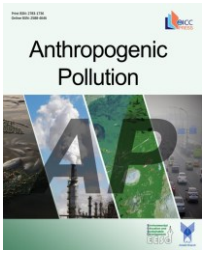

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Research Article

Chemical Speciation and Mobility of Potentially Toxic Elements (PTEs) in Urban Park Soils: Insights from Sequential Extraction and Visual MINTEQ Modeling

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Abstract

Potentially toxic element (PTE) contamination in urban soils, particularly in public green spaces, can pose environmental and human health risks. This study evaluated the geochemical behavior, mobility, and potential bioavailability of Pb, Cd, Ni, and as in surface soils collected from two urban parks (Chitgar and Lavizan) in Tehran, Iran. Total concentrations were measured, and metal partitioning among operationally defined geochemical fractions was determined using a sequential extraction procedure. In addition, metal speciation under site-specific soil geochemical conditions was simulated using Visual MINTEQ. Potential ecological risk was evaluated using the Risk Assessment Code (RAC), based on the proportion of metals in the exchangeable fraction. Mean total concentrations of Pb, Cd, Ni, and as were 68.4, 1.92, 34.7, and 8.6 mg kg−1−1, respectively, in Chitgar Park soils, compared with 52.1, 1.35, 29.4, and 7.2 mg kg−1−1 in Lavizan Park soils. The exchangeable fractions of Pb and Cd accounted for ~24% and ~31% in Chitgar and ~18% and ~22% in Lavizan, indicating higher mobility and potential bioavailability than Ni and As, which were predominantly associated with more stable soil fractions. RAC results indicated moderate-to-high ecological risk for Cd and moderate risk for Pb across the studied soils. The novelty of this work lies in integrating sequential extraction results with geochemical speciation modeling (Visual MINTEQ) to better interpret PTE mobility and environmental risk in urban park soils. Overall, the findings suggest that assessments based solely on total concentrations may underestimate risk, whereas combining chemical fractionation/speciation information with RAC provides a more realistic evaluation of PTE behavior in urban soils.

Keywords: Potentially toxic elements (PTEs); Bioavailability; Chemical fractionation; Geochemical partitioning; Soil contamination; Tehran; Visual MINTEQ; Risk Assessment Code

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1. Introduction

Rapid urbanization, expansion of transportation networks, growth of industrial activities, and population concentration in large metropolitan areas have led to the gradual accumulation of various pollutants in urban environments. Among these pollutants, potentially toxic elements (PTEs) are of particular concern due to their persistence, toxicity, and ability to accumulate in soils, plants, and other biotic compartments (Nieder and Benbi, 2024; Aali et al., 2024). Unlike many organic contaminants, most PTEs cannot be readily degraded and may remain in soils for long periods, thereby posing long-term ecological and health risks. Urban green spaces, especially parks and artificial forests, are recognized as important reservoirs for PTE accumulation because they are continuously influenced by multiple pollution sources such as traffic emissions, atmospheric deposition, surface runoff, and urban maintenance activities (Alloway, 2013; Li et al.,2001; Yuksel et al.,2025).

Potentially toxic elements (PTEs) in urban soils may pose significant risks to human health through multiple exposure pathways, including direct soil contact, inhalation of resuspended particles, and entry into the food chain (Nidar et al.,2024). Therefore, accurate assessment of the behavior, mobility, and environmental risk of these elements in urban green spaces—especially parks, which function as important recreational areas for the public—is of critical importance (Kabata-Pendias, 2011). However, a major challenge in soil contamination studies is that the environmental behavior and risk of PTEs cannot be reliably evaluated solely on the basis of their total concentrations.

A study of roadside soils along the old Rasht–Qazvin route reported that potentially toxic elements (PTEs), particularly Zn and Ni, occurred at concentrations above background levels and exceeded certain soil quality standards at several sampling sites. Nevertheless, the Igeo and PERI indices indicated low to moderate ecological risk for the area, suggesting that environmental processes and human activities contributed to limiting the accumulation of these contaminants (Mohammadi Gollankesh et al., 2020; Zaman et al.,2025).

In many environmental studies, the total concentration of potentially toxic elements (PTEs) has traditionally been used as the primary indicator of soil contamination and the main basis for risk assessment. Although this approach provides useful preliminary information on the extent of element accumulation in soils, it does not adequately reflect the mobility, bioavailability, or actual toxicity of PTEs. Numerous studies have demonstrated that only a portion of the elements present in soil is actively involved in biological uptake and environmental transfer, whereas a considerable fraction may remain strongly bound to mineral structures, organic matter, or other stable solid phases (McBride, 1994).

The geochemical behavior of potentially toxic elements (PTEs) in soils is strongly influenced by their chemical forms. Chemical speciation refers to the distribution of an element among different forms, such as free ions, soluble complexes, species adsorbed onto particle surfaces, or phases stabilized within mineral structures. Each of these forms differs in terms of mobility, bioavailability, and toxicity. For example, free ions and exchangeable species generally have the highest potential for transfer to groundwater and biological uptake, whereas residual and mineral-bound forms exhibit much lower mobility (Kabata-Pendias, 2011).

In this context, sequential extraction methods have been developed as useful tools for partitioning potentially toxic elements (PTEs) among different operationally defined soil fractions. These methods make it possible to determine the relative distribution of elements in exchangeable, carbonate-bound, Fe–Mn oxide-bound, organic matter-bound, and residual fractions, thereby providing valuable information on contamination sources, binding strength, and potential mobility (Tessier et al., 1979). However, sequential extraction also has certain limitations and, when used alone, may not fully predict the dynamic behavior of PTEs under changing environmental conditions, such as variations in pH, redox potential, dissolved organic matter, or ionic strength.

To complement sequential extraction, equilibrium-based geochemical speciation modeling has been increasingly used to simulate the behavior of potentially toxic elements (PTEs) in soil systems. Visual MINTEQ is one of the most widely applied geochemical models for predicting the distribution of dissolved element species under defined physicochemical conditions. By incorporating key parameters such as pH, dissolved organic carbon,

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background ion composition, and complexation reactions, Visual MINTEQ provides a mechanistic interpretation of PTE mobility, bioavailability, and potential toxicity (Gustafsson, 2019). This is particularly important because changes in soil chemistry can alter element speciation and thereby influence environmental risk. Accordingly, the combined use of sequential extraction and geochemical speciation modeling provides a more robust framework for assessing PTE behavior than approaches based solely on total concentrations. Sequential extraction identifies the distribution of elements among operationally defined geochemical fractions, whereas Visual MINTEQ predicts their aqueous speciation under site-specific soil conditions. Integrating these approaches can therefore improve the evaluation of PTE mobility, potential bioavailability, and environmental risk in urban soils. (Yang et al.,2021).

Urban park soils are of particular concern because they represent environments with frequent human exposure and diverse sources of contamination (Esmaili et al., 2023). Accordingly, investigating the chemical forms, partitioning, and potential mobility of potentially toxic elements (PTEs) in such environments is essential for a more realistic evaluation of environmental quality and associated ecological risks.

Assessing the risk of potentially toxic elements (PTEs) in soils solely on the basis of their total concentrations cannot provide an accurate picture of their actual behavior and potential hazards. This limitation arises because the mobility and bioavailability of PTEs largely depend on their chemical forms and distribution among different soil fractions. In this context, Perin et al. (1985) first proposed using the proportion of elements present in the mobile fractions of sequential extraction—particularly the exchangeable fraction—as an indicator for estimating potential release and environmental risk. This approach later formed the basis for the Risk Assessment Code (RAC), which differentiates between relatively stable elements and those with high potential mobility. Today, RAC is widely applied in studies of urban and industrial soils and sediments to evaluate the environmental risk associated with PTEs. However, despite the importance of chemical speciation, most previous studies on urban soils have emphasized total metal concentrations, while the combined use of sequential extraction, speciation modeling, and RAC remains limited—particularly for park soils in rapidly urbanizing cities like Tehran. Therefore, this study was conducted to address this research gap by investigating the chemical speciation, mobility, and potential risk of PTEs in urban park soils. In this research, Chitgar and Lavizan parks were selected as two important urban green spaces with different spatial and environmental characteristics to evaluate the influence of soil geochemical properties on the behavior of lead (Pb), cadmium (Cd), nickel (Ni), and arsenic (As). The findings of this study are expected to provide a clearer understanding of the behavior and distribution of PTEs in urban soils and offer a scientific basis for the management and reduction of environmental risks in urban green spaces .

This study was conducted to investigate the chemical speciation, mobility, and potential risk of potentially toxic elements (PTEs) in urban park soils. Chitgar and Lavizan parks were selected as two important urban green spaces with different spatial and environmental characteristics to evaluate the influence of soil geochemical properties on the behavior of lead (Pb), cadmium (Cd), nickel (Ni), and arsenic (As). The main novelty of this research lies in integrating sequential extraction data with geochemical speciation modeling using Visual MINTEQ to better interpret PTE mobility and environmental risk in urban park soils. The findings also demonstrate that relying solely on total concentrations may underestimate environmental risk, whereas combining chemical speciation with the Risk Assessment Code (RAC) provides a more reliable assessment of PTE behavior in urban soils. Therefore, this study is expected to provide a clearer understanding of the distribution and behavior of PTEs in urban soils and to offer a scientific basis for monitoring, management, and risk reduction in urban green spaces.

2. Materials & Method

2.1. Study area

This study was conducted in two major urban parks in Tehran, namely Chitgar Park (western Tehran) and Lavizan Park (eastern Tehran). Chitgar Park stations

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were distributed within the approximate range of 35.74°–35.77° N and 51.55°–51.64° E, while Lavizan Park stations were situated within the range of 35.75°–35.77° N and 51.51°–51.57° E (Fig. 1).

A total of 10 surface soil samples were collected, consisting of five stations in each park. Sampling points were selected to reflect local environmental conditions, primarily considering their proximity to adjacent highways and the overall green-space layout. At each station, soil samples were collected from the top 0–20 cm layer using a clean plastic trowel, stored in polyethylene bags, labeled, and transported to the laboratory for further preparation and analysis.

2.2. Soil sampling

Soil sampling was conducted using a systematic random sampling approach across representative locations in each park. At each station, surface soil samples were collected from a depth of 0–20 cm, as this topsoil layer represents the primary zone of interaction with plant root systems and the maximum exposure to anthropogenic activities. To prevent cross-contamination, samples were collected using a clean plastic trowel, stored in high-density polyethylene (HDPE) containers, and transported to the laboratory. In the laboratory, the samples were air-dried at ambient temperature (approximately 25°C) to a constant weight. Large debris, including plant residues and gravel, were manually removed. Subsequently, the soils were crushed and sieved through a 2-mm mesh to ensure homogeneity. The processed samples were stored in sealed, acid-washed containers until further chemical analysis.

2.3. Determination of Soil Physicochemical Properties

Soil pH was measured using a soil–distilled water suspension (1:2.5) with a calibrated pH meter according to ISO 10390. Soil texture was determined using the hydrometer method. The soil organic matter content was measured by the Loss on Ignition (LOI) method. The particle density of the soil was determined using a pycnometer.

2.4. Total PTE Analysis and Instrumentation

To determine the total concentrations of potentially toxic elements (PTEs), including lead (Pb), cadmium (Cd), nickel (Ni), and arsenic (As), soil samples were subjected to acid digestion.

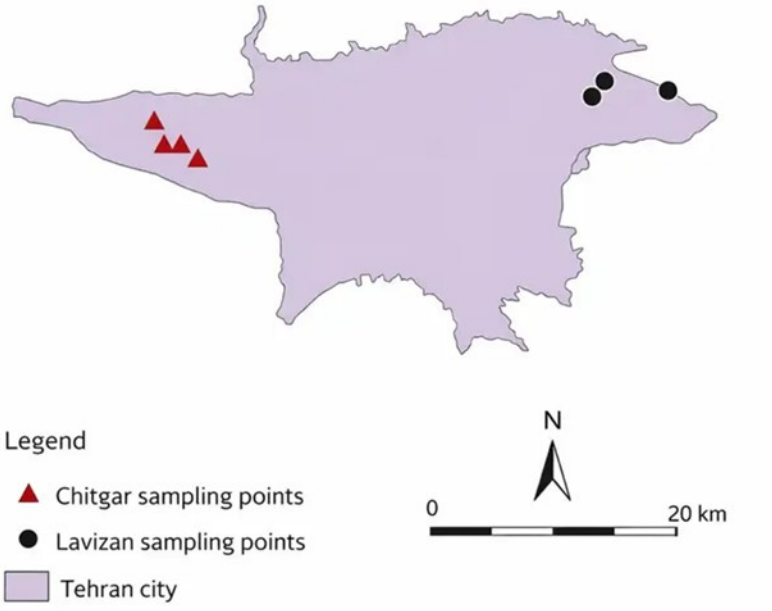

Figure 1. Location of sampling sites in urban parks of Tehran, Iran

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The digestion was performed using a mixture of nitric acid (HNO_3) and hydrochloric acid (HCl) following the USEPA 3050B standard protocol. After digestion, the solutions were filtered, and the concentration of PTEs was measured using an Atomic Absorption Spectrophotometer (AAS; Varian SpectrAA 220, Varian, USA) equipped with both flame and graphite furnace atomizers. Calibration was conducted using multi-element standard solutions (Merck, Germany), and all reagents, including HCl (37%, Merck, Germany), were of analytical grade. Quality assurance and quality control (QA/QC) protocols were strictly implemented to ensure the accuracy and precision of the analytical results. This included the use of reagent blanks, triplicate analyses (n=3), and certified reference materials (CRMs). The recovery rates for the analyzed elements in CRM samples were within the acceptable range of 92% to 105%, confirming the reliability of the digestion and analytical procedures.

2.5. Sequential Extraction of PTE

To investigate the distribution of potentially toxic elements (PTEs) among different soil geochemical fractions and assess their potential mobility, the sequential extraction method proposed by Tessier et al. (1979) was employed. This procedure is widely recognized for its ability to partition PTEs into five operationally defined geochemical fractions:

Exchangeable (F1): The most mobile fraction, representing elements weakly adsorbed on soil surfaces.

Carbonate-bound (F2): Elements associated with soil carbonates, susceptible to changes in pH.

Fe–Mn oxide-bound (F3): Elements bound to iron and manganese oxides, sensitive to redox potential changes.

Organic-bound (F4): Elements complexed with organic matter and sulfides, released under oxidizing conditions.

Residual (F5): The most stable fraction, where elements are bound within the silicate crystal lattice.

The distribution of PTEs across these fractions (Fig. 2) provides critical insights into the potential sources of contamination, the geochemical stability of elements in urban soils, and their bioavailability under fluctuating environmental conditions. This integrated approach allows for a more comprehensive assessment of environmental risk than total concentration analysis alone.

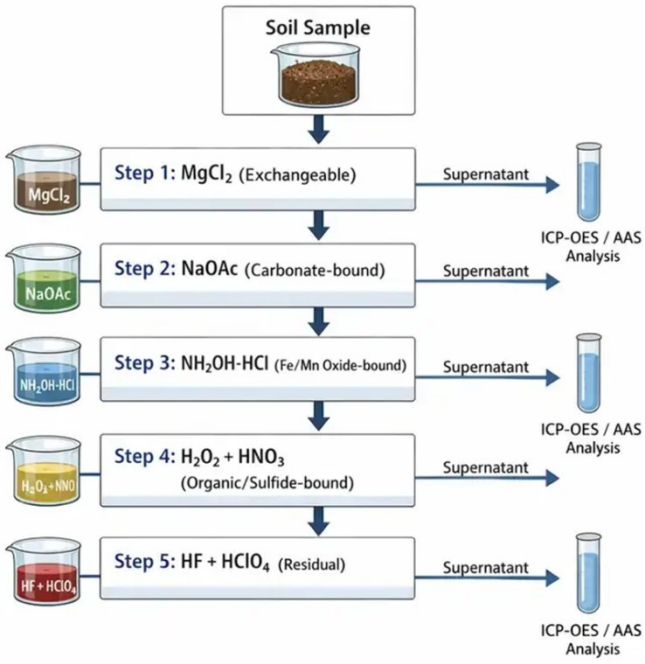

Figure 2. Schematic procedure of sequential extraction of PTE's from urban soil samples

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2.6. Chemical speciation modeling of PTE's

To simulate the chemical speciation of potentially toxic elements (PTEs) in the soil solution phase, Visual MINTEQ (version 3.1) was employed—a powerful thermodynamic equilibrium model for environmental applications. The model was parameterized using site-specific soil physicochemical properties to ensure accurate predictions. Key inputs included:

Physicochemical parameters: Measured soil pH, dissolved organic carbon (DOC), and major background ions (Ca2+, Mg2+, Na+, K+, and Cl−).

Element concentrations: Total dissolved concentrations of the studied PTEs (Pb, Cd, Ni, and As) obtained from the soil extracts.

Equilibrium settings: Thermodynamic stability constants and the NICA-Donnan model for organic matter complexation, assuming a system at thermodynamic equilibrium.

The modeling outputs provided the percentage distribution of various chemical species for each element, including free aqua-ions (e.g., Pb2+, Cd2+), inorganic complexes, and dissolved organic-bound species. These results were crucial for interpreting the mobility, bioavailability, and potential toxicity of PTEs, as the free ion activity is often a more reliable indicator of environmental risk than total metal concentrations.

3. Data Analysis And Interpretation

A comparative evaluation was performed by integrating total concentrations, sequential extraction fractions, and geochemical speciation outputs (Visual MINTEQ) for both Chitgar and Lavizan parks. This integrated approach focused on identifying dominant chemical species, assessing the mobility potential of potentially toxic elements (PTEs), and examining spatial variations in their geochemical behavior. The findings were benchmarked against national and international environmental standards and recent literature to discuss their broader environmental implications.

Descriptive statistics, including the mean, standard deviation, and range (minimum and maximum), were calculated for all measured parameters to characterize the data distribution and provide a baseline comparison of soil conditions between the two study areas. Prior to comparative testing, the normality of the data distribution was assessed using the Shapiro–Wilk test.

To evaluate the significance of differences in PTE concentrations and soil physicochemical properties between Chitgar and Lavizan parks, an independent samples t-test was employed for normally distributed data. For variables that did not meet the normality assumption, the non-parametric Mann–Whitney U test was used. All statistical analyses were performed at a significance level of $\alpha = 0.05$.

Correlation analysis was performed to investigate the interrelationships between soil physicochemical properties—such as pH, organic matter (OM) content, and particle size distribution—and the total concentrations, as well as the geochemical speciation of potentially toxic elements (PTEs). Pearson's correlation coefficient was utilized for variables following a normal distribution, while Spearman's rank correlation was employed for non-normally distributed data. This dual approach was instrumental in identifying the governing factors that control the mobility, fractionation, and bioavailability of PTEs in the urban park soils of Tehran

To evaluate the relative distribution and geochemical partitioning of the analyzed potentially toxic elements (PTEs), the percentage contribution of each sequential extraction fraction—specifically the exchangeable (F1), carbonate-bound (F2), Fe–Mn oxide-bound (F3), organic-bound (F4), and residual (F5) fractions—was calculated relative to the sum of all fractions. The partitioning profiles were subsequently visualized using stacked bar charts to facilitate a comparative assessment of PTE geochemical behavior both among the elements and between the Chitgar and Lavizan urban parks.

Statistical analyses were performed using SPSS (version 26). Data processing, correlation computations, and data visualization workflows were implemented in Python (version 3/10) utilizing the NumPy, Pandas, SciPy, and Matplotlib libraries. Additional graphical representations were generated using Origin and Microsoft Excel. All statistical tests were conducted at a 95% confidence level, with the threshold for statistical significance set at $p<0.05$.

The environmental risk of potentially toxic elements (PTEs) in the soil was evaluated using the Risk Assessment Code (RAC). This index is determined based on the percentage of metals associated with the

mobile fractions of the sequential extraction. Under this framework, metals present in the exchangeable and carbonate-bound fractions are considered potentially mobile and bioavailable. Originally introduced by Perin et al. (1985), the RAC serves as a quantitative tool to estimate the probability of metal release and its subsequent ecological hazards. It is now widely adopted in urban soil and sediment research to assess the mobility-based risk of trace elements.
Formula for calculating the RAC index.

$$RAC(\%) = (F^1 + F^2) / C\_total \times 100 \quad (1)$$

where F^1 is the metal concentration in the exchangeable fraction, F^2 is the metal concentration in the carbonate-bound fraction, and Ctotal represents the total metal concentration.

4. Result

The results of soil physicochemical analyses, total heavy metal concentrations, sequential extraction, and chemical speciation modeling are presented in Tables 1–5.

Table 1 presents the physicochemical properties of soils from the studied parks. The results show that soil pH in both parks is near neutral, and the dominant soil texture is sandy. These characteristics may significantly influence the mobility, retention, and bioavailability of potentially toxic elements (PTEs) in the studied soils.

The results presented in Table 1 indicate that soil pH in both Chitgar and Lavizan parks is close to neutral (approximately 7,3-7,5). Such conditions play an important geochemical role in controlling the speciation, mobility, and bioavailability of potentially toxic elements (PTEs).

Table 2 presents the total concentrations of potentially toxic elements (PTEs) in the soils of Chitgar and Lavizan parks.

Table 3 shows the distribution of potentially toxic elements (PTEs) among the sequential extraction fractions in soils from Chitgar Park. The location of Chitgar Park in proximity to major urban and industrial transportation corridors—including the Karaj Special Road, the Karaj–Tehran highway, and the Hemmat and Hakim expressways—plays a significant role in shaping the contamination pattern and geochemical behavior of potentially toxic elements (PTEs) in this area. Numerous studies have demonstrated that heavy traffic, tire and brake wear, fossil fuel combustion, and the emission of industrial particulates are among the major sources introducing metals such as lead, cadmium, zinc, and chromium into urban soils located near highways and industrial zones (Charlesworth et al., 2011; Wei & Yang, 2010).

Table 1. Physicochemical properties of soils in the studied parks

Parameter	Chitgar Park (mean ± SD)	Lavizan Park (mean ± SD)
pH	7.32 ± 0.18	7.45 ± 0.21
Sand(%)	68.5 ± 6.4	71.2 ± 5.9
Silt(%)	18.7 ± 4.1	17.4 ± 3.8
Clay(%)	12.8 ± 3.2	11.4 ± 3.5
Organic matter(%)	9.6 ± 2.1	11.3 ± 2.4

Table 2. Total concentrations of potentially toxic elements (PTEs) in soils of Chitgar and Lavizan parks (mg/kg)

Metal	Chitgar (Mean ± SD)	Lavizan (Mean ± SD)	Permissible limit (mg/kg)
Lead (Pb)	114 ± 32	137 ± 41	100
Cadmium (Cd)	1.62 ± 0.48	4.08 ± 1.12	3
Nickel (Ni)	67.1 ± 18	95.7 ± 26	75
Arsenic (As)	12.9 ± 3.4	19.1 ± 5.1	20

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Table 3. Distribution of potentially toxic elements (PTEs) among sequential extraction fractions in Chitgar Park soils.

Phase / Element	Ni	Pb	Zn	Be	Al	As	Cd	Cr	Hg
Total concentration	1.82	79.6	2.55	12.8	11300	2.15	196	210.4	83.5
Exchangeable fraction	0.6	28.4	0.9	4.1	3500	0.7	58.2	65.3	25.7
Carbonate-bound fraction	0.4	22.1	0.7	3.2	2800	0.5	45.3	52.1	20.1
Fe–Mn oxide-bound fraction	0.5	25.3	0.8	3.8	3200	0.6	55.1	60.8	22.3
Organic matter-bound fraction	0.2	2.8	0.15	1.3	1200	0.2	22.7	25.4	10.2
Residual fraction	0.12	1.0	0.001	0.4	600	0.1	14.7	6.8	5.2

Table 4. Distribution of potentially toxic elements (PTEs) among sequential extraction fractions in Lavizan Park soils

Phase / Element	Ni	Pb	Zn	Be	Al	As	Cd	Cr	Hg
Total concentration	41.8	65.5	124	0.001	7380	9.14	0.61	48.2	0.37
Exchangeable fraction	13.4	21.1	40.1	0.001	2400	3	0.21	16.8	0.13
Carbonate-bound fraction	8.8	13	25.2	0.001	1800	2.1	0.15	11.2	0.08
Fe–Mn oxide-bound fraction	11.2	16.4	32.4	0.001	2200	2.7	0.18	14.5	0.1
Organic matter-bound fraction	5.4	8.2	15.1	0.001	950	1.2	0.07	4.1	0.04
Residual fraction	3	6.8	11.2	0.001	830	0.14	0.1	1.6	0.02

Table 4 presents the distribution of potentially toxic elements (PTEs) among the sequential extraction fractions in the soils of Lavizan Park. The predominance of stable fractions in the sequential extraction results indicates that potentially toxic elements (PTEs) are largely controlled by geochemical adsorption and stabilization processes, resulting in a relatively limited environmental risk (Tessier et al., 1979; Kabata-Pendias, 2011).

The comparison of total concentrations of potentially toxic elements (PTEs) in soils from Chitgar and Lavizan urban parks indicates noticeable differences in the accumulation patterns of these elements between the two locations (Fig. 3).

Table 5 demonstrates that the combination of chemical speciation and sequential extraction provides a more realistic assessment of potentially toxic elements (PTEs) risk compared to total concentrations alone. This is particularly evident for cadmium and lead, which—despite their differing total levels—exhibit the highest environmental risk due to the predominance of soluble species and mobile geochemical fractions.

The comparison of the Risk Assessment Code (RAC) values for the studied metals further highlights differences in their potential mobility and bioavailability between the two parks (Fig. 4).

5. Discussion

The Risk Assessment Code (RAC) was applied to assess the potential environmental risk of PTEs based on the percentage of each element present in the mobile fractions (exchangeable + carbonate-bound). RAC values were classified as follows: <1% (no risk), 1–10% (low risk), 11–30% (medium risk), 31–50% (high risk), and >50% (very high risk).

According Table 1 at near-neutral pH, many potentially toxic elements (PTEs) tend to be adsorbed onto soil particles—particularly iron and manganese oxides—or form relatively stable complexes, which can reduce their mobility. However, for certain

elements such as lead and cadmium, appreciable proportions of soluble and exchangeable species have been reported even within this pH range, increasing their potential mobility and bioavailability (Kabata-Pendias, 2011). The dominant soil texture in both Chitgar and Lavizan parks is sandy, accompanied by a considerable proportion of silt and a smaller fraction of clay. Sandy textures, due to their lower specific surface area and limited adsorption capacity compared to clay-rich soils, generally exhibit a reduced ability to retain potentially toxic elements (PTEs). This typically leads to higher mobility and a greater proportion of metals remaining in the dissolved phase. Although the presence of silt and clay—though in lower amounts—can partially mitigate this effect by providing additional sorption sites, soils with predominantly sandy texture are overall more susceptible to the migration and redistribution of potentially toxic elements (PTEs) , particularly under fluctuating moisture conditions (Alloway, 2013).

Table 5. Chemical speciation, mobility, and geochemical risk of potentially toxic elements (PTEs) in urban-park soils (based on Visual MINTEQ modeling and sequential extraction)

Element	Parks	Dominant aqueous species (Visual MINTEQ)	Contribution of dominant dissolved Pb/Cd species (%)	Important secondary species	Solid-phase condition (Sequential Extraction)	RAC (%)	Environmental risk level
Lead (Pb)	Chitgar	Pb^{2+}	75.74	$PbCl^{+}$ (23.7%)	Predominantly in exchangeable and carbonate fractions	>50	Very high
Lead (Pb)	Lavizan	Pb^{2+}	Dominant	$PbCl^{+}$, $PbOH^{+}$	Mainly associated with Fe–Mn oxide and organic fractions	30–50	Moderate to high
Cadmium (Cd)	Chitgar	Cd^{2+}	Dominant (very high)	$CdCl^{+}$, $CdCl_2(aq)$	Very high proportion in exchangeable fraction	>50	Very high
Cadmium (Cd)	Lavizan	Cd^{2+}	Dominant	$CdCl^{+}$	Moderate exchangeable and carbonate fractions	30–50	Moderate to high
Nickel (Ni)	Chitgar	Ni^{2+}	Dominant	$NiCl^{+}$ (minor)	Exchangeable and oxide-bound fractions	11–30	Moderate
Nickel (Ni)	Lavizan	Ni^{2+}	Dominant	Minor hydroxyl species	Predominantly in stable fractions	<10	Low
Arsenic (As)	Chitgar	$HAsO_4^{2-}$	Dominant	$H_2AsO_4^{-}$	Adsorbed onto Fe–Al oxides	<10	Low
Arsenic (As)	Lavizan	$HAsO_4^{2-}$	Dominant	-	Predominantly in stable fractions	<10	Low

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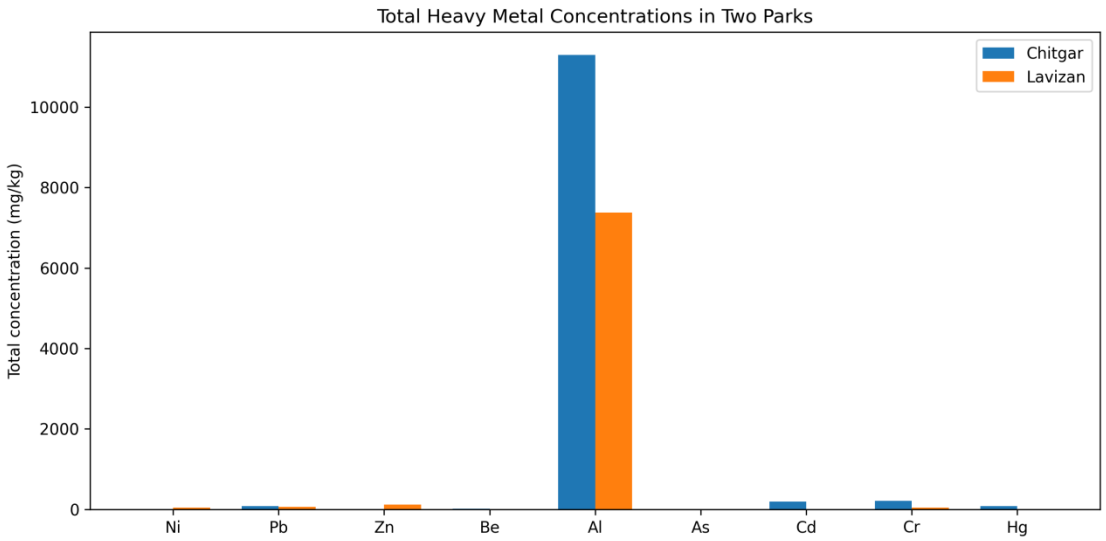

Figure 3. Comparison of total concentrations of potentially toxic elements (PTEs) in soils of Chitgar and Lavizan urban parks

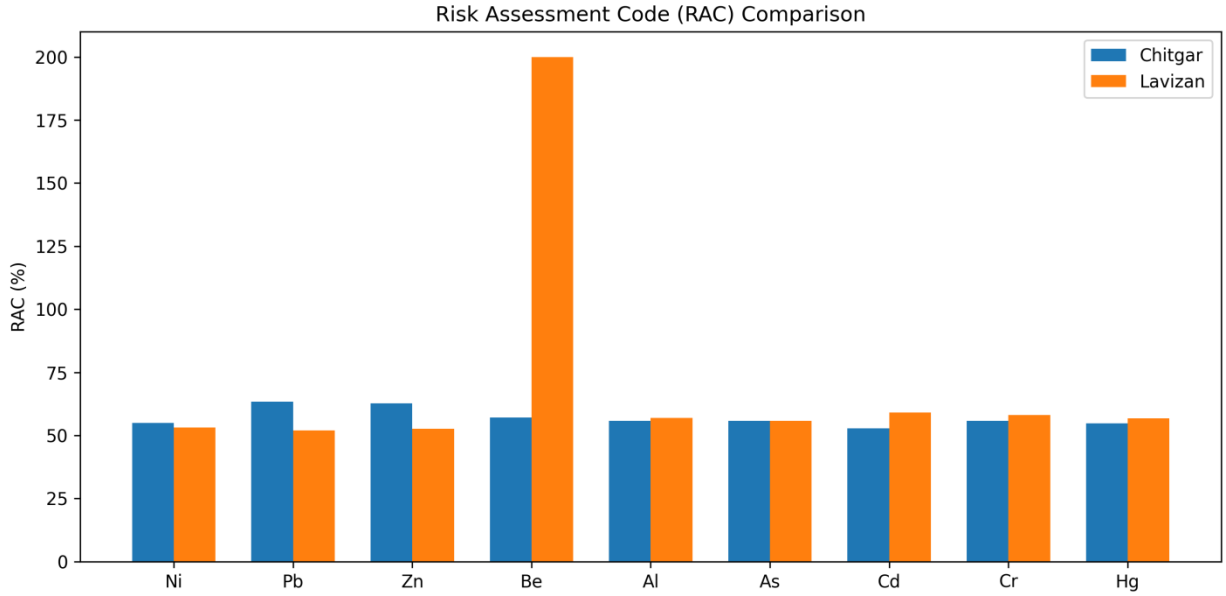

Figure 4. Comparison of Risk Assessment Code (RAC) values for potentially toxic elements (PTEs) in Chitgar and Lavizan park soils

The organic matter content of the soil was slightly higher in Lavizan Park compared to Chitgar Park. Soil organic matter plays a dual role in the geochemical behavior of potentially toxic elements (PTEs). On one hand, it can enhance the retention of metals in soil through the formation of stable metal–organic complexes and adsorption onto organic functional groups. On the other hand, the formation of soluble metal–organic complexes may increase the mobility of certain elements. This dual effect is particularly significant for metals such as lead and nickel and may partly explain the differences observed in metal behavior between the two parks McBride, (1994).

Overall, the results presented in Table 1 indicate that the physicochemical conditions of soils in both parks—particularly the near-neutral pH, the predominantly sandy texture, and the presence of organic matter—create an environment in which the chemical speciation of potentially toxic elements (PTEs) plays a key role in controlling their mobility and environmental risk. These findings suggest that assessing heavy metal behavior in urban soils without

considering the geochemical characteristics of the soil may lead to incomplete or potentially misleading interpretations of their environmental risk potential.

The total concentrations of potentially toxic elements (PTEs) observed in this study Table 2 reveal a clear spatial disparity, with Lavizan Park exhibiting significantly higher levels of Pb, Cd, Ni, and As compared to Chitgar Park. The elevated levels of Pb (114–137 mg/kg) and Cd (1.62–4.08 mg/kg) in both parks, particularly Lavizan, exceed the common permissible limits. These findings are consistent with previous studies in Tehran (e.g., Fazeli et al., 2019; Aali et al., 2024), which attributed high PTE concentrations in urban green spaces to intense vehicular emissions and the long-term deposition of atmospheric particulates. Regarding Ni, the concentrations in Lavizan (95.7 mg/kg) notably exceeded the permissible limit of 75 mg/kg. This elevation is consistent with the findings of Yüksel et al. (2025), who demonstrated that in metropolitan areas like Istanbul, Ni accumulation in street dust and topsoil is frequently linked to heavy traffic and industrial activities. Similarly, the urban park soils in Tehran, characterized as 'anthropogenic soils'—a concept thoroughly reviewed by Bakhmatova et al. (2022)—often exhibit higher PTE levels due to their proximity to transportation networks and the use of modified parent materials during park construction. In contrast, As levels remained within safe thresholds in both parks. This observation aligns with the spatiotemporal analysis by Yang et al. (2021), which suggests that while certain PTEs show increasing trends due to urbanization, others like arsenic often remain stable when geogenic (natural) sources dominate. Furthermore, as discussed by Zaman et al. (2025), the biogeochemical cycling of these elements in plant-soil systems is highly dependent on anthropogenic disruptions; the lower levels of As indicate that, unlike Ni, this element has not yet been significantly influenced by such disruptions in the studied recreational zones.

The results of the sequential extraction in this study Table 3, which show a high proportion of exchangeable and carbonate-bound fractions for lead and cadmium in the soils of Chitgar Park, are consistent with contamination patterns associated with anthropogenic sources. Previous studies have indicated that metals originating from traffic and industrial activities tend to accumulate in the more labile soil fractions and can be readily released under changes in pH and ionic conditions (Li et al., 2001; Sutherland,2010). This characteristic is particularly evident for cadmium and lead, which show a lower tendency to be incorporated into the residual fraction. Moreover, the proximity of Chitgar Park to the industrial zones of western Tehran may contribute to increased metal inputs through atmospheric deposition of industrial particulates. This process has been widely recognized in urban soil studies as one of the major pathways for the transfer of potentially toxic elements (PTEs) to surface soil layers (Alloway, 2013). These conditions, together with the lighter soil texture and the greater environmental dynamics, have resulted in potentially toxic elements (PTEs) in Chitgar Park predominantly remaining in more mobile geochemical forms. Consequently, the soils of Chitgar Park exhibit a higher potential environmental risk compared with those of Lavizan Park. The proximity of Chitgar Park to industrial corridors and heavily trafficked highways in western Tehran likely explains the predominantly anthropogenic origin of heavy metal contamination and their enrichment in the mobile soil fractions. Similar patterns have been reported in many urban soils located near industrial areas and major traffic routes (Ghobadi et al., 2024). A study conducted in the city of Arak reported that the spatial distribution of arsenic in urban soils is influenced by both natural and anthropogenic factors, with the highest concentrations observed in the central and industrial areas of the city (Solgi et al., 2015).

The sequential extraction results for potentially toxic elements (PTEs) in Lavizan Park soils Table 4 showed that a substantial proportion of the analyzed elements was associated with relatively stable geochemical fractions, particularly those bound to Fe–Mn oxides, organic matter, and the residual phase. In general, this distribution pattern indicates lower mobility and reduced immediate environmental risk compared with soils in which PTEs are predominantly concentrated in the exchangeable and carbonate-bound fractions (Tessier et al., 1979; Li et al., 2001). From a geochemical perspective, the predominance of oxide-bound, organic-bound, and residual forms suggests that the retention capacity of the soil matrix plays a major role in limiting the release of these elements under existing conditions.

For Pb, nearly one-third of the total concentration occurred in the exchangeable and carbonate-bound

fractions, while a considerable proportion was also associated with Fe–Mn oxides and organic matter. This distribution suggests that, although part of Pb may be relatively reactive, a significant fraction is retained through adsorption onto mineral surfaces and complexation with soil constituents. The strong affinity of Pb for oxide phases and organic matter has been widely documented and is generally associated with decreased mobility and bioavailability in soils (Alloway, 2013; Kabata-Pendias, 2011). In urban park environments, such behavior may reflect both anthropogenic inputs and subsequent stabilization within the soil matrix, especially in soils that have undergone long-term physicochemical aging (Bakhmatova et al., 2022).

In contrast, Cd displayed a substantial proportion in the exchangeable and carbonate-bound fractions despite its lower total concentration. This pattern highlights the comparatively high mobility of Cd relative to other PTEs and indicates a greater potential for release under changing environmental conditions. The elevated lability of Cd is consistent with its geochemical behavior in soil systems and has frequently been reported in previous studies, where cadmium is recognized as one of the most mobile and potentially bioavailable trace elements in urban soils (McLaughlin et al., 2000; Kabata-Pendias, 2011). From a risk perspective, this finding is important because even low total concentrations may not necessarily imply low environmental concern when a large share of the element is present in weakly bound fractions.

For Ni and Cr, the dominant proportions were found in the Fe–Mn oxide-bound and residual fractions. Such a partitioning pattern commonly indicates stronger geochemical stabilization and, in many cases, a predominantly lithogenic or geogenic origin. Similar fractionation trends have been reported in sequential extraction studies of natural and semi-natural soils, where Ni and Cr are often associated with mineral lattices or secondary oxide phases rather than with readily exchangeable pools (Li et al., 2001; Sutherland, 2010). This suggests that, under current soil conditions, these elements are less prone to mobilization and may pose a comparatively lower short-term environmental risk in Lavizan Park. At the same time, the persistence of Ni in relatively stable fractions does not eliminate long-term concern, particularly in urban soils affected by anthropogenic disturbances and altered biogeochemical cycling (Zaman et al., 2025).

For Zn, a more balanced distribution among the exchangeable, carbonate-bound, and oxide-bound fractions was observed, indicating an intermediate geochemical behavior and moderate mobility. Zinc is well known to occur in both labile and relatively stable fractions, with its partitioning strongly influenced by soil pH, organic matter, and mineralogical characteristics (Alloway, 2013). This mixed distribution suggests that Zn in Lavizan Park may respond more sensitively than Ni and Cr to changes in environmental conditions such as acidification or organic matter decomposition. Similar variability in Zn fractionation has been noted in urban soils, where the heterogeneous nature of anthropogenic soils can lead to a broad spectrum of retention mechanisms and mobility patterns (Bakhmatova et al., 2022; Yang et al., 2021).

Overall, the sequential extraction results indicate that although a considerable portion of the studied PTEs in Lavizan Park is retained in relatively stable fractions, element-specific differences in fractionation are critical for interpreting environmental behavior. In particular, the higher proportions of exchangeable and carbonate-bound Cd and, to a lesser extent, Pb suggest greater potential mobility than would be inferred from total concentrations alone. These findings confirm the importance of fractionation-based assessment for urban park soils, where total concentrations may underestimate the actual ecological relevance of more labile PTE pools (Tessier et al., 1979; Alloway, 2013; Liao et al.,2024).

Overall, the sequential extraction patterns in Lavizan Park indicate that although certain PTEs, particularly Cd and Pb, exhibit a degree of potential mobility, the predominance of their occurrence in relatively stable fractions points to a moderate to low environmental risk under current soil conditions. This fractionation behavior suggests that geochemical retention processes, including association with Fe–Mn oxides, organic matter, and residual mineral phases, play an important role in limiting the immediate release of these elements. Therefore, sequential extraction offers a more reliable approach for evaluating the geochemical behavior, mobility, and potential ecological hazards of PTEs in urban soils than assessments based solely on total concentrations (Tessier et al., 1979; Sutherland, 2010). This is

particularly relevant in urban park soils, where anthropogenic disturbances and soil heterogeneity may strongly influence element partitioning and environmental availability (Bakhmatova et al., 2022; Zaman et al., 2025).

The present results demonstrate that the geochemical behavior of PTEs in Chitgar Park soils is markedly affected by the park's location adjacent to industrial areas and major transportation corridors in western Tehran. The dominance of exchangeable and carbonate-bound fractions for Pb and Cd indicates not only enhanced mobility but also a likely anthropogenic origin for these elements. In geochemical terms, the occurrence of Pb and Cd in weakly bound fractions suggests greater environmental availability and a higher likelihood of remobilization under shifts in soil conditions.

By comparison, Lavizan Park soils exhibited a higher proportion of metals in more stable forms, especially those associated with Fe–Mn oxides, organic matter, and the residual fraction. This fractionation pattern reflects stronger retention within the soil matrix and points to relatively lower mobility and environmental risk. The clear distinction between the two parks underscores the value of fractionation-based assessments in urban environments, where total concentrations alone may overlook substantial differences in metal stability, origin, and potential ecological significance. Therefore, sequential extraction and chemical speciation should be regarded as essential tools for a more realistic assessment of PTE risks in urban park soils (Hosseini & Sobhan Ardakani, 2021; Zaman et al., 2025).

According to the results of Fig. 3, the concentration of some metals in Chitgar Park was higher than that observed in Lavizan Park. Such variations may be related to differences in the intensity of human activities, potential pollution sources, and the geochemical characteristics of soils in the two areas. The proximity of parts of Chitgar Park to major urban traffic routes and recreational activities may contribute to a greater input of potentially toxic elements (PTEs) into the soil. In contrast, environmental conditions and land use patterns in Lavizan Park may have limited the accumulation of certain metals. These findings suggest that even within urban green spaces, the distribution of potentially toxic elements (PTEs) can be strongly influenced by local environmental conditions and surrounding anthropogenic activities.

The results presented in Table 5 indicate that the geochemical behavior of potentially toxic elements (PTEs) in the studied urban park soils is not solely dependent on total concentration, but is significantly influenced by chemical speciation in the solution phase and their distribution within the soil's solid phases. According to the Visual MINTEQ output, free metal ion species were dominant in both Chitgar and Lavizan parks, particularly for lead (Pb) and cadmium (Cd). This dominance suggests a high potential for the mobility and bioavailability of these elements

The speciation pattern of lead in Chitgar Park, where Pb^{2+} appears as the dominant species followed by $PbCl^{+}$ as an important secondary complex, is consistent with the geochemical behavior of oxic environments with near-neutral pH conditions. Equilibrium modeling studies have reported that under such conditions the free Pb^{2+} ion typically constitutes the major dissolved species, while an increase in chloride concentration or ionic strength can enhance the formation of chloride complexes (e.g., $PbCl^{+}$) without necessarily eliminating metal mobility. This phenomenon has been discussed in studies on soil–water solution speciation as well as in equilibrium modeling applications used to predict Pb species in natural and experimental systems (Cuske et al., 2017). Similarly, for cadmium, the dominance of $Cd2^{+}$ accompanied by a meaningful presence of $CdCl^{+}$ at near-neutral pH aligns with prior findings that emphasize the importance of solution speciation and the role of accompanying anions—particularly chloride—in controlling the stability and chemical activity of Cd(II). Increased chloride concentration and ionic strength can shift speciation toward chloro-complexes (e.g., $CdCl^{+}$), while the free Cd^{2+} ion often remains the principal species under oxic, circumneutral conditions. These patterns are consistent with studies highlighting the interplay between aqueous complexation, ionic strength, and cadmium mobility/bioavailability in natural and experimental systems (Meers et al., 2005). In Chitgar Park, the dominance of free $Pb2^{+}$ and $Cd2^{+}$ species in the soil solution, together with the high proportion of these metals in the exchangeable and carbonate-bound fractions of the sequential extraction results, leads to elevated RAC values and consequently a very high environmental risk (Fig. 4).This pattern indicates that potentially toxic elements (PTEs) in this park are mainly present in unstable and readily mobilizable

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forms, such that even minor changes in soil chemical conditions could significantly enhance their mobility. In contrast, the soil of Lavizan Park exhibits a more stable geochemical behavior. Although free metal ions are still present in the soil solution, a larger proportion of the metals is associated with Fe–Mn oxide-bound and organic-bound fractions, resulting in relatively lower mobility and reduced environmental risk. In particular, the low contribution of mobile fractions and the small RAC values for nickel and arsenic indicate higher geochemical stability and lower hazard levels for these elements in both parks (Liao et al., 2024). Overall, the results presented in Table 5 confirm that the use of an integrated approach combining chemical speciation modeling and sequential extraction provides a more realistic tool for assessing the environmental risk of potentially toxic elements (PTEs) in urban soils. Reliance solely on total metal concentrations cannot adequately reflect the actual differences in geochemical behavior and hazard potential of these elements.

Moreover, studies employing the Tessier sequential extraction method for metals in contaminated soils have demonstrated that the differentiation of operationally defined fractions—exchangeable, carbonate-bound, Fe–Mn oxide-bound, organic-bound, and residual—serves as a key framework for interpreting the origin, stability, and potential release of metals. In this context, the findings of the present study, particularly the higher proportion of mobile fractions in Chitgar soils compared with the greater contribution of more stable fractions in Lavizan soils, are consistent with this widely accepted conceptual framework for evaluating heavy-metal mobility and environmental risk (Qayyum et al., 2017).

Despite the strengths of the integrated framework used in this study (sequential extraction, RAC, and Visual MINTEQ), several limitations should be considered. First, the investigation was limited to two urban parks, which may restrict the extrapolation of the results to other urban soils with different land-use histories, parent materials, and pollution sources. Second, sampling was conducted during a single campaign, and therefore potential seasonal or temporal variability in mobility, fractionation, and risk classification was not captured. Third, Visual MINTEQ is an equilibrium-based geochemical model and assumes that the soil–water system approaches thermodynamic equilibrium. This assumption may not fully represent field conditions where kinetic constraints, transient changes in pH, redox state, and ionic strength can control PTE partitioning. In addition, the modeled speciation outputs were not independently validated through direct measurements of pore-water/soil-solution composition (e.g., via lysimeter sampling or extraction of soil solution), introducing uncertainty into the speciation estimates. Future work should therefore expand spatial coverage, incorporate repeated sampling across seasons, and validate modeled predictions with solution-phase measurements to further strengthen inference regarding PTE mobility and exposure pathways.

The integration of sequential extraction, the Risk Assessment Code (RAC), and Visual MINTEQ modeling provides a robust, multi-dimensional framework for understanding PTE behavior that transcends the inherent limitations of individual analytical methods. While sequential extraction identified the specific geochemical partitioning of PTEs into operationally defined pools, the application of the RAC translated these fractions into quantifiable metrics of ecological risk, highlighting the high-risk status of labile Pb and Cd pools in Chitgar Park. Visual MINTEQ complemented these findings by elucidating the chemical speciation within the soil solution, offering mechanistic insights into the thermodynamic stability and bioavailable ionic forms of these elements. By triangulating these datasets, we successfully discerned that while Chitgar Park faces elevated ecological pressure due to the dominance of labile phases in the exchangeable and carbonate-bound pools—as confirmed by high RAC values and speciation modeling—Lavizan Park exhibits greater geochemical resilience through the sequestration of PTEs in stable oxide and residual phases. This multi-tool approach confirms that assessing the environmental hazard of urban soils requires moving beyond total concentration to a nuanced consideration of chemical fractionation, speciation, and thermodynamic behavior.

6. Conclusion

Overall, the findings indicate that the geochemical behavior of potentially toxic elements (PTEs) in urban park soils is controlled not only by their total concentrations, but also by their chemical forms and distribution among soil fractions. The results suggest

that Chitgar Park is characterized by relatively higher mobility and potential bioavailability of Pb and Cd, whereas Lavizan Park shows comparatively lower mobility due to greater association of PTEs with more stable fractions. The combined use of sequential extraction, Visual MINTEQ modeling, and RAC provides a more comprehensive and realistic assessment of PTE behavior and environmental risk in urban soils than total concentration data alone. This integrated approach may therefore be useful for pollution monitoring and risk management in urban parks and green spaces. Future studies should expand the spatial scope, include seasonal monitoring, and validate model outputs using direct soil-solution measurements.

Authors' Contribution
All authors contributed equally to the conception, design, data collection, analysis, and writing of the manuscript. All authors read and approved the final version of the article.

Availability of data and materials
All data supporting the findings of this study are included in the manuscript. Additional raw data are available from the corresponding author on request.

Conflict of interests
The authors declare that they have no conflict of interest.

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