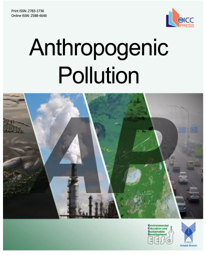

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Assessment of potentially toxic elements pollution in soils and plant leaves along the high-traffic highway zones in Tehran, Iran

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Abstract:

The accumulation of potentially toxic elements (PTEs) in roadside soils and plant leaves due to vehicular emissions presents significant environmental and public health risks, particularly in densely populated urban areas. This study evaluated the concentrations of five PTEs—copper (Cu), lead (Pb), nickel (Ni), cadmium (Cd), and zinc (Zn)—in soils and leaves of three urban plant species (Pine, Cypress, and Mulberry) across six highways in Tehran, Iran, categorized into high, medium, and low-traffic zones. Soil samples were collected at a depth of 0–30 cm, and leaf samples were obtained from the canopy's outer sections. Samples were digested with aqua regia (soil) and nitric-hydrochloric acid (leaves) and analyzed using atomic absorption spectrophotometry. Pollution indices, including Pollution Load Index (PLI), Transfer Factor (TF), and Bioaccumulation Factor (BCF), were applied to assess contamination levels and metal mobility.The results showed moderate pollution levels across high-traffic zones (PLI = 3.94), with cadmium (Cd) contributing the most significant ecological risk (RI = 154.50). Transfer Factor (TF) analysis revealed high bioavailability for zinc (TF = 0.78) and lead (TF = 0.81), while cadmium exhibited limited uptake by plants (TF $<$ 0.004). Bioaccumulation Factor (BCF) calculations indicated Pine and Cypress species had higher potential for metal uptake, with BCF values exceeding 1 for zinc and lead in high-traffic areas, whereas Mulberry demonstrated relatively lower accumulation. Despite a normalized NIPI index value of 1, the enrichment factor (EF) for zinc (EF = 98.04) underscores significant anthropogenic contributions, particularly from non-exhaust vehicular emissions. These findings highlight the need for ongoing monitoring, effective traffic management, and remediation strategies to address heavy metal pollution in urban environments.

Keywords: Bioaccumulation factor; Pollution load index; Transfer factor; Tehran highways

1. Introduction

The degradation of essential ecosystem components - air, soil, and water - due to industrialization, urbanization, and increased transportation activities is a significant concern for environmental health and sustainability (Fataei, 2017). The effect of traffic zones on urban mobility and environmental factors is multifaceted, influencing congestion, travel behavior, and local economies. Traffic zones, such as construction work zones and limited traffic zones (LTZs), can lead to both positive and negative outcomes, impacting travel times, air quality, and economic activities. The following sections elaborate on these effects. Construction work zones often result in increased congestion and longer travel times due to lane reductions and detours (Vyas and Varia, 2023). In Tehran, the introduction of Restricted Traffic Zones (RTZ) and Odd-Even Zones (OEZ) reduced car usage but increased travel times due to inadequate infrastructure for alternative transport modes (Salarvandian et al., 2017). Work zones contribute to air pollution and noise, necessitating effective traffic management strategies to mitigate these effects (Vyas and Varia, 2023). The implementation of LTZs can improve local air quality by reducing vehicle emissions, although the economic impact on local businesses must be considered. LTZs can have mixed effects on local economies; successful zones like Vomero in Naples saw positive outcomes, while others like Chiaia faced challenges due to insufficient public transport and parking (Biggiero, 2014). Traffic management innovations, such as reversible lanes in work zones, can enhance traffic flow and reduce travel time losses, benefiting commuters. While traffic zones aim to improve urban mobility and environmental conditions, they can also lead to unintended consequences, such as increased travel times and economic strain on local businesses. Balancing these factors is crucial for effective urban planning.

Soil pollution along highways is a significant environmental concern, primarily driven by potentially toxic elements accumulation from vehicular emissions and other anthropogenic activities (Ghobadi et al., 2024). Studies indicate that roadside soils often exhibit elevated levels of potentially toxic elements, which can pose risks to both ecological health and human well-being (Fataei et al., 2018). The following sections outline the key aspects of soil pollution along highways. Traffic is a notable contributor, with studies showing that potentially toxic elements like lead (Pb), cadmium (Cd), and arsenic (As) are prevalent in roadside soils due to vehicle exhaust. While traffic contributes approximately 9.77% to metal pollution, natural sources account for 64.51%, indicating a complex interplay of factors affecting soil quality (Peng et al., 2024). Research indicates that while some potentially toxic elements remain below national limits, others like Cd and Hg show slight enrichment, suggesting ongoing pollution (Peng et al., 2022). In certain areas, pollution load indices indicate confirmed pollution states, raising concerns about long-term health risks. Metal accumulation can disrupt soil ecosystems and enter the food chain, posing risks to public health (Al-Mashhadi and Alabadi, 2023). Continuous environmental monitoring is essential to assess soil health and implement remediation strategies, especially in areas with high metal concentrations (Martsev and Selivanov, 2024). Conversely, while potentially toxic elements pollution is a pressing issue, some studies suggest that natural soil processes can mitigate pollution effects over time, highlighting the need for balanced management strategies that consider both human and environmental factors (Fazeli et al., 2018). Monitoring and remediating soil pollution along highways in urban areas requires a multifaceted approach that integrates various methodologies and technologies. Effective strategies encompass both monitoring techniques to assess soil health and remediation practices to restore contaminated soils (Fataei, 2020). Soil Testing and Remote Sensing: Utilizing soil testing kits and remote sensing technologies allows for the assessment of soil health indicators, including nutrient levels and contaminant concentrations. Regular bio indication through the analysis of potentially toxic elements in vegetation provides insights into soil pollution trends, enhancing the objectivity of monitoring efforts. Combining chemical-analytical methods with bio diagnostic techniques, such as phytotoxicity assessments, offers a comprehensive evaluation of soil health. This technique employs plants to absorb and detoxify pollutants, effectively improving soil quality (Schan et al., 2024). Utilizing organic waste materials can enhance soil structure and fertility while mitigating pollution (Sut-Lohmann et al., 2024). A combination of physical, chemical, and biological remediation methods is recommended to address the complexities of urban soil contamination (Rahman et al., 2022). While these methods are effective, challenges remain, such as the need for continuous monitoring and the variability in soil types, which can affect remediation success. Addressing these challenges is crucial for sustainable urban soil management.

The presence of plants and green spaces in high-traffic zones significantly mitigates environmental pollution, particularly air quality issues. Research indicates that urban green areas can effectively reduce concentrations of harmful pollutants such as PM2.5, NO2, and SO2, thereby improving public health outcomes. The following sections elaborate on the mechanisms and benefits of green spaces in urban environments. Urban green spaces correlate with lower levels of air pollutants, as demonstrated in studies across various cities (Wang et al., 2022). Vegetation acts as a natural barrier, absorbing pollutants and improving air quality downwind of traffic sources (Baldauf et al., 2020). Specific plant types, such as trees, are particularly effective in trapping particulate matter and gases (Dhadse, 2022). Green spaces help regulate urban microclimates by reducing temperatures and humidity, which can further decrease pollution levels. The cooling effect of parks can mitigate the urban heat island effect, leading to less energy consumption and lower emissions from cooling systems (Makhelouf, 2009). The reduction of air pollutants is linked to decreased respiratory diseases and overall improved public health (Wang et al., 2022). Green areas not only enhance air quality but also provide psychological benefits, promoting well-being in urban populations. Conversely, while green spaces are beneficial, their effectiveness can vary based on factors such as plant species, density, and urban design. In some cases, poorly planned vegetation may inadvertently trap pollutants, highlighting the need for strategic urban planning to maximize benefits.

In recent decades, the continuous increase in industrialization, urbanization, and transportation has led to the degradation of all three main components of the ecosystem: air, soil, and water (, n.d.). Among these, soil plays a vital role as a source of protection and food production, and its quality is influenced by human activities. In this context, road transportation is a major factor contributing to soil pollution and exacerbating environmental threats (Abderrahmane et al., 2021; Hamidi et al., 2024; Yousefi et al., 2024). Various levels of soil pollution along roads are linked to the construction, maintenance, and operation of roads, primarily caused by exhaust (fuel combustion) or non-exhaust emissions (particles from road surface wear, vehicle body wear, engine components, brake pads, tires, clutches, motor oil leakage, and battery corrosion). Further-more, different environmental (climatic conditions such as rainfall and temperature), traffic (traffic volume and vehicle speed), and road conditions (road age, slope, length, and surface coverage type) affect the dispersion of metal pollutants in the roadside environment. Globally, the increase in motor vehicles is positively correlated with higher air pollution levels in urban areas (Norton et al., 2024; Patel et al., 2024; Yousefi et al., 2024).

Potentially toxic elements are among the most significant chemical pollutants and are considered one of the most dangerous emissions related to traffic. Unlike organic pollutants, they are not degraded by biological or chemical processes and tend to accumulate in the environment and biological systems (Pascu et al., 2024). Soil contamination with these metals has become a major environmental issue. Toxic metals are not biodegradable and, due to their mobility and accumulation potential in plants and vegetation, they quickly enter the food chain (Patel et al., 2024). Potentially toxic elements such as cadmium, lead, zinc, and copper are found among the materials emitted from traffic. The impact of road transportation on the environment and, consequently, on roadside soil ecosystems is now far more significant than other transportation sectors. Other studies have identified potential sources of pollution, such as paints used in coatings (containing chromium and nickel) and the corrosion of metal parts at high temperatures, which can release toxic metals like lead, cadmium, copper, and zinc. Older roads with high traffic density, compared to newly built roads with lower traffic, can contribute to higher concentrations of metals in roadside soils (Salarvand et al., 2021; Terzi and Kalkan, 2024; Wang et al., 2024; Yousefi et al., 2024).

The accumulation of potentially toxic elements in roadside soils and plants due to transportation activities worldwide poses various environmental risks. The increasing levels of metals in the surrounding environment are particularly concerning due to their non-biodegradable nature. The accumulation of potentially toxic elements in soils around roads and highways can lead to their transfer to nearby vegetation. Some plant species can accumulate high levels of toxic metals, which potentially threaten animals and humans (Terzi and Kalkan, 2024). Some metals like zinc, iron, manganese, and copper are essential nutrients for plants, while others such as lead, cadmium, mercury, and chromium are highly toxic. Various plant species are capable of absorbing potentially toxic elements from their environment, but trees have unique characteristics. Trees produce large amounts of biomass, possess extensive root systems for absorbing potentially toxic elements from the soil, do not serve as food sources for animals like agricultural and grass species, and their high evapotranspiration rates increase water flow through the tree, facilitating metal transfer to aerial parts. Since trees are stationary and their leaves are constantly exchanging with atmospheric gases through transpiration, they play an important role in trapping and accumulating atmospheric pollutants. Therefore, trees are considered excellent for biological monitoring and surveillance of air pollution, and subsequently, soil contamination. Thus, studies on determining the level and type of pollutants from urban and industrial traffic in tree leaves can help indicate the status of potentially toxic elements and offer practical solutions for environmental remediation (Mansour et al., 2024; Nazai et al., 2022; Terzi and Kalkan, 2024). Tehran, one of the major cities in Iran, faces environmental pollution challenges, particularly air pollution. Natural factors contributing to this problem include the city's mountainous surroundings, lack of consistent winds with adequate speeds, and low precipitation. Human-induced factors such as rapid urban population growth, numerous old and inefficient industries, and an excessive number of vehicles entering the city's transportation system contribute to significant pollution in air, soil, and vegetation. Traffic is a major source of metal pollution in plants and soil along roadways, as reported by various researchers (Won et al., 2022). Due to the physical and chemical properties of soil, different compounds of potentially toxic elements accumulate in the soil particles, particularly in the top layer, and the particles are affected by them. It has been shown that soils along roadsides and dust across the world are contaminated with Pb, Zn, Cd, Ni, Cr, Cu, As, and Hg (Wang et al., 2024). Other sources of metal pollution in urban soils include fuel combustion and lubricating oils, brake wear, and tire friction. The presence of metals like copper, cadmium, lead, and zinc in roadside soils is a major indicator of pollution, originating from components of gasoline, oil lubricants, vehicle parts, and industrial emissions. Studies have shown that high concentrations of zinc are associated with non-exhaust traffic emissions. The use of zinc in lubricants and vehicle tire coatings and the continuous use of vehicles in urban environments contribute to significant emissions of zinc into the atmosphere, ultimately accumulating in the soil. Lead concentrations in roadside soils are significantly correlated with the number of motor vehicles (Sager, 2020).

The accumulation of potentially toxic elements in plants and soils along urban highways can pose direct and indirect risks to all living organisms, disrupting ecosystem balance. Monitoring potentially toxic elements is crucial for identifying and controlling pollution. Sager (2020) evaluated soil pollution in an old highway in Romania. The results showed the concentration ranges of metals: cadmium between 0.15 to 0.42 mg/kg, copper between 16.2 to 76.27 mg/kg, nickel between 17.4 to 28.4 mg/kg, and zinc between 149 to 535 mg/kg. The evaluation of pollution indices and the soil accumulation index indicated moderate pollution levels. Akinsete and Olatimehin (2024) assessed the concentrations of potentially toxic elements in soils along high-traffic roads in Ibadan, Nigeria. The concentrations of cadmium, nickel, and lead ranged from 1.3 to 5.3, 15 to 24.5, and 41.6 to 56.8 mg/kg, respectively. Health risk assessments for children and adults showed that ingestion was the primary exposure route for metals. The hazard index and cumulative hazard index were less than 1, indicating a safe level of exposure. Lei et al. (2024) evaluated the concentration and ecological risk assessment of potentially toxic elements in plant leaves along roads in Baoji City, China. Five plant species (Ophiopogon japonicus, Ligustrum vicaryi, Platanus acerifolia, Sophora japonica, and Cedrus deodara) were selected. Results indicated relatively high concentrations of zinc, copper, and lead in roadside plant leaves. In May, the concentration of potentially toxic elements in C. deodara leaves was the highest, while in November, it was the highest for S. japonica. The study highlighted that areas with high pollution levels were affected by traffic and industrial activities. The pollution index and the potential ecological risk index for cadmium were the highest, indicating that potential cadmium damage to the environment should be a focus for governmental attention. Kaur et al. (2022) examined metal concentrations in soils and plants (Alstonia scholaris, Nerium oleander, Tabernaemontana divaricata, and Thevetia peruviana) along roads in urban areas of Amritsar, Punjab, India, under different traffic densities. The results showed that the concentration trend for potentially toxic elements in soils and plants was Zn $>$ Cu $>$ Pb $>$ Cd. They reported significant pollution in soils and plants linked to vehicle emissions, posing potential health risks. Amuah et al. (2024) monitored and assessed surface soils impacted by regional roads and different traffic conditions. The results showed that the concentrations of cadmium, lead, and zinc were between 0.21 to 0.58, 13.6 to 41.96, and 40.31 to 63.97 mg/kg, respectively, regardless of the road type. These metal concentrations decreased as the distance from the road increased. **Ho2017<empty citation>** assessed the health risks of potentially toxic elements in urban soils in China. The results indicated that non-carcinogenic risks for all metals (Cd, As, Pb, Cu, Hg, and Cr) were acceptable, while the 95% cumulative cancer risk exceeded 1×10^{-6}, indicating a high potential for cancer risk. The sensitivity analysis identified key factors affecting daily pollutant absorption, including particle emission factor (PEF), exposure frequency (EF), and metal concentrations. Norouzi et al. (2015) studied the potential of using plane tree leaves as a biomonitor for air pollution. The results showed that plane tree leaves have a high potential for determining pollution indices for metals. Barinova et al. (2020) investigated the concentrations of lead and nickel in tree leaves along roads in the city of Umuahia. Leaf samples were collected during the dry season from five dominant trees along a high-traffic route (SS1) and a low-traffic route (SS2). The average concentrations of lead in SS1 and SS2 were 12.09 and 0.05 mg/kg, respectively, while the average concentrations of nickel in SS1 and SS2 were 2.26 and 0.09 mg/kg, respectively. Significant differences were observed for the concentrations of lead and nickel between the two locations, indicating that traffic volume may influence levels of lead, nickel, and other metals, along with pollutants.

The literature emphasizes the need for continuous monitoring of potentially toxic elements concentrations in urban environments to identify pollution sources and mitigate risks. The review suggests that trees can serve as effective bio indicators for monitoring air and soil pollution due to their ability to absorb and accumulate pollutants.

Despite the extensive research on the impact of traffic zones and soil pollution, several gaps remain. Firstly, while the effects of construction work zones and LTZs on urban mobility and air quality have been studied, there is limited research on their combined impact on soil pollution. Secondly, the interplay between natural and anthropogenic sources of soil pollution is not fully understood, necessitating more comprehensive studies to disentangle these factors. Thirdly, while the benefits of green spaces in mitigating air pollution are well-documented, their effectiveness in reducing soil pollution and the specific mechanisms involved require further investigation. Lastly, there is a need for more integrated approaches that combine monitoring, remediation, and urban planning to address the multifaceted nature of urban pollution. This study aims to address these gaps by providing a comprehensive analysis of the impact of traffic zones on both urban mobility and soil pollution. The novelty of this research lies in its integrated approach, combining the assessment of traffic management strategies, soil pollution monitoring, and the role of green spaces in mitigating environmental pollution. By addressing these objectives, this study aims to contribute to the development of effective strategies for mitigating urban pollution and enhancing environmental sustainability.

2. Materials and methods

2.1 Study area

The study area is the urban region of Tehran, located between latitudes 35°35′N to 35°48′N and longitudes 51°17′E to 51°33′E, covering an area of 733 km^2. The average elevation is 1220 m above sea level, with an annual mean temperature of 18 °C and an average annual rainfall of 210 mm. The dominant wind direction, based on meteorological data, is northwesterly. Tehran faces significant air pollution challenges, influenced by the presence of over 8 million vehicles and traffic, which contribute to soil pollution through deposition. The population of Tehran in 2021 was approximately 9 million. Additionally, industrial activities, due to improper placement and lack of environmental regulations, play a major role in Tehran's pollution. Over 7000 industrial units are located in Tehran, with 30% in the west, 54% in the south, and 16% in the east. The dominant wind patterns direct pollutants from these factories into the city, intensifying pollution. Alongside large industries, smaller operations like auto repair shops and gas stations also contribute to the city's environmental contamination. Industrial activities in Tehran pollute both air and soil, leading to health and environmental problems for residents.

2.2 Sampling locations

To examine the potential of tree species used in Tehran's green spaces to absorb potentially toxic elements resulting from traffic, six highways with varying traffic densities were selected (figure 1):

1. High-traffic highways: Hemmat and Imam Ali highways
2. Medium-traffic highways: Chamran and Modarres highways
3. Low-traffic highways: Bakeri and Yadegar Imam highways

Selection of highways and plant species in a study is typically based on several scientific, practical, and environmental considerations. High-traffic highways are expected

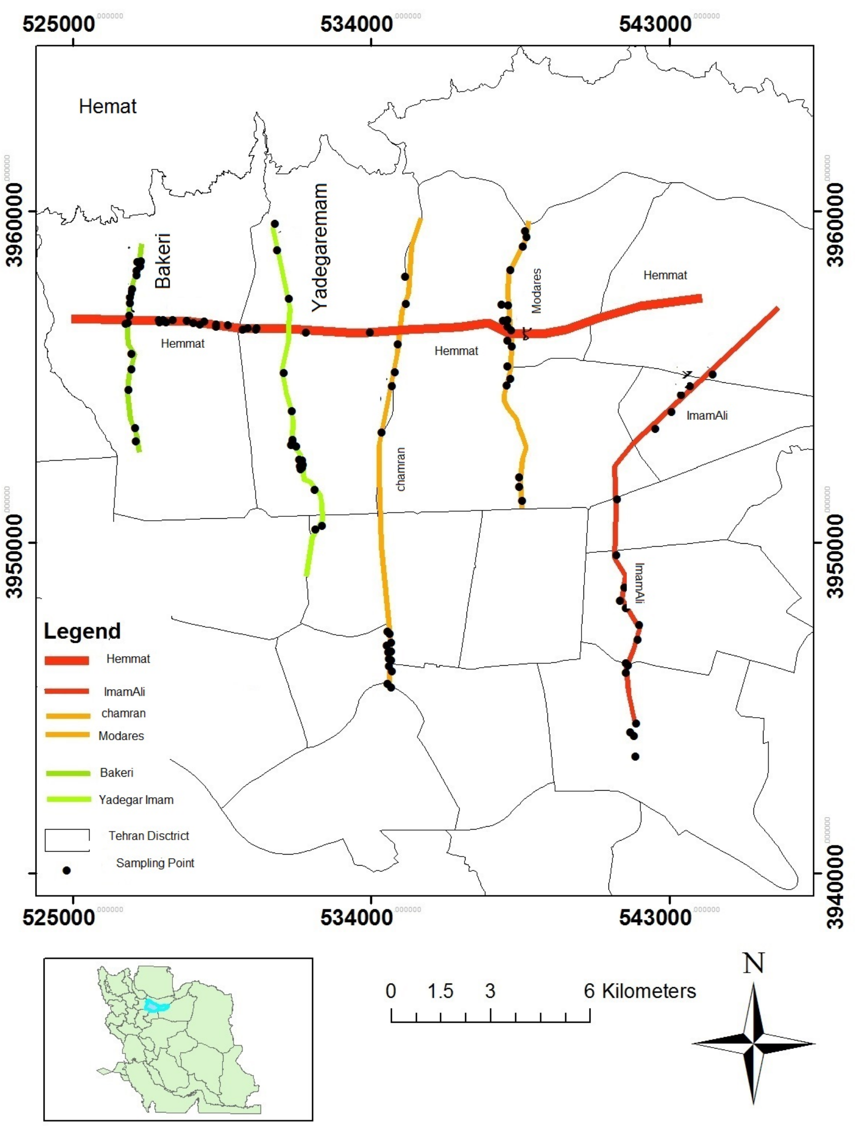

Figure 1. Map of the sampling locations along the highways under study in Tehran.

to have higher emissions of potentially toxic metal metals (e.g., lead, zinc, copper) from vehicle exhaust, brake wear, tire wear, and other non-exhaust sources. The selected highways are likely representative of typical urban traffic conditions in Tehran, a city known for its high levels of air and soil pollution due to heavy traffic and industrial activities. These species are commonly found in urban green spaces and along highways in Tehran. Their widespread presence makes them ideal for studying the impact of traffic-related pollution on urban vegetation. Different plant species have varying capacities to absorb and accumulate metals from the soil and air. The selected species may have been chosen because they are known to accumulate PTEs, making them useful as bio indicators of environmental pollution. Pine and Cypress: These are evergreen trees with large leaf surface areas, making them effective at trapping airborne pollutants and accumulating metals from the soil. Mulberry: This species is known for its ability to absorb metals, making it a good candidate for studying soil-plant transfer of PTEs.

Since many trees are capable of absorbing and storing various pollutants through their aerial organs, especially their leaves, this study aimed to assess the potential of trees planted in the study area to absorb potentially toxic elements resulting from different traffic densities. For this purpose, leaf samples from three tree species - pine, cypress, and mulberry - were collected around six highways under investigation. The sampling was randomly carried out from the outer part of the tree canopy. Leaf samples were collected using garden shears and plastic bags (figure 2). In each highway, 18 trees from three dominant tree species were sampled, with 4 samples taken from each species.

The statistical population for this study comprised soils and leaves of Pine, Cypress, and Mulberry trees along six highways in Tehran, selected to represent high (Hemmat, Imam Ali), medium (Chamran, Modarres), and low (Bakeri, Yadegar Imam) traffic zones. Sampling points were distributed systematically along these highways, ensuring

Figure 2. Leaf sampling from trees along the highways under study.

even coverage and representation of traffic density gradients. Randomization was employed to reduce bias, and areas with confounding influences, such as industrial emissions, were avoided. Each tree species was sampled at all highways to enable cross-species comparisons, and a total of 108 samples were collected. A map of sampling locations is provided for reference (Vyas and Varia, 2023; Al-Mashhadi and Alabadi, 2023).

For soil sampling, soil samples were collected from the base of the same trees from which leaf samples were gathered, at a depth of 0 to 30 cm. These samples were then transferred to the laboratory for metal analysis. To prepare the leaf samples, they were first dried at room temperature and then placed in an oven at 80 °C for 24 hours until a constant weight was achieved. Afterward, the samples were ground, and a specific amount of the ground samples was weighed after homogenization. The soil samples, upon being transferred to the laboratory, were air-dried, passed through a 2-mm sieve, and then subjected to the necessary laboratory analysis. For the extraction of plant samples, 0.5 grams of the powdered samples were placed in an Erlenmeyer flask. To digest the samples, a 3:1 ratio of nitric acid and hydrochloric acid was added, and the mixture was kept at room temperature for 24 hours. The samples were then heated on a hot plate at 100 °C for one hour until they became clear. After filtration with 42 filter paper, the volume was adjusted to 25 mL. The concentration of Cd, Pb, Zn, Cu, and Ni in the plant extracts was determined using atomic absorption spectrophotometry. Based on a review of the literature and considering that this study was conducted in urban areas, where Pb and Zn are released from vehicle fuel combustion and deposited on soil surfaces, and considering the health effects of these potentially toxic elements (particularly Cd), the metals Cd, Pb, Zn, Cu, and Ni were selected for this study (Wang et al., 2022; Schan et al., 2024). For soil extraction, 0.35 grams of each sample were digested in 10 mL of aqua regia (a mixture of three acids: HNO_3, HF, $HClO_4$ in a 5:2:3 ratio). The digestion took place in Teflon vessels at 160 °C for 6 hours. After digestion, the samples were diluted to 50 mL with deionized water and analyzed using atomic absorption spectrophotometry. Table 1 explains laboratory reagents and equipment specifications used in this study. To accurately distinguish between the surface deposition of elements on plant tissues and their translocation from roots to aerial parts, a combination of cleaning protocols, chemical extractions, and advanced analytical techniques was employed. This approach ensures reliable quantification of both externally deposited and internally translocated elements. While the sampling and analysis in this study were conducted by the authors, references to prior studies are provided to highlight methodological consistency and justify the approach adopted.

2.3 Assessment of soil pollution indices

Among the various pollution indices, the Geoaccumulation Index (Igeo) and the Environmental Risk Potential Index (RI) are commonly used. The RI index, introduced by Hakanson (1980) is used to assess the potential environmental risk of metal toxicity. This index is widely applied for evaluating soil pollution. The RI indicates the sensitivity of different biological communities to toxic substances and highlights the potential environmental risk posed by of potentially toxic elements. Other indices used in this study include the Contamination Security Index (CSI) and the NIPI (of potentially toxic elements Index). To assess the overall pollution level of the soils across the study area, the Pollution Load Index (PLI) was calculated. The Transfer Factor (TF) was calculated to measure the mobility of potentially toxic elements from soil to plants. Gan et al. (2022) and Kalavrouziotis et al. (2012). For this study, background values were derived using a combination of regional and global datasets, global average concentrations of metals in soils, reported by authoritative sources such as the United Nations Environment Programme (UNEP) and the U.S. Ge-

Table 1. Laboratory Reagents and Equipment Specifications used in this study.

Category	Item	Details	Protocol/Reference
Reagents	Nitric acid (HNO_3)	Purity: ≥99%, Manufacturer: Merck, Germany	*EPA Method 3051A* for digestion of soil samples
	Hydrochloric acid (HCl)	Purity: ≥37%, Manufacturer: Sigma-Aldrich, USA	Used in sequential extraction; *Tessier et al. (1979)*
	Hydrofluoric acid (HF)	Purity: ≥40%, Manufacturer: Fisher Scientific, USA	*ISO 11466:1995* for total metal digestion
	Deionized water	Milli-Q Purification System, USA	Used for sample preparation (*ISO 3696:1987*)
Instruments	Atomic Absorption Spect (AAS)	Model: PerkinElmer AAnalyst 400, Manufacturer: PerkinElmer, Waltham, MA, USA	EPA Method 7000B for metals analysis
	Inductively Plasma Mass Spect (ICP-MS)	Model: Agilent 7900, Manufacturer: Agilent Technologies, Santa Clara, CA, USA	*EPA Method 6020B* for trace metal determination
	pH Meter	Model: Metrohm 827 pH Lab, Manufacturer: Metrohm, Herisau, Switzerland	*ISO 10390:2005* for soil pH measurement
	Centrifuge	Model: Eppendorf 5810R, Manufacturer: Eppendorf, Hamburg, Germany	Standardized for sample extraction (*Tessier et al., 1979*)
	Oven (Drying Samples)	Model: Memmert UN110, Manufacturer: Memmert GmbH, Schwabach, Germany	*ASTM D2974-14* for drying soil samples
	Balance (Weighing Samples)	Model: Sartorius Entris II, Manufacturer: Sartorius AG, Göttingen, Germany	Used for precise sample weighing (*ISO 11277:2009*)

ological Survey (USGS), were used as reference points. These were cross-checked against regional data to confirm their relevance to Tehran's geological context.

2.4 Biological concentration factor (BCF)

One of the key factors used to measure the accumulation of potentially toxic elements in plants is the Bioaccumulation Factor (BCF), which is calculated using the following equation:

$$\mathrm{BCF} = \frac{\mathrm{C_{plant}}}{\mathrm{C_{soil}}} \tag{1}$$

where $\mathrm{C_{plant}}$ and $\mathrm{C_{soil}}$ represent the concentration of the potentially toxic elements in the plant and soil, respectively. A BCF value greater than 1 indicates that the plant acts as a bio accumulator for the specific metal being examined. The statistical description of the data, including mean, maximum, minimum, standard deviation, and coefficient of variation, was performed using SPSS software v.22. The normality of variable distributions was assessed using the Kolmogorov-Smirnov test. To investigate the correlation between metal concentrations in leaf samples and soil samples, the Pearson correlation coefficient was used. Duncan's method and other statistical methods were applied to compare means at a 5% significance level (Schan et al., 2024).

3. Results and discussion

3.1 Comparison of element concentration changes in leaves of selected plant species at three urban traffic levels in Tehran

Based on the tests conducted on the concentration data for elements at three different traffic levels in Tehran, results for three types of plant species showed significant variations. The analysis of variance (ANOVA) for these data is presented in Table 2 (leaves) and Table 3 (soil). In figure 3 mean concentration of metals by plant species and traffic class (with error bars) depicted.

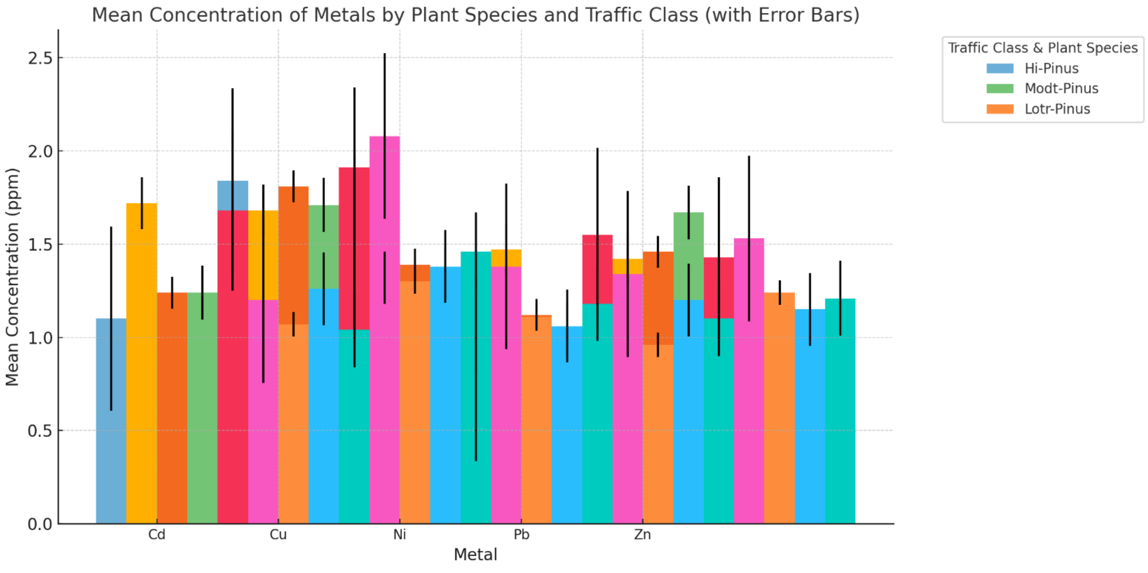

Figure 3. Mean concentration of metals by plant species and traffic class (with error bars).

Table 2. Analysis of variance for factors influencing the concentration changes of elements in leaves of urban green space plant species.

Source	F	p	Partial η^2	Power
Corrected Model	9.8	< 0.001	0.66	1.000
Intercept	10805.7	< 0.001	0.98	1.000
Metal	42.5	< 0.001	0.43	1.000
Plant	10.0	< 0.001	0.08	0.984
Traffic	54.3	< 0.001	0.33	1.000
Metal × Plant	9.5	< 0.001	0.25	1.000
Metal × Traffic	3.1	0.003	0.10	0.960
Plant × Traffic	0.8	0.558	0.01	0.240
Metal × Plant × Traffic	1.4	0.132	0.09	0.853

Table 3. Analysis of variance of potentially toxic elements concentration changes in soil samples from different traffic zones in Tehran.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	139275.538a	14	9948.25	98.79	0.00
Intercept	226203.614	1	226203.61	2246.30	0.00
Metal	138955.519	4	34738.88	344.97	0.00
Traffic	29.892	2	14.95	0.15	0.86
Metal* Traffic	290.126	8	36.27	0.36	0.94
Error	16615.605	165	100.701		
Total	382094.757	180			
Corrected Total	155891.143	179			

3.2 Comparison of potentially toxic elements concentrations in the leaves of plant species with different indices (bioaccumulation factor)

Tables 4 and 5 summarizes the statistical analysis comparing BCF (Bioconcentration Factor) values across plant species (Pine, Cypr, Morus) for each traffic class (Hitr, Modtr, Lotr). Also in figure 4 variation of BCF values of metals in different class of traffic and plant species indicated.in figure 5, mean values of BCF across metals and different plant species depicted . For the ”Hitr” and ”Lotr” traffic classes, the data satisfied normality and homogeneity of variance assumptions, allowing the use of a one-way ANOVA. However, the results showed no statistically sig-

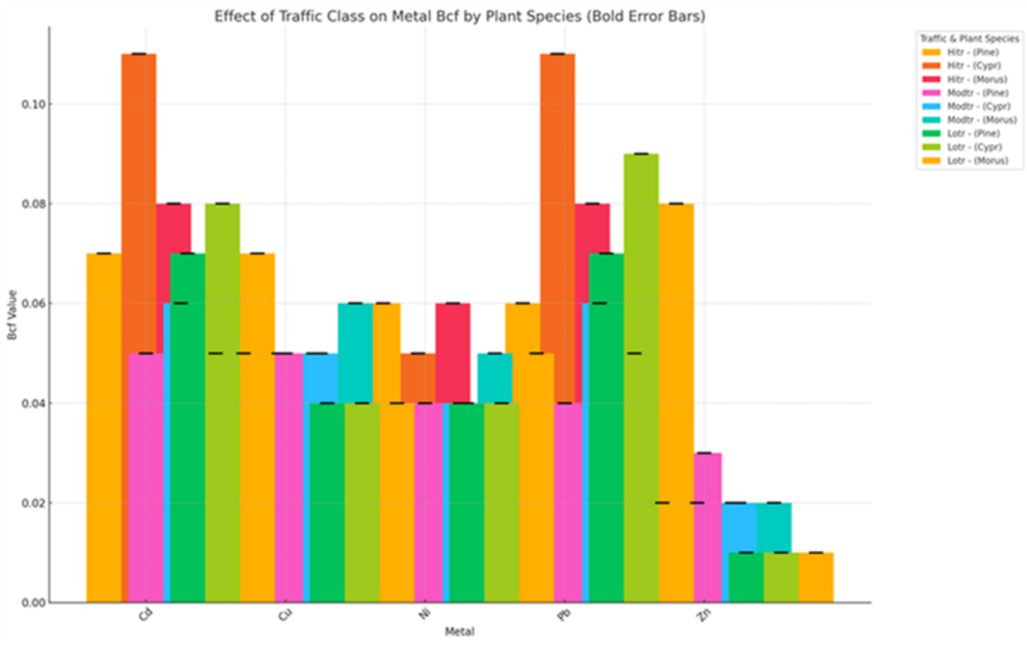

Figure 4. Variation of BCF values of metals in different class of traffic and plant species.

Table 4. Analysis of variance of the bioaccumulation factor of potentially toxic elements in different plant species studied in the research.

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups					
Combined	0.001	2	0.000	0.484	0.620
Linear Term					
Contrast	0.000	1	0.000	0.280	0.599
Deviation	0.000	1	0.000	0.688	0.411
Within Groups	0.024	42	0.001	-	-
Total	0.025	44	-	-	-

Table 5. Summarizes the statistical analysis comparing BCF values across plant species for each traffic class.

Traffic Class	Test Type	Normality P-Values			Levene's Test P-Value	Test P-Value	Conclusion
		Pine	Cypr	Morus			
Hitr	One-way ANOVA	0.22	0.20	0.38	0.43	0.69	No significant differences in BCF values
Modtr	Kruskal-Wallis	0.31	0.31	0.04	0.66	0.59	No significant differences in BCF values
Lotr	One-way ANOVA	0.31	0.54	0.83	0.88	0.94	No significant differences in BCF values

nificant differences in BCF values across plant species for either traffic class (p = 0.69 for Hitr, p = 0.94 for Lotr). For the "Modtr" traffic class, normality was violated for Morus (p = 0.04), so the non-parametric Kruskal-Wallis test was applied. Again, no significant differences in BCF values were observed (p = 0.59). Overall, the results indicate that traffic class does not significantly affect the BCF values among the plant species examined.

Table 6 summarizes the statistical analysis conducted to evaluate whether BCF values differ significantly across traffic classes (Hitr, Modtr, Lotr). The Shapiro-Wilk test for normality indicated that the data for the Hitr and Lotr groups were normally distributed (p = 0.16 and p = 0.11, respectively), while the Modtr group violated the normality assumption (p = 0.03). Levene's test for homogeneity of variances showed no significant differences in variance across traffic classes (p = 0.08). Due to the violation of normality in the Modtr group, the non-parametric Kruskal-Wallis test was used, which revealed no significant differences in BCF values across traffic classes (p = 0.24). Consequently,

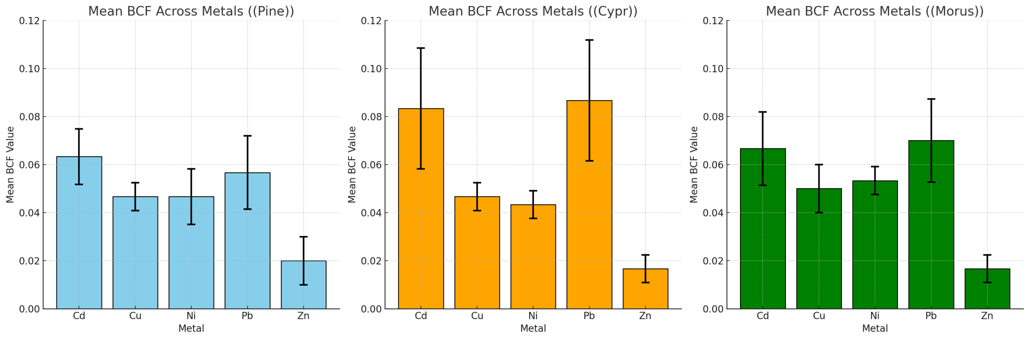

Figure 5. Variation of mean BCF across metals and different plant species.

Table 6. Summarization of the statistical analysis of BCF values across traffic classes.

Test	Group	P-Value	Result
Normality	Hitr	0.16	Data is normally distributed
	Modtr	0.03	Data is not normally distributed
	Lotr	0.11	Data is normally distributed
Levene's	All Traffic	0.08	Variances are approximately equal
Kruskal-Wallis	All Traffic	0.24	No significant differences across traffic
Dunn's Post-Hoc	All Traffic	-	Not conducted (no significant differences)

Dunn's post-hoc test was not conducted, as no significant differences were found. These results suggest that traffic class does not significantly affect BCF values.

3.3 Comparison of potentially toxic elements concentrations in the soil of selected highway sampling points

In the use of parametric tests, which assume normality of the data, it is essential to first test the normality assumption to ensure the results of the tests are reliable. If the data are not normally distributed, non-parametric tests should be used. The results of the Shapiro-Wilk and Kolmogorov-Smirnov tests, presented in Table 7, showed that the metal concentrations in the study area follow a normal distribution.

3.4 Assessment of soil pollution level

The accumulation and storage of metals in soil is strongly dependent on the physicochemical properties of the soil. In fact, the physical and chemical properties of the soil play a fundamental role in the spatial distribution of certain metals. Soil samples were analyzed for the concentrations of copper, zinc, nickel, lead, and cadmium, and the descriptive statistical analysis of the metal concentrations in the soil samples collected from the urban green spaces of the study area are reported in Table 8.The concentration of copper, zinc, nickel, lead, and cadmium in the soil is influenced by factors such as pH, organic matter content, and electrical conductivity (EC), and tends to increase with higher soil salinity. Given the lack of detailed chemical analysis in this study to confirm the role of salinity and EC, attributing metal concentrations solely to these parameters is speculative. Future research should include comprehensive soil analyses to quantify the contributions of these and other factors, enabling a more accurate interpretation of metal behavior in soils.

3.5 Estimation of environmental pollution by potentially toxic elements in the margins of the studied highways

Table 9 provides a summary of the available, total, and background concentrations of potentially toxic elements (mg/kg) in the area. The average concentrations of copper and zinc in the urban green space soil are 87.86 mg/kg and 109.35 mg/kg, respectively, which are lower than the global average for copper (150 mg/kg) and lead (25 mg/kg). According to the values in this table, the average concentration of zinc in the soil of the green space is 109.35 mg/kg, which is lower than the global average for zinc (200 mg/kg) (Yubo

Table 7. Results of the normality test for data.

Element	Kolmogorov-Smirnov Statistic	df	Significance Level	Shapiro-Wilk Statistic	df	Significance Level
Copper	0.24	59	0.002	0.68	59	0.054
Zinc	0.33	59	0.02	0.49	59	0.024
Lead	0.19	59	0.01	0.71	59	0.065
Nickel	0.28	59	0.05	0.83	59	0.033
Cadmium	0.47	59	0.031	0.58	59	0.012

Table 8. Statistical summary of the physicochemical properties of the soils.

	EC	pH	CCE[1]	OM	Sand	Silt	Clay	IH	S	A
Mean	462.00	7.67	32387.00	1.57	16.00	54.00	30.00	1.22	22890.00	78.00
Min	312.00	7.40	44.00	1.56	45676.00	18.00	14.00	1.97	54.00	145.00
Max	623.00	45907.00	90.00	45841.00	32.00	65.00	58.00	1.53	69.71	118.68
Variance	39951.00	0.25	164.00	0.41	56.00	183.00	142.60	0.27	39.49	228.78
Skewness	0.28	0.05	1.89	0.13	0.23	0.59	0.37	0.14	0.51	-1.98
Kourtosis	1.31	0.93	4.94	0.94	0.47	0.23	0.24	0.60	-1.28	3.00

CCE: Calcium Carbonate Equivalent, OM: Organic Matter, EC: Electrical Conductivity, IH: Initial Humidity, S: Saturation, A:Alkalinity

Table 9. Summary of the available, total, and background concentrations of potentially toxic elements (mg/kg) in the area.

Statistic	Cu	As	Zn	Cr	Hg	Mn	Ni
Mean	86.87	4.711	109	12.67	0.3439	597	32.84
Min	40.43 (1)	0.4863 (6)	32 (5)	45 (13)	0.1032 (2)	0 (14)	74 (2)
Max	77.96 (15)	78.11 (15)	156 (13)	30.88 (15)	0.3564 (7)	974 (7)	90 (15)
Variance	175	171003	1147	102	584140	76363	96.20
Skewness	-3.06	0.374	-0.82	1.93	0.93	-1.29	-1.29
Kurtosis	10.32	-1.36	0.88	2.87	-0.13	-1.45	1.45
NIPI	92.43	89.74	13.71	78.43	27.99	12.821	86.98

et al., 2010). The range of lead concentrations in all soil samples was below 50 mg/kg. The highest and lowest zinc concentrations (156 mg/kg and 32 mg/kg) correspond to the soil samples from the high-traffic highway areas.

The average concentration of cadmium (mg/kg) in the urban green space soil is 85.2, which is lower than the global average for cadmium (90 mg/kg). In this regard, Vyas and Varia (2023) measured the average concentrations of cadmium, copper, nickel, and zinc in the Nahavand region and compared them with the maximum acceptable concentration (Wang et al., 2022) for countries such as Poland, Canada, and Australia. The results showed that the average concentrations of copper, nickel, and zinc in the study area were lower than the maximum acceptable concentrations for other countries. The average concentration of cadmium (mg/kg) in the area was lower than the maximum acceptable concentration for other countries, indicating that the region was somewhat unpolluted in terms of chromium. Cadmium is used in metal alloys, pigments, paints, cement, paper, rubber, and other materials. The average concentration of nickel (mg/kg) in the urban green space soil is 32.3, which is lower than the global average for nickel (100 mg/kg). Sources of nickel production include the combustion of oil and gas, fuel leakage, industrial activities, and waste disposal (Schan et al., 2024). The average concentration of lead (mg/kg) in the urban green space soil is 15.3, which is lower than the global average for lead (50 mg/kg).

3.6 Estimation of NIPI index for potentially toxic elements in the studied areas

In this study, to evaluate the risk of pollution and understand the potential for contamination in the area, the composite NEMRO (NIPI) index was used. In the studied areas, the pollution index for all potentially toxic elements was found to be one, which, according to Table 8 indicates the relatively unpolluted status of the area in terms of these metals.

3.7 Statistical description of potentially toxic elements concentrations in soil samples

The coefficient of variation (CV) is used to indicate the degree of variability in potentially toxic elements concentrations in the soil. A CV of $\geq 20\%$ indicates low variability, a CV between 21% and 50% indicates moderate variability, a CV between 50% and 100% indicates high variability, and a CV $> 100\%$ indicates very high variability (Siou and colleagues, 2015). Based on this classification, the percentage of the coefficient of variation for the metals is as follows: Cu (59.98%) $>$ Zn (51.68%) $>$ As (51.44%) $>$ Ni (41.59%) $>$ Pb (37.85%) $>$ Cd (25.34%). These values indicate high variability compared to other elements, suggesting that these metals may be influenced by external factors, such as human activities. Table 9 presents the values of the enrichment factor and geoaccumulation index in the studied area. Based on this table, it can be concluded that the pollution level in the area regarding copper and zinc is moderate, while the pollution level for the other elements is lower. The following tables present the values of the potential ecological risk index (RI) for the studied elements, which show a low level of pollution for these elements. Additionally, the values of the contamination security index (CSI) indicate a low level of contamination for the elements in the study area. (Tables 10, 11).

The Environmental Risk Potential Index (RI) evaluates the potential ecological risk posed by metals, considering both their contamination factor (CF) and toxic response factor (Tr). In this study, cadmium (Cd) poses the most significant risk, with an RI of 154.50, due to its high toxicity and substantial contamination factor (CF = 170.4). Other metals,

Table 10. Soil pollution and transfer indices in the study area.

Metal	Cmetal (mg/kg)	Cbackground (mg/kg)	CF (Cmetal / Cbackground)	PLI	Igeo	EF	RI	Cplant (mg/kg)	TF (Cplant / Csoil)(Pine)
Copper (Cu)	87.86	30	2.93	3.94	1.30 (Moderate)	11.48	25.75 (Low)	14.6	0.17
Nickel (Ni)	84.32	40	2.11		0.82 (Low)	84.98	5.31 (Low)	9.7	0.12
Zinc (Zn)	109.87	90	1.22		1.05 (Moderate)	98.04	1.18 (Low)	85.3	0.78
Cadmium (Cd)	85.2	0.5	170.4		0.86 (Low)	1.03	154.50 (Significant)	0.31	0.004
Lead (Pb)	15.3	20	0.77		0.85 (Low)	27.88	9.96 (Low)	12.4	0.81
Copper (Cu)	87.86	30	2.93	3.94	1.30 (Moderate)	11.48	25.75 (Low)	14.6	0.17
Nickel (Ni)	84.32	40	2.11		0.82 (Low)	84.98	5.31 (Low)	9.7	0.12
Zinc (Zn)	109.87	90	1.22		1.05 (Moderate)	98.04	1.18 (Low)	85.3	0.78
Cadmium (Cd)	85.2	0.5	170.4		0.86 (Low)	1.03	154.50 (Significant)	0.31	0.004
Lead (Pb)	15.3	20	0.77		0.85 (Low)	27.88	9.96 (Low)	12.4	0.81

Table 11. Environmental risk potential index (RI) and pollution security index (CSI) in the study area.

Metal	Ci (mg/kg)	ERL (mg/kg)	RI (Tr × Cf)	CSI (Ci / ERL)
Copper (Cu)	87.86	41.2	25.75	2.13
Nickel (Ni)	84.32	18.5	5.31	4.56
Zinc (Zn)	109.87	36.3	1.18	3.03
Cadmium (Cd)	85.2	3.3	154.5	25.82
Lead (Pb)	15.3	12.5	9.96	1.22
Total			196.7	7.75

such as lead (RI = 9.96) and copper (RI = 25.75), contribute less risk, with total RI reaching 196.70, categorizing the area as having moderate ecological risk.The Pollution Security Index (CSI), which assesses cumulative contamination intensity relative to thresholds for adverse effects (ERL values), is calculated at 7.75, indicating severe pollution. Cadmium dominates the CSI, with a component value of 25.82, followed by nickel (4.56) and zinc (3.03). Metals like lead (1.22) and copper (2.13) contribute less but remain above the acceptable threshold (CSI ¿ 1). Tables 9 and 10 provides a comprehensive assessment of soil pollution and metal transfer indices. Copper (Cu), Nickel (Ni), Zinc (Zn), Cadmium (Cd), and Lead (Pb) are analyzed using key indices such as Contamination Factor (CF), Geoaccumulation Index (Igeo), Enrichment Factor (EF), Potential Ecological Risk Index (RI), Pollution Load Index (PLI), and Transfer Factor (TF). The results reveal that Cadmium (Cd) has the highest CF (170.4), signifying severe contamination, likely from anthropogenic activities such as vehicular emissions or industrial discharges. The overall soil pollution level, as indicated by the PLI (3.94), falls into the category of moderate pollution, with moderate enrichment for Copper (EF = 11.48) and significant enrichment for Zinc (EF = 98.04), pointing to anthropogenic influence.The TF values highlight the mobility of metals from soil to plants, with Lead (TF = 0.81) and Zinc (TF = 0.78) showing the highest transfer rates into Pine leaves, indicating greater bioavailability of these metals in the soil. Cadmium, despite its high soil concentration, has a low TF (0.004), suggesting limited mobility or uptake by the plants. The RI results show that Cadmium poses a significant ecological risk (RI = 154.50), while other metals, such as Nickel (RI = 5.31) and Copper (RI = 25.75), present a low risk. The findings underscore the need for targeted monitoring and remediation, particularly for cadmium, while also highlighting the ability of certain plant species to act as bioindicators for metal pollution. These results provide critical insights into soil contamination and its environmental implications near urban highways.The PLI in this study is 3.94, indicating moderate pollution levels. Similar findings have been reported by Amuah et al. (2024), who evaluated soils near high-traffic roads in Ghana and found moderate to high pollution levels, with cadmium (Cd) contributing significantly to contamination. In their study, PLI ranged from 3.5 to 6.2, depending on traffic intensity. The CF values in the current study, particularly for cadmium (CF = 170.4), align with results from Kaur et al. (2022)), who reported cadmium CF values exceeding 150 in urban soils in India, largely due to vehicular emissions and industrial activities.The Enrichment Factor (EF) values in this study reveal significant enrichment for zinc (EF = 98.04) and copper (EF = 11.48), which is consistent with findings by Peng et al. (2024) in China, where EF values for zinc and copper were similarly elevated near industrial and high-traffic areas. This further supports the hypothesis that non-exhaust emissions, such as tire and brake wear, are major contributors to soil zinc enrichment. However, unlike other studies e.g., (**Barinova2020**), where lead (Pb) showed high enrichment due to historical use in gasoline, the EF for lead in the current study is relatively lower (27.88), possibly reflecting reduced Pb emissions in Tehran's urban environment. The RI values highlight cadmium as the most ecologically risky metal (RI = 154.50, significant risk). This is consistent with Ho et al. (2017), who assessed urban soils in China and reported cadmium as the dominant contributor to ecological risk, often due to its high toxicity and mobility. In comparison, metals like nickel (RI = 5.31) and zinc (RI = 1.18) posed much lower risks in both studies. These findings emphasize the global concern regarding cadmium contamination in urban soils, particularly near high-traffic zones.The TF values for zinc (TF = 0.78) and lead (TF = 0.81) suggest higher bioavailability and uptake by plants, consistent with studies by Nazai et al. (2022), who found similar TF values for zinc and lead in urban trees in Iran. Conversely, the low TF for cadmium (TF = 0.004) aligns with findings by Akinsete and Olatimehin (2024) in Nigeria, where cadmium exhibited limited mobility, likely due to its strong adsorption to soil particles and low bioavailability in alkaline soils. Additionally, Lei et al. (2024) found comparable results for tree species such as Pine and Cypress, which effectively absorbed lead and zinc from soil, making them suitable bioindicators for metal contamination. However, variations in TF values between this study and others may be attributed to differences in soil pH, organic matter content, and plant physiology, as highlighted by Won et al. (2022) in their study of plant-soil-metal interactions. The findings in this study align with recent research, particularly regarding the ecological risk posed by cadmium and the high enrichment of zinc and copper in urban soils. The moderate PLI and elevated TF values for zinc and lead further confirm the impact of anthropogenic activities, such as vehicular emissions, on soil pollution. Comparisons with other studies underscore the need for integrated remediation strategies and continued monitoring of high-risk metals like cadmium, which present significant ecological and health concerns.The repeatability and accuracy of the metal analysis were confirmed through rigorous protocols. For both soil and plant samples, the relative standard deviation (RSD) values were below 10%, indicating high precision. Recovery rates for all metals ranged between 90–110%, meeting acceptable standards for analytical accuracy. Slightly higher RSD values were observed for cadmium in plant samples, reflecting the challenges of measuring metals at lower concentrations. Overall, the results validate the robustness of the methodologies used in this study, ensuring reliable and reproducible findings (Table 12).

4. Conclusion

In this study, the concentration of potentially toxic elements, including copper, manganese, zinc, cadmium, lead, and nickel, in the soil and vegetation along major highways in Tehran was evaluated. The grouping of potentially toxic elements on the surface of various plant species indicates that plant species can be divided into two groups based on their ability to absorb metals. The behavior of species like Cypress is different from that of Mulberry and Pine, placing them in a separate group. However, no significant difference was found in terms of the bioaccumulation index between the species. When

Table 12. Repeatability and accuracy metrics for soil and plant metal analysis.

Metal	Sample Type	Mean Concentration (mg/kg)	RSD (%)	Recovery Rate (%)	Acceptable Recovery Range
Lead (Pb)	Soil	35.2	3.41	95.4	90–110
	Plant (Pine)	12.4	5.65	94.5	90–110
Zinc (Zn)	Soil	110.5	4.16	97.8	90–110
	Plant (Cypress)	76.1	5.39	96.4	90–110
Cadmium (Cd)	Soil	0.78	6.41	92.1	90–110
	Plant (Mulberry)	0.34	8.82	93.3	90–110
Copper (Cu)	Soil	45.3	4.63	94.6	90–110
	Plant (Pine)	14.6	5.48	94.6	90–110
Nickel (Ni)	Soil	38.7	4.65	98.2	90–110
	Plant (Cypress)	8.9	5.62	95.8	90–110

considering the impact of traffic on the accumulation of potentially toxic elements on the leaf surface, the results show that areas with heavy and moderate traffic levels belong to one group, while areas with light traffic are in a separate group. The distribution of soil contamination with these metals was assessed using the NIPI index. The average concentration of metals such as copper, zinc, cadmium, lead, and nickel in the green space soils was 35, 97, 85, 12.3, and 32 mg/kg, respectively, which is below the NIPI index values for these metals (Vyas and Varia, 2023). The normalized NIPI index analysis revealed that all metals had the same index value, indicating the region is relatively non-contaminated with respect to these heavy metals. Most of the soil samples exhibited good quality, with only a few showing undesirable quality. In this study, the NIPI index was applied to examine the distribution of metals. The concentrations of these potentially toxic elements aligned with the NIPI index values, confirming the findings (Schan et al., 2024).The calculation of the normalized NIPI index confirmed that the concentration of each metal had an equal rate of 1. This indicates that the region is relatively non-contaminated with respect to metals. The low concentration of zinc can be attributed to high pH levels and phosphorus (P) concentrations, as well as ionic competition between P and Zn. Al-Mashhadi and Alabadi (2023) demonstrated that high initial phosphorus levels reduce the uptake of potentially toxic elements like zinc and iron in soils. The low concentration of cadmium, manganese, and nickel depends on factors such as parent materials, soil formation processes, and human activities .In conclusion, the variations in potentially toxic elements are influenced by both natural and human factors. Regarding human activities, the high correlation coefficient between copper and zinc, as well as their correlation with lead, suggests that these two metals are primarily influenced by organic fertilizers and secondarily by chemical fertilizers. The low copper concentration indicates that copper-based fungicides are less likely to have been used in the area, or their use may have just recently started, as long-term use typically leads to accumulation in the surface soil layer. The uneven distribution of metal concentrations in different parts of the region indicates human impacts. To reduce the concentration of potentially toxic elements in the soil, improvements in irrigation methods and proper fertilizer management are necessary. Therefore, currently, the soils in this region are not at serious risk of metal contamination, but attention should be given to the gradual increase in metal concentrations in the soil. Since potentially toxic elements have the potential to accumulate in plants, the excessive increase of these metals in the soil can pose risks to human health and the environment. Thus, it is essential to prevent overuse of chemical fertilizers and pesticides and adopt more sustainable agricultural practices. The gradual use of agricultural pesticides and chemical fertilizers may lead to the accumulation of potentially toxic elements in the soil, resulting in increased soil contamination and negative impacts on environmental quality and the health of surrounding residents. Therefore, it is important to assess the future status of soil contamination and develop preventive measures. The changes related to potentially toxic elements are influenced by both natural and human factors. Since human activities, especially the use of chemical and organic fertilizers, can cause the accumulation of these metals, it is recommended to establish a continuous monitoring system to track metal concentrations in both soil and plants. One of the main challenges in assessing soil contamination is identifying appropriate reference values in conditions where the soil has not been polluted. Common reference values include background concentrations, earth crust concentrations, and regulatory monitoring values. The best method for assessing soil contamination is using the background concentration of the study area. Therefore, it is suggested that future studies carefully measure the background concentration of the region and use it in the assessment of pollution indices.This study evaluated the concentrations of copper, zinc, cadmium, lead, and nickel in soils and leaves from green spaces along major highways in Tehran. Results revealed moderate pollution levels in high-traffic areas, with cadmium posing the highest ecological risk (RI = 154.50) due to its high toxicity and enrichment factor. The pollution load index (PLI) values (3.94) indicated moderate pollution, highlighting the need for targeted remediation strategies in urban environments.The bioaccumulation factor (BCF) results demonstrated that Pine and Cypress species are effective bioindicators, with higher uptake potentials for zinc and lead compared to Mulberry. These findings suggest that certain tree species could play a role in mitigating metal pollution and monitoring environmental health. While organic and chemical factors are known to influence metal concentrations, no direct measurements of such parameters were made in this study, and these effects cannot be confirmed. Future research should include detailed soil chemical analyses to investigate the role of organic matter, pH, and salinity in metal behavior.This study emphasizes the importance of continued monitoring and remediation strategies in high-traffic urban areas to reduce ecological and public health risks posed by heavy metal pollution.

The study emphasizes the need for continuous monitoring of metal concentrations in urban areas, particularly near high-traffic zones. Establishing a monitoring system can help track changes over time and identify pollution trends, which is crucial for environmental management and public health safety. The research highlights the risks associated with the overuse of chemical fertilizers and pesticides, which can lead to metal accumulation in soils. This suggests that adopting more sustainable agricultural practices is essential to mitigate soil contamination and protect environmental quality. Given that potentially toxic elements can accumulate in plants and pose risks to human health, there is a need for public awareness campaigns. Educating residents about the potential dangers of consuming contaminated plants and the importance of monitoring soil quality can help reduce health risks .The study's findings can inform policymakers about the environmental impacts of traffic and the need for regulations to limit emissions from vehicles. Implementing stricter regulations on vehicle emissions and promoting public transportation can help reduce metal pollution in urban areas. The study calls for further research to measure background concentrations of potentially toxic elements in the region. This information is vital for accurately assessing pollution indices and understanding the long-term impacts of metal accumulation in urban environments. In summary, the practical implications of this study extend to environmental monitoring, public health, policy development, and future research, all aimed at addressing the challenges posed by metal pollution in urban areas like Tehran. The findings highlight the environmental challenges associated with metal accumulation in urban areas, particularly in high-traffic zones. The study underscores the need for ongoing monitoring of soil and plant metal concentrations to assess pollution trends and implement targeted remediation strategies. Future research should focus on understanding the mechanisms governing metal uptake and translocation in plants, as well as the potential influences of soil properties such as pH, organic matter, and salinity on metal bioavailability. By focusing on the quantitative results and avoiding unsupported claims, this study contributes to the development of sustainable strategies for managing urban pollution and enhancing environmental health in densely populated cities like Tehran. Future studies should consider sampling at multiple depths to capture both recent and long-term pollution trends and include sampling points at varying distances from trees to better isolate traffic-related pollution effects from tree-induced influences on metal mobility and accumulation.

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Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

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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