents of the filters. The findings revealed elevated levels of Cr, Cu, Mn, and Ni within the ambient coarse particulate matter gathered in this research, substances that are recognized for their toxicity and capacity to induce cellular inflammation, thereby posing potential adverse health effects [30].

Since atmospheric pollution is a significant concern within the urban landscape of Tehran, and no extensive research has yet been undertaken on the biomonitoring of air quality utilizing lichens to evaluate the presence of heavy metals across the 22 districts of Tehran, the aim of the present study is to carry out an investigative spatial analysis of atmospheric pollution involving toxic elements within a multifaceted urban context by integrating the biomonitoring of the lichen *A.a setifera* alongside source apportionment analysis to assess the cumulative pollution burden and determine the principal sources of emissions.

2. Materials and Methods

2.1. Study Area, Lichen Species, and Sampling Design

The Tehran metropolis is located in the north of Iran and has a population of approximately 8.7 million inhabitants. Since people from the surrounding cities commute daily to Tehran for work or study, during the day, the population can exceed 12.5 million people [31]. The average relative humidity of the air is about 40%, and the prevailing wind is westerly [32]. The topographic and meteorological conditions contribute to the inadequate quality of air in the Tehran metropolis. At an altitude of 1050–1800 m asl and encircled by the Alborz mountain range, the city is susceptible to air pollution [33].

The species used in this research is the fruticose epiphytic lichen *Anaptychia setifera* (Figure 1), which is widely found on trunks and branches of *Quercus macranthera* trees of the Hyrcanian and Arasbaran forests of Iran [34]. Thalli of *A. setifera* were collected from the Kalpush forest in Semnan Province and deployed in triplicate at 22 monitoring stations (Supplementary Materials), one for each of the 22 districts of the Tehran metropolis, as well as at 2 monitoring sites located outside the Tehran metropolis (Figure 2; Table 1). Lichen transplants were exposed for 4 months (from February 2023 to May 2023) at 2–3 m above ground at each station.

The average temperature for February and March 2023 was approximately 6.05 °C, while in April and May 2023, it reached around 16.1 °C. Additionally, during the four-month exposure period, the prevailing wind direction was from the western region [35].

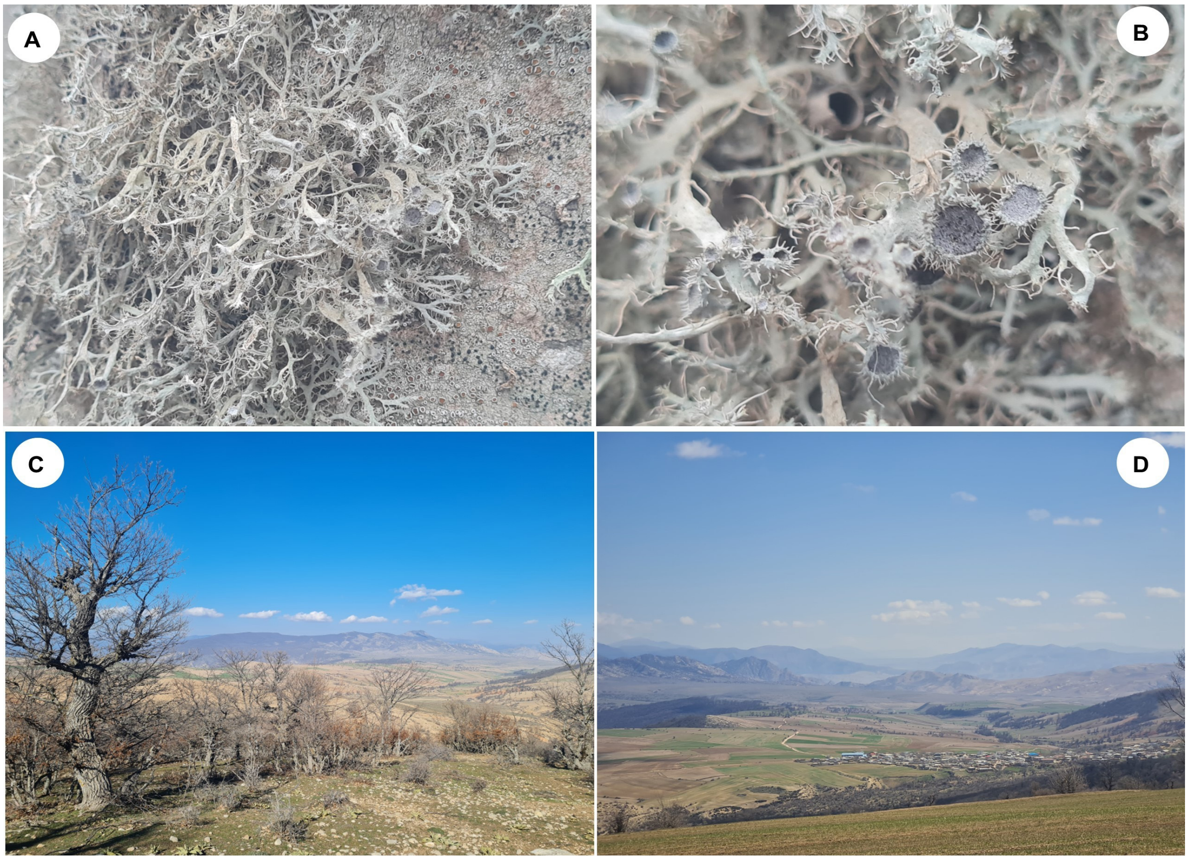


Figure 1. (**A**,**B**) Thallus of *Anaptychia setifera* displaying key morphological features. (**C**,**D**) Semi-arid habitat of the species, highlighting its characteristic environment.

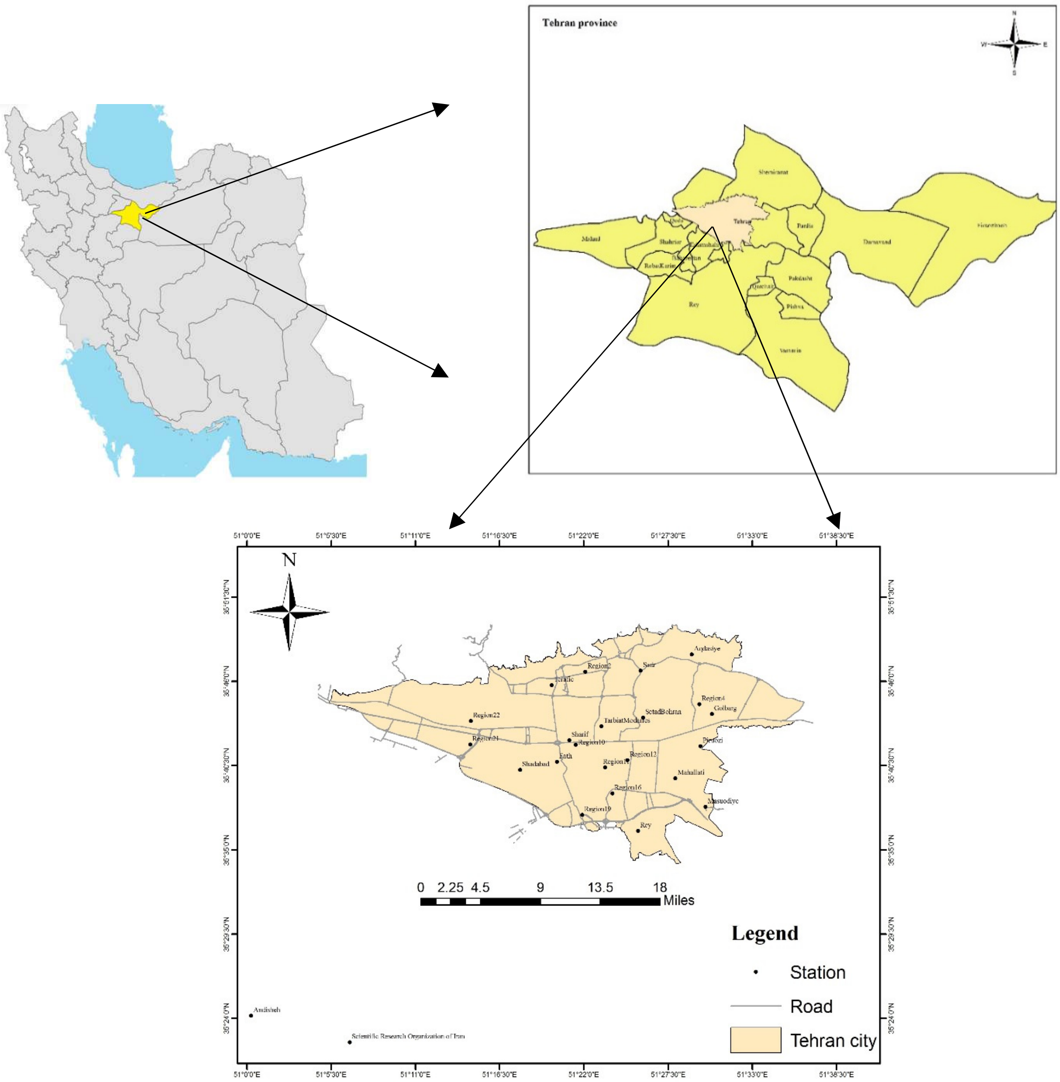


Figure 2. Map of the study area with the location of monitoring stations.

Table 1. Geographic coordinates of the monitoring stations.

Station	Longitude N	Latitude E	District	Location
Aqdasiyeh	51.48414	35.79587	1	North
District 2	51.368175	35.777089	2	North
Sharif	51.35094	35.70227	2	West
Sadr	51.428623	35.778232	3	North
District 4	51.49245192	35.74177414	4	East
Traffic	51.33168	35.7623	5	West
Tarbiat-Modares	51.385909	35.71751	6	Center
Setad Bohran	51.4312	35.72708	7	Center
Golbarg	51.50613	35.73103	8	East
Fath	51.33753	35.67882	9	West
District 10	51.35803	35.69748	10	Center
District 11	51.38973	35.67298	11	Center
District 12	51.414368	35.680708	12	Center

Table 1. *Cont.*

Station	Longitude N	Latitude E	District	Location
Pirouzi	51.49376	35.69599	13	East
Mahallati	51.46636	35.661083	14	East
Masoudiyeh	51.49902	35.63003	15	East
District 16	51.397657	35.644584	16	South
Shadabad	51.29735	35.67005	18	South
District 19	51.36490547	35.62107505	19	South
Shahr-e Rey	51.42571	35.60363	20	South
District 21	51.24311	35.697773	21	West
District 22	51.24364	35.723398	22	West
Iranian Research Organization for Science and Technology (IROST) *	51.42971	35.7223	-	Southwest
Andisheh *	51.01242	35.6732	-	West

* Monitoring sites outside the Tehran metropolis.

2.2. Chemical Analysis

After harvest, the lichen samples were thoroughly cleaned in the laboratory to remove extraneous materials such as debris, moss, and necrotic portions. Afterward, the samples were dried at 65 °C, ground using liquid nitrogen, and sieved through a 500 µm mesh. Approximately 200 mg of the lichen powder was digested with 2 mL of HNO3 in a block digestion system at 150 °C for 15 min [36]. The digested samples were diluted with deionized water once they had cooled to room temperature, filtered through 0.45 µm filters, and made up to 50 mL. The solutions were stored at 4 °C until analysis. The concentrations of the PTEs, namely Al, Co, Cr, Cu, Fe, Ni, Pb, and Zn, were determined by ICP-OES (Optima 8300, Perkin-Elmer), and the results were expressed on a dry weight basis. The analytical quality was checked using the certified reference material IAEA-336 "Lichen".

2.3. Data Analysis

In the field of biological monitoring, several indices have been proposed, including the contamination factor (*CF*) [17], the enrichment factor (*EF*) [37], and the pollution load index (*PLI*) [38], which were used in this study.

2.3.1. Contamination Factor (*CF*)

Equation (1) was used to calculate the contamination factor (*CF*):

$$\mathrm{CF} = C_m / C_c \tag{1}$$

where C_m is the average concentration of each pollutant in the lichens at the monitoring site, and C_c is the average concentration of the same pollutant in the unexposed lichens. The *CF* indicates the pollution levels of each pollutant at each site. The air quality status based on the contamination factor is interpreted as unpolluted ($CF < 1.2$), low pollution ($1.2 \leq CF < 2$), moderate pollution ($2 \leq CF < 3$), and high pollution ($CF \geq 3$) [17].

2.3.2. Enrichment Factor (*EF*)

Equation (2) was used to calculate the enrichment factor (*EF*) as a percentage for every element and monitoring station:

$$EF_E = CE_A - CE_C/CE_C \times 100 \tag{2}$$

where EF_E is the enrichment factor for element E, CE_A is the concentration of element E in the lichen sample, and CE_C is the concentration of the element in the pre-exposure samples. For the interpretation criteria, EF values greater than 100% are considered indicative of a significant enrichment (e.g., a concentration at least twice that of unexposed samples). EF values from 50% to 100% indicate moderate enrichment, while EF values less than 50% are considered to represent normal conditions [39].

2.3.3. Pollution Load Index (*PLI*)

The pollution load index (*PLI*), which uses the ratio of pollutants in the same areas and their levels in the control site, was first reported by [38] and later applied by other researchers using lichens [38]. The *PLI* was calculated as follows [36]:

$$PLI = \left(CF_1 \times CF_2 \times CF_3 \times \ldots \times CF_{n)}\ 1/\mathrm{n}\right. \tag{3}$$

where CF is the contamination factor for each pollutant, and n is the number of pollutants studied. The air pollution load at each monitoring site was evaluated using this index [38]. The interpretation scales for the PLI are $PLI < 0.9$ (unpolluted), $PLI = 1 \pm 0.1$ (background levels), $1.1 < PLI < 1.5$ (low pollution), $1.5 \leq PLI < 2$ (moderate pollution), $2 \leq PLI < 2.5$ (high pollution), and $PLI \geq 2.5$ (very high pollution) [40].

2.4. Statistical Analysis

As the data were not normally distributed (Shapiro–Wilk test, $p < 0.05$), the relationship between the concentrations of PTEs was examined using the Spearman correlation test ($p < 0.05$). Principal component analysis (PCA) was used to investigate the possible sources of PTEs in the study area. Statistical analyses were performed using SPSS version 22 and Microsoft Office Excel. Additionally, a geographical information system (QGIS) was used to generate distribution maps of PTEs and the results of the calculated indices using the inverse distance weighted (IDW) interpolation algorithm.

3. Results and Discussion

The results of the chemical analysis are summarized in Table 2 (the complete dataset is reported in Table 3). Overall, the ranges and median concentrations of the most toxic elements are quite modest compared with other similar studies [41]. The only exceptions are Fe and especially Al, whose values span over an order of magnitude, for which both the minimum and median values are quite high. Notably, the lowest concentrations of the most toxic elements, namely Co, Cu, Ni, Pb, and Zn, were measured at the Iranian Research Organization for Science and Technology (IROST), outside of the Tehran metropolis area, while the highest concentrations for all toxic elements were all inside the Tehran metropolis area, with Cu and Ni at the Shahr-e Rey station, Al and Cr at the Pirouzi station, and the other toxic elements at different stations. The values of the contamination factor (Table 2) indicated that all the study sites, including the two sites outside the Tehran metropolis, were severely polluted ($CF > 3$). The pollution load index (Table 3) was very high ($PLI \geq 2.5$) at all monitoring stations.

Table 2. Concentrations of the investigated PTEs (mg/kg), contamination factors (CFs), and pollution load index (PLI). MAD = median absolute deviation.

	Median ± MAD	Minimum	Maximum	CF
Al	1112 ± 408	550	13,350	63 ± 34
Co	0.31 ± 0.06	0.15	0.49	16 ± 4
Cr	3.5 ± 0.4	2.7	8.0	27 ± 5
Cu	3.1 ± 0.8	0.7	9.3	23 ± 8
Fe	1275 ± 125	849	1864	29 ± 3
Ni	1.4 ± 0.3	0.2	2.1	11 ± 2
Pb	2.4 ± 0.4	0.7	3.9	22 ± 5
Zn	19.1 ± 2.8	12.9	70.9	35 ± 5
PLI	25 ± 3	14	31	-------

Table 3. Contamination factor (*CF*) and pollution load index (*PLI*) at the study sites.

Site	CF								PLI
	Al	Co	Cr	Cu	Fe	Ni	Pb	Zn	
Aqdasiye	102	16	30	25	33	11	17	30	26
District 2	158	16	34	21	30	11	19	38	28
Sharif	36	19	23	25	27	14	20	29	23
Sadr	48	12	29	20	31	8	26	35	26
District 4	29	17	23	20	31	11	23	31	22
Traffic	25	17	21	45	27	11	20	27	22
Tarbiat-Modarres	48	9	21	11	23	6	12	26	16
Setad Bohran	105	18	30	31	32	13	22	37	29
Golbarg	20	17	29	31	23	12	24	31	22
Fath	157	12	34	23	27	8	20	38	27
District 10	41	14	22	20	28	9	25	34	22
District 11	213	15	40	19	32	10	23	47	31
District 12	63	10	23	14	29	6	15	30	19
Pirouzi	250	12	43	13	34	8	16	40	27
Mahallati	36	20	22	35	24	12	27	58	26
Masoudiye	87	18	28	35	32	13	32	34	30
District 16	40	20	21	29	26	14	29	37	25
Shadabad	22	19	21	29	24	13	28	63	25
District 19	79	14	27	25	30	10	23	37	26
Shahr-e Rey	71	21	28	30	33	14	32	40	30
District 21	109	12	29	15	34	8	18	52	25
District 22	36	20	23	35	29	13	28	67	28
IROST	68	9	25	6	24	4	8	24	14
Andisheh	145	10	33	11	30	6	13	30	21

Spearman correlation analysis was utilized to examine the interrelationship among elemental concentrations within the *A. setifera* lichen (Table 4). The findings revealed that several of the toxic elements under investigation in the lichen samples displayed statistically significant correlations ($p < 0.05$ and $p < 0.01$). For example, a positive and statistically significant correlation at the 0.01 level was identified among the following pairs of toxic elements: Co-Pb, Cu-Pb, Cu-Co, Fe-Cr, Al-Cr, Al-Fe, Ni-Pb, Ni-Co, Ni-Cu, and Zn-Pb ($p < 0.01$). Moreover, significant negative correlations were detected between the toxic elements Al-Co, Al-Cu, and Ni-Al. A noteworthy positive correlation was also established between the toxic elements Zn-Co at the 0.05 level ($p < 0.05$).

Table 4. Correlation coefficients between the toxic element concentrations (values in bold = $p < 0.05$).

	Al	**Co**	**Cr**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
Al	-----							
Co	**−0.46 ***	-----						
Cr	**0.81 ****	−0.30	-----					
Cu	**−0.45 ***	**0.81 ****	−0.26	-----				
Fe	**0.63 ****	0.02	**0.63 ****	−0.10	-----			
Ni	**−0.44 ***	**0.97 ****	−0.28	**0.81 ****	−0.03	-----		
Pb	−0.39	**0.77 ****	−0.28	**0.71 ****	0.01	**0.77 ****	-----	
Zn	0.15	**0.43 ***	0.18	0.28	0.30	0.33	**0.54 ****	-----

* and ** indicate significant correlation at 0.05 and 0.01 levels, respectively.

The enrichment factor (*EF*) for the eight toxic elements investigated exhibited significant enrichment (*EF* > 100%) at all monitoring stations (Figure 3).

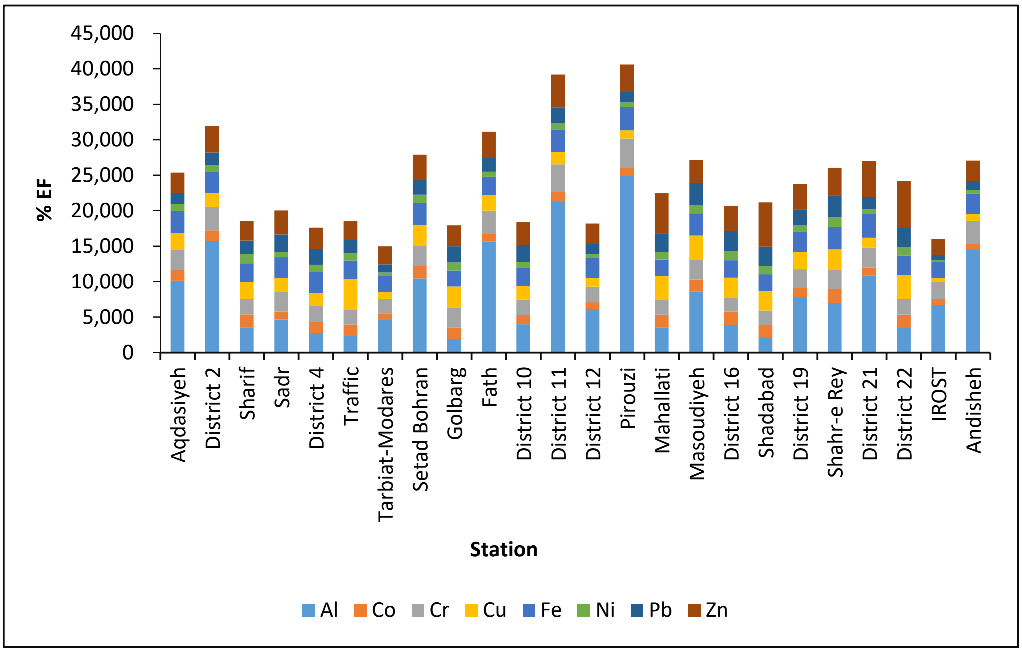


Figure 3. Enrichment factors (%EF) of the investigated toxic elements at the study sites.

The results of the PCA (Table 5) showed that two components had eigenvalues >1 and explained 78% of the total variance. The factor loadings that represent the correlation coefficients between the components and individual toxic elements indicate that the toxic elements with similar factor loadings are characteristic of a specific source. The first components accounted for 50.50% of the total variance and had strong positive factor loadings for Pb, Cu, Co, Ni, and Zn. Al, Fe, and Cr showed higher factor loadings in the second component, explaining 27.50% of the total variance.

Table 5. Factor loading from two main components (principal component analysis, standard varimax rotation) for the lichen sample *Anaptychia setifera*.

Toxic Element	PC1	PC2
Al		0.92
Co	0.94	
Cr		0.93
Cu	0.83	
Fe		0.81
Ni	0.94	
Pb	0.89	
Zn	0.57	
% of variance	50.5	27.5

The distribution maps of the investigated toxic elements showed a wide array of patterns, which were synthesized by the *PLI* map (Figure 4).

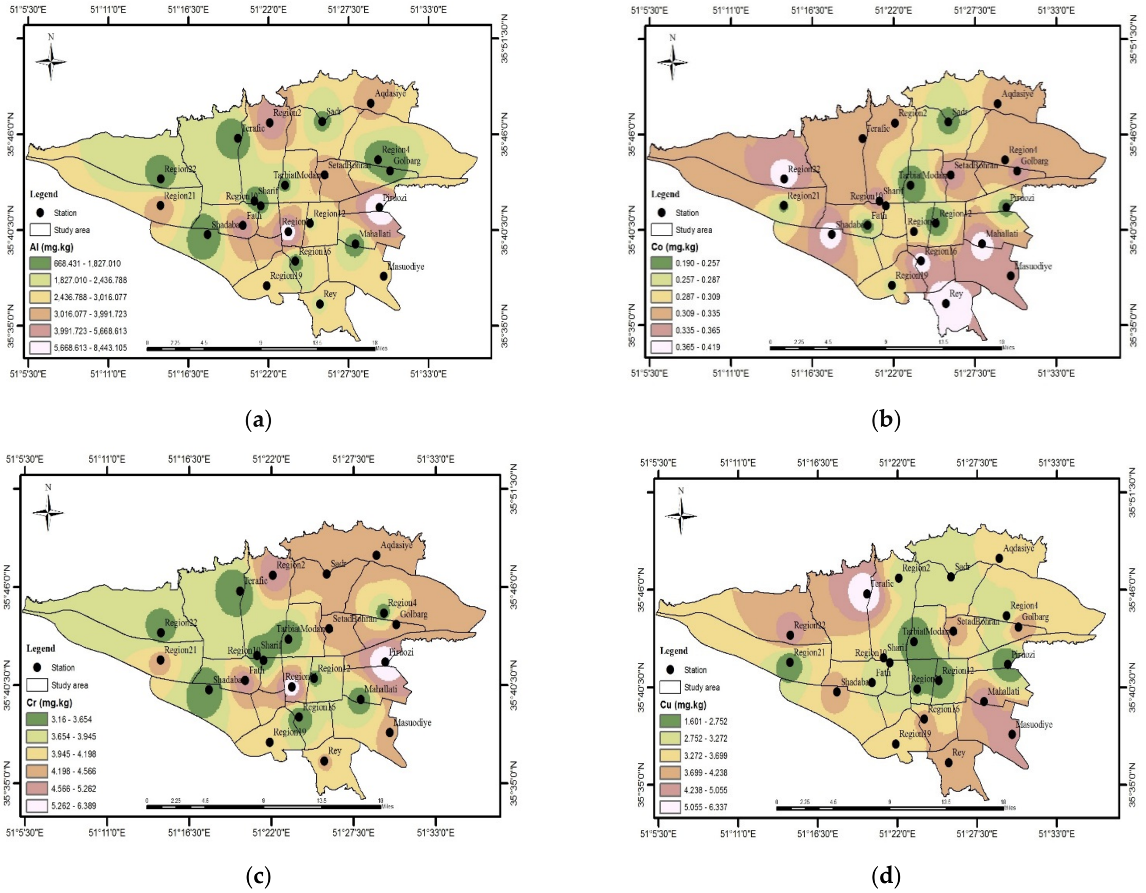
The mean Al concentration within the investigated region was approximated to be around 2796.34 mg.kg of dry weight, exhibiting a coefficient of variation of 73.64%. Elevated Al concentrations were detected in the eastern segment of the study area, particularly at the Pirouzi monitoring station (Figure 4a). The mean Co concentration across the monitoring locations varied between 0.19 to 0.42 mg.kg of dry weight, accompanied by a coefficient of variation of 24.06%. The peak Co concentration was recorded at the Shahr-e Rey station, situated in the southern portion of the urban area (Figure 4b). Cr concentrations throughout various districts of the Tehran metropolis ranged from 3.16 to 6.39 mg.kg of dry weight. The most significant concentrations were located in the eastern sector of the city at the Pirouzi station and in the central region at the District 11 station (Figure 4c). Cu concentrations within the study area fluctuated between 0.90 and 6.34 mg.kg of dry weight. The spatial distribution of copper concentration in the *A. setifera* lichen suggested that the maximum concentration was found at the Traffic station within the western expanse of the Tehran metropolis (Figure 4d).

The Fe concentration in lichen samples varied in a wide range from 1043.92 to 1533.17 mg.kg dry weight with a coefficient of variation of 11.87%, and its highest concentration was observed at stations in District 21 in the west and Pirouzi station in the east of the study area (Figure 4e). The maximum Ni concentration was 1.86 mg.kg dry weight in the southern part of the region and at Shahr-e Rey station and District 16 (Figure 4f). The concentration of Pb in the lichen thalli varied from 0.92 to 3.49 (mg.kg dry weight), and its coefficient of variation was 27.60%, which indicates the homogeneity of the concentration of this toxic element in the lichen thalli in the study area. The Pb distribution map (Figure 4g) shows high concentrations of this toxic element at the Masoudiyeh station (located in District 15) and at the Shahr-e Rey station (located in District 20). The average concentration of Zn was 22.48 mg.kg dry weight, and its coefficient of variation was 29.62%. The highest concentration of Zn was observed at the station in District 22, located in the western part of the Tehran metropolis (Figure 4h).

Since there is strong evidence that the availability of a toxic element is the primary determinant of its bioaccumulation, lichens can be used profitably to assess the environmental levels of PTEs [42]. As a matter of fact, our study with the lichen *A. setifera* exposed for 4 months in the Tehran metropolis and also at two sites outside showed remarkable enrichments (11–63 fold) for all the toxic elements investigated compared to unexposed samples, with *CF* values for all toxic elements classified as high ($CF \geq 3$). Therefore, based on this index, the pollution levels in different parts of the Tehran metropolis are considerable. The synthetic pollution load index (*PLI*) showed values ranging from 14 to 31, confirming very high pollution ($PLI \geq 2.5$) in the study area. This may be due to anthropogenic sources, as well as local geological factors.

Based on the outcomes of the correlation analysis and PCA, we suggest that Co, Cu, Ni, Pb, and Zn are derived mostly from anthropogenic activities, while Al, Cr, and Fe originate from local soils. These results are consistent with those of several other studies in the area.

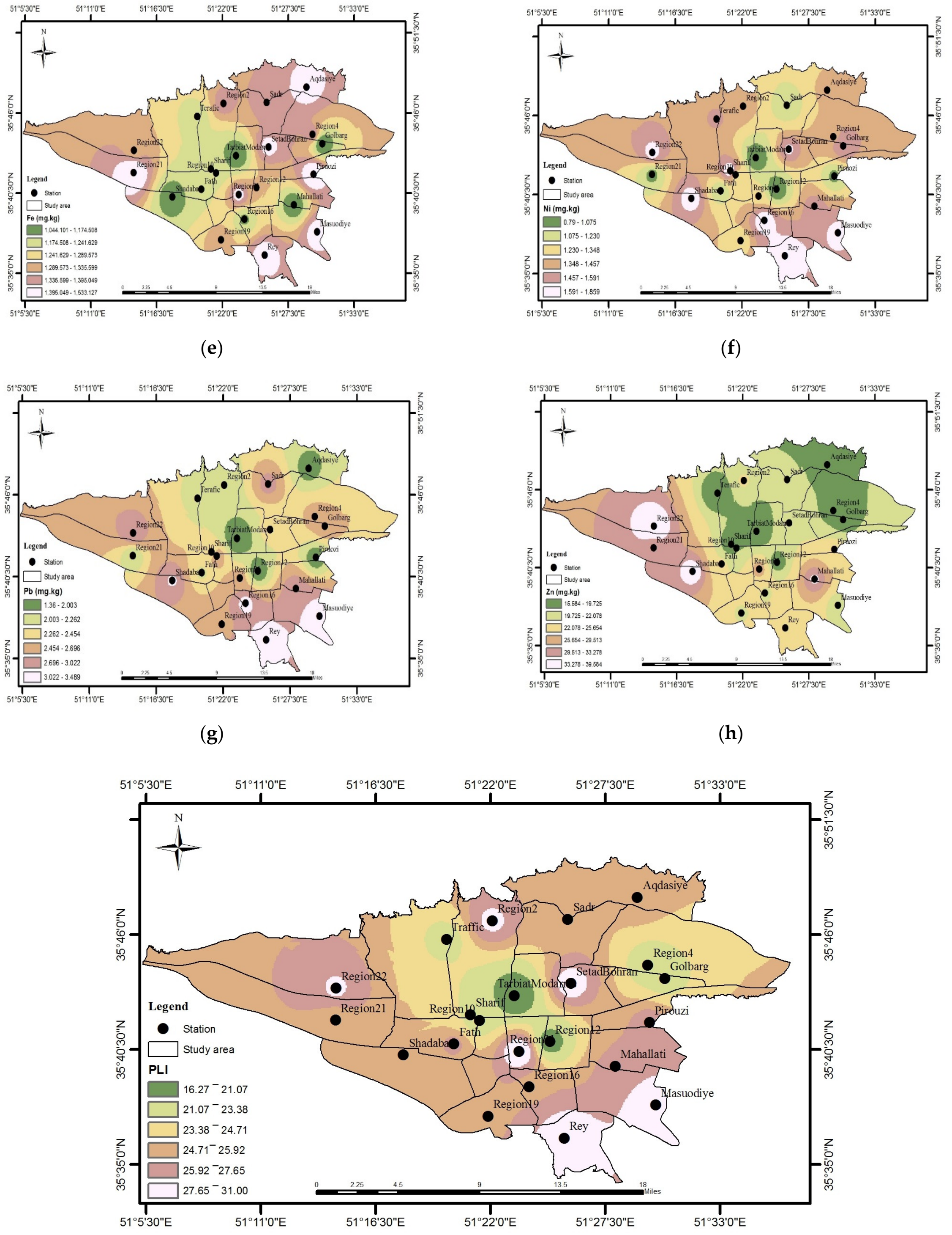
Analysis of the concentration and emission sources of heavy metals associated with PM2.5 particles in the air of the Tehran metropolis by [43] found that Fe and Al originated from natural sources such as the Alborz mountains and aluminum production activities; they also identified human sources such as coal combustion and motor vehicles as the emission sources of Cr [43]. A study of the pollution by PTEs (As, Cd, Co, Cr, Fe, Ni, Pb, Zn) in the atmospheric dust at 44 sites in the Tehran metropolis by [41] showed that the toxic elements were apportioned into two groups: the first one, including As, Co, and Fe, mostly originating from geogenic sources, and the second one, including Ni, Cr, Cd, Pb, and Zn, mostly derived from anthropogenic sources such as traffic, fossil fuel combustion, and industrial activities [41].



(**a**) (**b**)

(**c**) (**d**)

Figure 4. *Cont.*



(e) (f)

(g) (h)

Figure 4. Distribution maps of the investigated toxic elements and PLI.

Investigation of the concentration of toxic elements in the ambient air of industrial and residential areas of the Tehran metropolis by [44] showed that the concentrations of Ce, Co, Cs, La, Sc, Sm, Th, Br, and Hf were higher in industrial areas, and their sources were primarily anthropogenic, while As, Cr, and Zn were similar in residential and industrial areas, suggesting that these toxic elements may originate from natural sources. Moreover, Ag, Mn, Sb, and Cu were higher in residential areas than in industrial areas [44].

Positive Matrix Factorization (PMF) by [45] was used to apportion the sources of toxic elements associated with PM2.5 particles in the air of the Tehran metropolis, and it identified soil and dust resuspension as the main sources of Al and Fe, heavy fuel combustion and fuel oil combustion as the sources of Ni and V, vehicle emissions as the sources of Cu and Mo, and industrial activities and fuel combustion as the sources of Pb, Zn, As, and Cd.

Investigation of the sources and temporal variations of Cu, Zn, Mn, Ba, Al, Fe, Se, Li, Ti, and Si in the coarse particulate matter in the central areas of the Tehran metropolis by [30] showed that road dust is the main source of Cu, Zn, Mn, and, to some extent, Ba; soil and industrial activities had the highest contribution to the emissions of Ba, Al, Fe, Se, Li, Ti, and Si.

Analysis of heavy metal concentrations and emission sources related to heavy metals present in particulate matter in the air of the Tehran metropolis identified Al and Fe as the main components of atmospheric pollution in the study area. Al and Fe are frequent crustal toxic elements that exhibit similar behavior in environmental and atmospheric deposition due to the dispersion of soil dust particles and industrial emissions. The high contents of Al and Fe are probably caused by fine and coarse particles of soil dust in the air, which mainly originate from eroded soils in areas with low vegetation [46].

In addition to lithogenic sources, other factors, such as the lack of green spaces and vegetation cover, industrial activities, and emissions from fuel combustion, can contribute to the elevated concentrations of Al and Fe in the atmosphere [47]. The distribution maps of these toxic elements and the *EFs* showed that the highest concentrations of Al and Fe were observed at the Pirouzi station and District 21 station. The low density of vegetation and the presence of highways and road dust in these areas, as well as the presence of the Tehran-Karaj road and the intensification of dust caused by vehicle traffic, are the main factors of Al and Fe concentrations.

The spatial distribution pattern of Cr was similar to that of Al and Fe, with the highest concentration being found at the Pirouzi station (District 13) and District 11 station (in the center) of the Tehran metropolis. The proximity of the Sorkheh-Hesar protected area and the lack of green space near Pirouzi station can link the high concentration of Al and Cr to geological factors. Also, the presence of various human resources at Pirouzi station and District 11 station, such as fossil fuel combustion, battery manufacturing industries, and various service activities on a high-density urban and suburban scale, are among the main reasons for the Cr concentration at these stations.

Ni and Co toxic elements are naturally present in small quantities in the soil [46]. However, human sources such as dust from mining and construction materials, motor vehicles, fossil fuel combustion, and lubricating oils are potential emission sources of Co and Ni [21,47]. Based on the zoning map of these two toxic elements in the study area, the highest concentrations were found at the Shahr-e Rey station (District 20) in the south of the Tehran metropolis. The highest values of the pollution load index and the contamination factor of the Co and Ni toxic elements were observed in the Shahr-e Rey station. The population density, the slope of Tehran, the existence of industries such as the margarine factory, the cement factory, the petrochemical refinery, and the burning of fuel oil and the use of fossil fuels in the surrounding factories and industries may have led to an increase in the concentration of Co and Ni at this station.

Among the toxic elements studied, Pb showed the lowest concentration. According to the spatial distribution map of toxic elements, the highest concentration of Pb was observed in Masoudiyeh station (in District 15) and Shahr-e Rey (in District 20). The loss of orchards, population density, the impact of ring highways, the direction of the slope, and the presence of westerly currents that transport pollutants from the west to the central areas of the city are among the reasons for the release of Pb. Also, high levels of Pb in the lichen *Flavoparmelia caperata* in relation to traffic by dilapidated cars were found [48].

The presence of Cu and Zn toxic elements in lichen samples can be related to long-range atmospheric emissions from other areas of the city or to local emission sources that play an important role in the contamination of dry and wet sediments with metals [49]. Fuel combustion, natural sources such as dust from local soils [50], vehicle traffic, fossil fuel combustion, and tire and brake pad abrasion are other sources of emission of these toxic elements [21].

The Traffic station (in District 4) also showed high contamination of Cu element due to its proximity to the highway and main boulevards and high traffic. Also, gasoline and diesel combustion, vehicle brake abrasion, and dispersion of suspended particles could have increased the copper concentration in this area.

High concentrations of Zn toxic elements were observed in a belt in the west and southwest at stations in District 22, Shadabad, and District 21, respectively. Areas were characterized by high traffic volumes, industrial and workshop activities, the presence of automotive industries, pharmaceuticals, repair shops, the presence of carburetor motorcycles, road transportation, wasteland, and, to some extent, agricultural activities in the western part.

Also, it has also been shown that various human activities, including vehicle traffic, construction, and fossil fuel burning, are the main components for the accumulation of Cu, Zn, Pb, and Ni in several lichen species in Srinagar city, India [51]. A study was conducted to investigate the spatial distribution of toxic elements such as Cu, Cd, Ni, Pb, and Zn in soil particles across different land uses in an industrial area in the western part of the Tehran metropolis [52].

Based on the results obtained, the main anthropogenic source of Co, Cu, Ni, Pb, and Zn is vehicular traffic. Continuous investigation of the seasonal and spatial variations of Zn, Cd, Pb, Ni, and Cu in atmospheric dust in the Tehran metropolis by [53] showed remarkable pollution by these toxic elements and identified traffic as the main contributor to their concentrations. As a further confirmation, the distribution patterns of these toxic elements showed that their peaks are located near sites with heavy traffic loads.

The results showed that proximity to highway, heavy traffic, and large industrial factories are the main contributors to the increased PTE concentration. In addition, high population, low land and housing prices, the slope of Tehran, the use of dilapidated vehicles, the lack of minimum facilities due to the urban zoning, and the lack of a green belt may have led to the increased concentration of these toxic elements.

4. Conclusions

Heavy metals found in atmospheric particulate matter are a significant component of urban environmental pollution. In the present study, which is the first report on the biomonitoring of air pollutant toxic elements across all regions of the metropolitan area of Tehran using the epiphytic lichen species *Anaptychia setifera*, an initial assessment of the overall air quality status in terms of various toxic elements was carried out based on the results of the bioaccumulation of toxic elements by this lichen species.

The results indicated that the entire area displayed high levels of pollution. The results showed a significant accumulation of all investigated toxic elements. Toxic elements such as Fe, Al, and Cr were primarily derived from natural geogenic sources, whereas Co, Cu, Ni, Pb, and Zn originated from anthropogenic sources, predominantly vehicular traffic.

The results of this study confirmed both natural and anthropogenic components contributing to elevated heavy metal levels in the samples. In the southern and central regions, anthropogenic factors play a significant role, while a combination of both anthropogenic and natural factors is most influential in the eastern and western regions, contributing the most to atmospheric heavy metal levels.

The northern regional areas of the city exhibit a higher proportion of urban zones compared to some factors that contribute to vehicle tire wear, traffic congestion, fuel combustion, and dust infiltration.

The southern regions have faced elevated pollution levels due to factors such as population density, the presence of waste incineration facilities, the Tehran refinery, vacant lands, ring roads, emissions from various industries and vehicles, and westerly winds that carry pollutants from the western suburbs to the southern parts of the city. The central areas of Tehran structurally encompass a variety of urban and metropolitan-scale service activities with high density. Simultaneously, they feature an extensive network of streets and squares throughout Tehran. This area itself attracts population growth and leads to heightened pollution in the central regions.

Air pollution in the eastern and western regions results from a combination of natural and human factors, including soil erosion, loss of gardens and vegetation, traffic and fossil fuel combustion, population density, a high density of buildings and construction activities, the presence of various industries, carburetor motorcycles, and the proximity of Mehrabad Airport to these areas. This study highlights the need for integrated land use planning and optimization of public transportation systems. Restricting polluting activities, expanding green spaces, and relocating industries could significantly reduce pollution levels.

As the first study on lichen transplant and its relationship with exposure to air pollutants in the metropolitan city of Tehran, one limitation of this research is that if conditions had allowed for the preparation of a larger number of samples, sampling in different seasons, or sampling of a greater variety of sensitive lichen species, we could have certainly achieved better results in assessing air quality in Tehran.

One of the advantages of this study is that it represents the first comprehensive report on the biological monitoring of air pollutant toxic elements across all areas of the Tehran metropolis, utilizing the epiphytic lichen species *A. setifera*. This provides a preliminary assessment of the overall air quality status concerning various toxic elements.

In addition, the results of this study show that this approach can serve as a baseline for future periodic repetitions to monitor the temporal trends of toxic element deposition. It can be concluded that the lichen transplant method with *A. setifera* is suitable and cost-effective for monitoring airborne PTEs and mapping the different levels of air pollution in the Tehran metropolis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos16020206/s1.

Author Contributions: Methodology, Software, Validation, Writing—Original Draft, S.A.; Supervision, Conceptualization, Investigation, Funding Acquisition, N.H.; Methodology, Investigation, M.S.; Methodology, Investigation, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Malayer University. (Grant No. 84.9-162).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all the subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, [Hassanzadeh., N], upon reasonable request.

Acknowledgments: The authors of the article express their gratitude and appreciation to the air quality control experts in Tehran, especially Khalili, for their cooperation and issuance of the necessary permits to conduct the lichen transplantation process at the air quality control stations and the Aria Shimi Sharif laboratory in Karaj for performing the analyses.

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

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