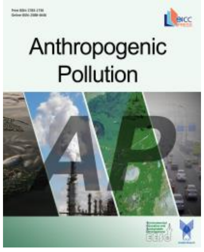

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Research Article

Urban Street Dust as a Mirror of Industrial Identity: A Comparative Analysis of Metal Pollution Profiles and Health Risks(caseud Study:Borujerd City,Iran)

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Abstract

Urban street dust serves as a critical reservoir for toxic potentially toxic elements, posing significant environmental and public health risks—particularly in industrializing regions of the Global South. While numerous studies have assessed metal pollution in individual cities, a cross-regional synthesis linking contamination profiles to socio-industrial contexts remains lacking. To address this gap, we conducted a systematic review and comparative meta-analysis of peer-reviewed studies (2015–2025) from urban centers across Iran and South Asia, integrating new empirical data from Borujerd City, Iran—a representative case of small industrial cities in semi-arid zones. Our analysis reveals a striking regional divergence: Iranian cities consistently exhibit arsenic (As)-dominated pollution, with hazard quotients (HQ) for children reaching 17.05 in Borujerd, far exceeding safe thresholds. In contrast, South Asian cities (e.g., Gazipur, Bangladesh) show rising contamination from technology-critical elements (Bi, Ga, In) linked to e-waste and electric mobility. Source apportionment across the region identifies industrial gas emissions (29.6% in Borujerd) and traffic-related activities as dominant contributors, though their chemical fingerprints differ markedly. While carcinogenic risks remain below the U.S. EPA threshold (10^{-6}), non-carcinogenic risks—especially from As-demand urgent intervention. We propose a dual-track policy framework: (i) strict emission controls on As-laden industrial gases in Iran, and (ii) e-waste recycling regulations to curb emerging metal leakage in South Asia. This study provides a scalable model for context-sensitive urban dust management that balances industrial development with public health protection.

Keywords: Urban street dust; potentially toxic elements; Source apportionment; Health risk assessment; Industrial emissions

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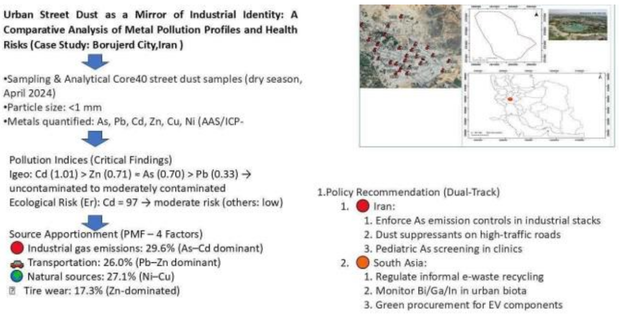

Urban Street Dust as a Mirror of Industrial Identity: A Comparative Analysis of Metal Pollution Profiles and Health Risks (Case Study: Borujerd City,Iran)

- Sampling & Analytical Core40 street dust samples (dry season, April 2024)
- Particle size: <1 mm
- Metals quantified: As, Pb, Cd, Zn, Cu, Ni (AAS/ICP-

Pollution Indices (Critical Findings)
Igeo: Cd (1.01) > Zn (0.71) ≈ As (0.70) > Pb (0.33) → uncontaminated to moderately contaminated
Ecological Risk (Er): Cd = 97 → moderate risk (others: low)

Source Apportionment (PMF – 4 Factors)
● Industrial gas emissions: 29.6% (As–Cd dominant)
🚗 Transportation: 26.0% (Pb–Zn dominant)
🌍 Natural sources: 27.1% (Ni–Cu)
▯ Tire wear: 17.3% (Zn-dominated)

1.Policy Recommendation (Dual-Track)
1. ● Iran:
    1. Enforce As emission controls in industrial stacks
    2. Dust suppressants on high-traffic roads
    3. Pediatric As screening in clinics
2. ● South Asia:
    1. Regulate informal e-waste recycling
    2. Monitor Bi/Ga/In in urban biota
    3. Green procurement for EV components

1. Introduction

Urbanization and industrialization have significantly intensified anthropogenic activities, leading to the accumulation of potentially toxic elements in street dust—a critical environmental and public health concern. Higher population densities in urban areas drive increased resource consumption and waste generation, resulting in voluminous and chemically diverse waste streams compared to rural settings (Selonen & Setälä, 2015; Hashemi et al., 2025). When exposed to rainfall, these wastes contribute to surface runoff that contaminates water bodies, thereby reducing the availability of usable water and threatening both ecological integrity and human well-being (Liu et al., 2008). Street dust acts as a reservoir for trace metals originating from both natural and anthropogenic sources. In densely populated urban environments, elevated concentrations of potentially toxic elements —including arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), and nickel (Ni)—are commonly observed (Amato et al., 2014; Chen et al., 2014; Hosseinzadeh et al., 2024; Ghiasi et al., 2025). These metals originate from vehicular emissions (e.g., tire wear, brake abrasion), industrial discharges, construction activities, atmospheric deposition, and even pavement materials themselves. For instance, Zn and Cu are frequently associated with tire and brake wear, respectively (Amato et al., 2014), whereas Pb and Cd often reflect historical and ongoing industrial emissions (Cui et al., 2021). Notably, recent studies show that highway pavements—particularly concrete containing fly ash—contribute significantly to Pb, V, Cr, Ni, and Co in road dust, expanding the traditional view of non-exhaust emissions beyond vehicle components (Fiala & Hwang, 2021; Yari et al., 2021). While such pollution is globally documented, its manifestation varies significantly across socio-industrial contexts—particularly between regions dominated by legacy metallurgical emissions (e.g., Iran) and those influenced by emerging e-waste processing and electric mobility (e.g., South Asia). Unlike organic pollutants, trace metals are non-degradable and exhibit strong tendencies for bioaccumulation. Human exposure occurs primarily through inhalation, ingestion, and dermal contact—routes that are especially significant for children due to frequent hand-to-mouth behavior and outdoor play (Mihankhah et al., 2020). Certain metals, such as As, Cd, Pb, and Hg, serve no known biological function and can induce toxic effects even at low concentrations (Duruibe et al., 2007). Chronic exposure has been linked to neurological and respiratory disorders, cardiovascular and gastrointestinal diseases, and carcinogenic effects (Doabi et al., 2018).

In urban Iran, studies have identified As as posing the highest non-carcinogenic risk to children due to elevated exposure through dust ingestion (Dehghani et al., 2017). To evaluate contamination levels, researchers commonly employ geochemical indices such as the geo-accumulation index (Igeo) and the potential ecological risk index (RI). The Igeo, introduced by Muller (1969), classifies pollution from “uncontaminated” to “extremely contaminated.” Application of this index in industrial zones of Iran revealed significant Cd and Pb enrichment in soils (Esmaeili et al., 2014). Similarly, studies in Nigeria highlight persistent trace-metal pollution in legacy waste sites, underscoring the need for robust policy and remediation frameworks (Ogbeide & Henry, 2024). The RI, proposed by Hakanson (1980), integrates metal toxicity and concentration to prioritize ecological threats. In Turkey, RI assessments identified As and Cd as high-risk elements in agricultural soils near urban centers (Varol et al., 2021). Although numerous studies have applied PMF and health risk models to urban dust in cities like Tehran (Dehghani et al., 2017), Isfahan (Esmaeili et al., 2014), and Gazipur (Howlader et al., 2025), no systematic effort has yet synthesized these findings to answer a critical question: Do industrializing cities in the Global South share a common pollution fingerprint, or do local economic structures produce distinct metal signatures?

Source identification is essential for effective mitigation. Positive Matrix Factorization (PMF), a receptor model recommended by the U.S. EPA, is widely used to apportion pollution sources (Park et al., 2007). Although PMF applications in smaller cities remain limited, studies in northwestern China have successfully distinguished natural, industrial, traffic-related, and agricultural sources of metal contamination (Guan et al., 2018). In urban dust, traffic and industrial activities consistently emerge as dominant contributors to Zn, Pb, and Cd loads (Cui et al., 2021). Health risk assessments typically calculate hazard quotients (HQ), hazard indices (HI), and carcinogenic risk (CR). In Tehran, children exhibited elevated HQ values for As, emphasizing their heightened vulnerability (Dehghani et al., 2017; Mihankhah et al., 2020). Long-term exposure to As, Cd, and Ni may exceed acceptable carcinogenic risk

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thresholds, particularly in areas with poor dust management (Varol et al., 2021). Accurate assessment of metal contamination in road dust is highly dependent on sampling and preparation methods. Lanzerstorfer and Logiewa (2019) demonstrated that the upper particle size limit significantly influences reported metal concentrations, with finer fractions (<50 μm) showing markedly elevated levels of potentially toxic elements. They advocate for a combined sieving and air classification approach to enable flexible data use—whether for resuspension modeling, runoff studies, or health risk assessments—while also improving comparability across studies that historically used inconsistent size cutoffs.

To address the high cost and complexity of conventional chemical monitoring, alternative screening tools are gaining traction. Salazar-Rojas et al. (2023) validated environmental magnetism as a rapid, low-cost proxy for trace-metal pollution by showing strong correlations (e.g., $r \geq 0.9$) between magnetic susceptibility in biomonitors (e.g., Casuarina equisetifolia leaves) and concentrations of Fe, Cr, and V. Their findings support the use of magnetic properties of both road dust and urban vegetation as effective indicators of spatial and temporal variations in traffic-related air pollution, especially in tropical urban settings. However, the reliability of field-based dust studies also hinges on methodological consistency. Hargiss et al. (2017) compared three application techniques—sifter, sieve, and sprayer—for controlled road dust deposition and found that while all performed well at low application rates, the sprayer showed poor uniformity (>50% variability) at higher loads. They concluded that simple, low-cost tools like sifters and sieves are preferable for small-scale, precision-dependent experiments, underscoring the importance of standardized protocols in environmental exposure studies. Moreover, the effectiveness of dust suppressants on paved roads can reduce resuspension and human exposure (Shaikh et al., 2023), and emerging detection techniques, such as dielectric property-based sensing in the 10 MHz–1 GHz range, show promise for rapid identification of contaminated soils, particularly when water content is controlled (Guan et al., 2018; Hamidi et al., 2024).Finally, the human and ecological implications of metal contamination extend beyond dust to aquatic systems. Cui et al. (2021) conducted a comprehensive risk assessment in China's Haihe River basin and identified arsenic (As), chromium (Cr), mercury (Hg), and antimony (Sb) as posing significant human health risks, while nickel (Ni), copper (Cu), cadmium (Cd), and tin (Sn) presented notable ecological threats. Their derivation of human health-based ambient water quality criteria (AWQC) highlights the necessity of integrating multi-media monitoring (water, sediment, and biota) to fully characterize exposure pathways and protect vulnerable populations. Wetland and sediment studies in Iran further demonstrate how urbanization, industry, and agriculture collectively alter metal distribution in environmental matrices (Heidarzadeh et al., 2023), reinforcing the need for integrated monitoring approaches. The biogeochemical behavior and bioavailability of trace elements in semi-arid regions are strongly influenced by soil properties such as high pH, calcareousness, and low organic matter, which limit metal solubility and plant uptake—factors that distinguish Middle Eastern dust and soil systems from those in more humid or industrialized regions (Kabata-Pendias & Mukherjee, 2007).

Despite extensive research, gaps remain—particularly regarding seasonal variability in semi-arid regions, source apportionment in less-industrialized cities, and holistic integration of geochemical, receptor modeling, and health risk frameworks. To address this knowledge gap, we conduct a systematic review and comparative meta-analysis of trace metal pollution in street dust across 18 urban centers in Iran and South Asia (2015–2025). Our Borujerd dataset—collected in April 2024 during the dry season—is integrated as a representative case of small industrial cities in semi-arid Iran. By synthesizing source apportionment results (PMF/PCA), pollution indices (Igeo, RI), and health risk metrics (HQ, CR), we aim to:

(i) identify regional divergence in dominant pollutants (e.g., As vs. Bi/Ga),

(ii) link these patterns to underlying industrial and policy contexts, and

(iii) propose a dual-track framework for pollution mitigation tailored to each region's risk profile.

Despite extensive research on street dust pollution in individual cities, a critical gap remains in cross-regional synthesis that connects metal signatures to socio-industrial drivers(table 1). While Iranian cities like Tehran and Isfahan consistently report arsenic (As) as the dominant health threat—linked to metallurgical industries and As-rich fossil fuels—recent studies in South Asia, particularly Bangladesh and India, highlight emerging risks from technology-critical elements (e.g., Bi, Ga, In) associated with electric vehicles and e-waste (Howlader et al., 2025). This divergence suggests that universal mitigation strategies may be ineffective without context-specific understanding. Following PRISMA guidelines, we conducted a systematic review of peer-reviewed studies from urban centers across Iran and South Asia (2015–2025), integrating our new Borujerd dataset—collected in April 2024 during the dry season—as a representative case of small industrial cities in semi-arid Iran. By synthesizing source apportionment results (PMF/PCA), pollution indices (Igeo, RI), and health risk metrics (HQ, CR), this study aims to:

Table 1. Concentration of potentially toxic elements in Street Dust Across Eight Iranian Cities with Corresponding References

City	Metal	Avg. Concentration (mg/kg)	Pollution Index / Igeo	Main Source	Reference
Isfahan	Cu	85	Moderate	Traffic, industrial activities	Akbary & Khademi, 2019
	Zn	120	Moderate	Traffic, industrial activities	
	Pb	70	High	Traffic, industrial activities	
	Co	15	Low	Natural, minor anthropogenic	
Flavarjan	Cu	60	Moderate	Traffic, local sources	Akbary & Khademi, 2019
	Zn	130	High	Traffic, industrial emissions	
	Cu	55	Moderate	Traffic	Akbary & Khademi, 2019
Najafabad	Zn	110	Moderate	Traffic	
Shahreza	Co	20	Moderate	Traffic, industrial	Akbary & Khademi, 2019
Ahvaz	Pb	59	High	Traffic, oil activities, industrial	
	Zn	220	High	Traffic, oil activities, industrial	Hojati, 2015; Adelpour & Rafati, 2020
	Cu	78	Moderate	Traffic, oil activities, industrial	
Zabol	Cr	1.04	Moderate	Dust storms, local activities	Farahi et al., 2024
	Cd	0.014	Moderate	Dust storms, local activities	
	Pb	0.009	Moderate	Traffic, dust storms	
	Zn	0.055	Moderate	Dust storms, traffic	
Birjand	Pb	16.93 µg/m³	Moderate	Urban dust	Farahi et al., 2023
	Zn	5.55 µg/m³	Low	Urban dust	
	Cr	1.04 µg/m³	Low	Urban dust	
	As	5.98 µg/m³	High	Urban dust	
Tehran	Cd	0.081	Moderate	Industrial, traffic	Arsalani et al., 2021
	Cr	0.104	Low	Industrial, natural	
	Cu	0.078	Moderate	Industrial, traffic	
	Ni	0.040	Low	Industrial, natural	
Tehran	Pb	0.085	High	Industrial, traffic	Arsalani et al., 2021

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(i) identify regional divergence in dominant pollutants (e.g., As vs. Bi/Ga),

(ii) link these patterns to underlying industrial structures and policy environments, and

(iii) propose a dual-track framework for pollution mitigation tailored to each region's risk profile.

2. Materials and methods

2.1. Study area

The research was conducted in Borujerd City, geographically located between 48°27′ and 49°27′ eastern longitude and 33°36′ to 34°6′ northern latitude. The region's average elevation is approximately 1,570 meters above sea level. The climate is classified as semi-arid according to the Demarton system and cold semi-humid based on the Amberge classification. Meteorological data from the Borujerd weather station indicate an average annual precipitation of 444 mm and a mean annual temperature of 14.9°C. Administratively, Borujerd Municipality comprises two districts (Ashtrinan and Markazi), two urban centers (Borujerd and Ashtrinan), and seven rural districts. The topography of the region is characterized by three distinct zones: high mountains, the Mahuri hill unit, and plains. This study encompassed both field sampling and laboratory analyses.

2.2. Sampling and Analytical Procedures

To evaluate the concentrations of potentially toxic elements in Borujerd, a total of 41 street dust samples were collected during the dry season in April 2024. Sampling sites included urban hotspots, squares, main streets, residential areas, sidewalks, and other locations where dust had accumulated. The spatial distribution of sampling points is illustrated in Figure 1. In the laboratory, the collected street dust samples were sieved through a 1-mm mesh, accurately weighed using an AND jewelry balance FX-300GD with a precision of 0.001 g, and stored in plastic containers for further analysis. For metal determination, 0.5 g of each sample was digested using 12.5 mL of 4 M nitric acid (HNO_3) in a hot water bath at 80°C for 16 hours. After cooling, the digested samples were filtered using Whatman No. 42 filter paper and subsequently diluted with deionized water to a final volume of 50 mL . The total metal concentrations in the solution extracts were quantified using a flame atomic absorption spectrophotometer (AAS Model, GBC 932AB Plus). Arsenic (As) concentrations were analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, GBC Integra XL), while cadmium (Cd) was measured using a graphite furnace atomic absorption spectrophotometer (GF-AAS, GBC Avanta Ultra Z). All analyses were performed in triplicate to ensure accuracy. The wavelengths used for Pb, Cd, Cu, Ni, Zn, Co, and As were 217 nm, 225.8 nm, 324.7 nm, 232 nm, 213.4 nm, 240.7 nm, and 189 nm, respectively.

2.3. Trace element pollution assessment

2.3.1. *Geo-accumulation index*

The geo-accumulation index (Igeo), introduced by Müller (1969), was employed to assess the geochemical contamination levels of trace elements in street dust. The Igeo was calculated using Equation (1):

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5B_n}\right] \tag{1}$$

where C_n represents the measured concentration of the trace element in street dust samples (mg/kg), B_n denotes the geochemical background value of the respective trace element (mg/kg), and the factor 1.5 accounts for potential lithogenic variations in background concentrations. The Igeo values were categorized as follows: Igeo<0: practically uncontaminated; 0–1: uncontaminated to moderately contaminated; 1–2: moderately contaminated; 2–3: moderately to heavily contaminated; 3–4: heavily contaminated; 4–5: heavily to extremely contaminated; and >5: extremely contaminated (Ogbeide & Henry,2024).

2.3.2. *Potential risk*

The potential ecological risk index (RI), first proposed by Hakanson (1980), was utilized to evaluate the ecological risks posed by potentially toxic elements in street dust. The RI was estimated using Equations (2)–(4):

$$RI = \sum_{i=1}^{m} E_r \tag{2}$$

$$E_r = T_r \times C_f \tag{3}$$

$$C_f = \frac{C_s}{C_n} \tag{4}$$

where RI is the sum of the ecological risk index for trace elements in stree dust samples, E_r is the ecological risk of certain element, T_r is the toxic response factor, C_f is the contamination factor, C_s and C_n are the concentration trace elements in dust sample and geochemical background value of certain element (n), respectively. The toxic response factor values for Hg, Cd, As, Pb, Cu, Ni, Co and

Zn are 40, 30, 10, 5, 5, 5, 5, 1, respectively. Ecological risk and risk index values categorized as follows (Hakanson, 1980): $E_r \leq 40$; $RI \leq 150$: low risk, $40 < E_r < 80$; $150 < RI < 300$: moderate risk, $80 < E_r < 160$; $300 < RI < 600$: considerable risk, $160 < E_r < 320$; $RI \geq 600$: high risk, $E_r \geq 320$: very high risk.

In this study, trace elements concentrations in the soil of Isfahan city, Iran due to the similar industrial structure with this region were used as the geochemical background values to calculate the Igeo and RI (Esmaeili et al., 2014).

2.4. Human health risk assessment

2.4.1. *Exposure Dose Estimation*

The health risk assessment model developed by the United States Environmental Protection Agency (US EPA) was employed to evaluate the potential risks posed by trace elements in street dust . Human exposure to street dust occurs through three primary pathways: ingestion, inhalation, and dermal contact. The population residing in the study area was stratified into two groups—children and adults—to account for differences in exposure patterns. The average daily dose (ADD) for each exposure route was calculated using Equations (5)–(7):

$$ADD_{ingest} = [(C_i \times IngR \times CF \times EF \times ED)/(BW \times AT_{noncarc})] \quad (5)$$

$$ADD_{inhale} = [(C_i \times InhR \times EF \times ED)/(PEF \times BW \times AT_{noncarc})] \quad (6)$$

$$ADD_{dermal} = [(C_i \times SA \times CF \times AF \times ABF \times EF \times ED)/(BW \times AT_{noncarc})] \quad (7)$$

where ADD (mg kg^{-1} day^{-1}) is average daily dose through ingestion ($ADD_{ingestt}$), inhalation (ADD_{inhale}) and dermal contact (ADD_{dermal}); IngR (mg kg^{-1}) is the ingestion rate of dust; EF (days $year^{-1}$) is the exposure frequency; ED (year) is the year of exposure; BW (kg) is the mean body weight; $AT_{noncarc}$ (day) is the average exposure time for non-carcinogenic effect; CF (unitless) is the conversion unit; InhR (m^3 day^{-1}) is respiration rate; PEF (unitless) is the particulate emission factor; SA (cm^2) is the exposed skin surface factor; AF (mg cm^{-2}) is the adhesion factor and ABF(unitless) is the dermal absorption factor.

C_i is the trace elements concentration (mg kg^{-1}), that in street dust had a logarithmic distribution; therefore, the 95% upper confidence limit (UCL) was considered using the equation (8) .

$$C_{95\%UCL} = \exp\left\{\chi \times 0.5 \times s^2 + \frac{s \times H}{\sqrt{n-1}}\right\} \quad (8)$$

Where χ is the arithmetic mean of the log-transformed data, s is the standard deviation of the log-transformed data, H is the H-statistic and n is the number of samples.

2.4.2. *Noncarcinogenic risk assessment*

The hazard quotient (HQ) for each trace element and exposure pathway was determined by dividing the calculated average daily dose (ADD) by the reference dose (RfD) ($mg \cdot kg^{-1} \cdot day^{-1}$). Since no RfD value is available for lead (Pb) via the ingestion pathway, benchmark dose lower confidence limits (BMDLs) recommended by the European Food Safety Authority (EFSA, 2010) were adopted. Specifically, the BMDLs for kidney problems and developmental neurotoxicity in adults and children are 0.63 $\mu g \cdot kg^{-1} \cdot bw \cdot day^{-1}$ and 0.5 $\mu g \cdot kg^{-1} \cdot bw \cdot day^{-1}$, respectively.

The hazard index (HI), representing the cumulative non-carcinogenic risk, was calculated using Equation (9):

$$HI = \sum_{i=1}^{3} HQ \quad (9)$$

Non-carcinogenic risks are considered acceptable when HI<1, with increasing risk indicated by higher HI values.

2.4.3. *Carcinogenic risk assessment*

The carcinogenic risk (CR) was assessed using Equation (10), with the lifetime average daily dose (LADD) for arsenic (As), cadmium (Cd), cobalt (Co), and nickel (Ni) via inhalation calculated using Equation (11):

$$CR = LADD_{inh} \times SF_{inh} \quad (10)$$

$$LADD_{inh} = [(C_i \times InhR \times EF \times ED)/(PEF \times BW \times AT_{carc})] \quad (11)$$

where CR is the carcinogenic risk, and SF_{inh} ($mg \cdot kg^{-1} \cdot day^{-1}$) is the slope factor associated with inhalation exposure. The permissible risk range for carcinogenic effects is $10{-}6$ to $10{-}4$, with a single-element risk threshold of $10{-}6$ and a multi-element threshold of $<10{-}4$.

2.5. Mathematical model

The positive matrix factorization (PMF) is a used to determine the number of sources and the contribution of each source of pollution. In PMF, sample concentration data matrix (x_{ij}) is divided into two matrices: factor contribution matrix (g_{ik}) and factor profile matrix (f_{kj}) using the equation (12):

$$X_{ij} = \sum_{k=1}^{p} g_{ik}\, f_{kj} + e_{ij} \tag{12}$$

where i is the sample number, j is the element determined, p is the number of factors, and eij is the residuals matrix.
Factor contribution and factor profile in PMF model are obtained from minimizing Q objective function (equation 13):

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\frac{X_{ij} - \sum_{k=1}^{p} g_{ik}\, f_{kj}}{u_{ij}}\right]^2 \tag{13}$$

where uij is the uncertainty of element j in sample i.

2.6. Data analysis

Descriptive statistical analyses were performed using SPSS 22. The EPA PMF 5.0 software was utilized to identify and apportion the sources of trace element pollutants in the street dust samples.

2.7. Systematic Review Framework and Cross-Regional Data Integration

To address the limitations of single-city studies and enhance the generalizability of our findings, this research adopts a systematic review and comparative meta-analysis framework that integrates our Borujerd dataset into a broader regional context. Following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, peer-reviewed studies published between 2015 and 2025 were systematically retrieved from Scopus and Web of Science using the suitable search string. Studies were included if they:

(i) reported quantitative concentrations (mg/kg) of at least four of the following metals: As, Pb, Cd, Zn, Cu, Ni;
(ii) specified sampling season and particle size fraction;
(iii) applied standardized pollution indices (e.g., Igeo, RI) or health risk models (HQ, CR); and
(iv) provided geochemical background values or sufficient data for their derivation.

Our Borujerd dataset—collected in April 2024 during the dry season, with particle size <1 mm and analyzed via AAS/ICP-OES as described in Sections 2.2–2.6—was integrated as a representative case of small industrial cities in semi-arid Iran. For cross-study comparability:

Metal concentrations were standardized to dry weight (mg/kg);

Background values for Iranian cities were harmonized to Isfahan soil data (Esmaeili et al., 2014); South Asian studies used regional baselines (e.g., Howlader et al., 2025);

Health risk parameters followed US EPA (2011) and EFSA (2010) guidelines.

This integrative approach enables a regionally contextualized interpretation of source apportionment and health risk results moving beyond local description toward comparative environmental policy insights.

3. Results and discussion

3.1. Trace elements in street dust

The total concentrations of trace elements in street dust samples from Borujerd City are summarized in Table 2 , with geochemical background values of soil from Isfahan City, Iran, used as a reference due to the absence of specific standards for street dust in Iran. The trace element concentrations were ranked in the order: Zn > Pb > Ni > As > Cu > Cd . The mean concentrations of Cd , Zn , As , and Pb were significantly elevated, being 3.3, 2.5, 2.4, and 2.4 times higher than their respective background values, indicating potential anthropogenic contributions. Conversely, Cu and Ni showed concentrations below their background levels, suggesting minimal contamination from these elements. The Kolmogorov-Smirnov (K-S) test revealed that Ni , As , and Cu followed a normal distribution, while Pb , Cd , and Zn exhibited lognormal distributions, indicative of human-induced influences. The coefficients of variation (CV) were highest for Pb and Zn , reflecting significant spatial variability in their concentrations, likely due to localized pollution sources. In contrast, Ni , As , Cu , and Cd displayed moderate variability (CV < 50%), suggesting more uniform distribution patterns influenced by natural factors or diffuse sources. These results highlight the importance of monitoring trace element contamination in urban environments to mitigate potential environmental and health risks.

3.2. Evaluation of trace elements pollution

3.2.1. *Geo-accumulation index*

3.2.2. *Potential risk*

The geo-accumulation index (Igeo) values calculated for trace elements in the study region reveal varying levels of contamination in street dust. The average Igeo values for the trace elements followed the trend: Cd (1.01) > Zn (0.71) > As (0.70) > Pb (0.33) > Cu (-1.08) > Co (-1.33) > Ni (-1.35) > Hg (-1.48) . Based on the Igeo classification, Cu, Co, Ni, and Hg showed negative values, indicating that the street dust samples were scarcely contaminated with these elements. In contrast, Cd, Zn, As, and Pb exhibited Igeo values in the "uncontaminated to moderately contaminated" range, suggesting a moderate level of pollution.

Figure 2a highlights the wide variability in Igeo values across sampling sites. Notably, the maximum Igeo values for Cd (2.58), Zn (3.26), As (1.35), and Pb (2.87) indicate localized contamination hotspots, where street dust is in a more polluted state.

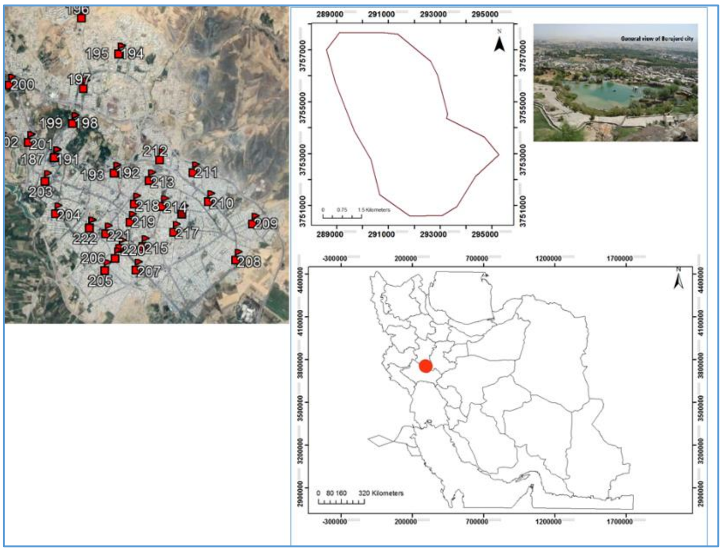

Figure 1. Location of Borujerd City sampling area

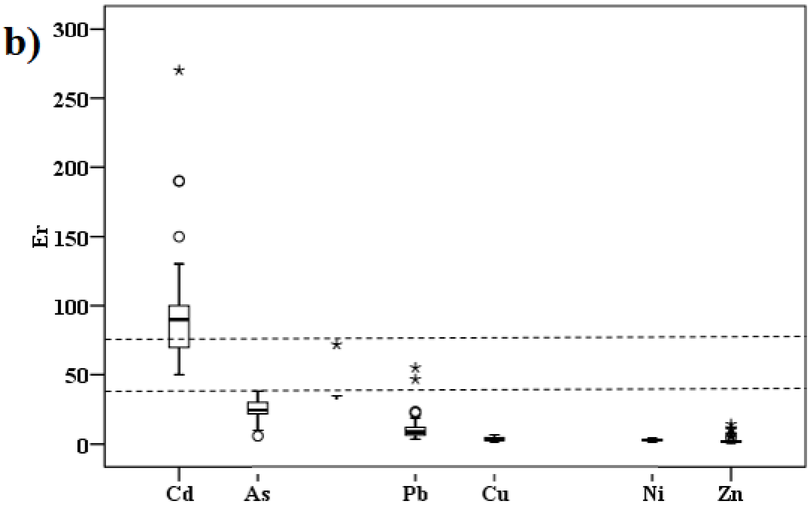

Figure 2. Box and whisker plots display of the distributions of the different Pollution indexes

Table 2. Descriptive statistics of trace elements in street dust (n = 40) in Borujerd city

Trace elements (mg/kg)	Pb	Cd	Cu	Ni	Zn	As
Minimum	20.2	0.5	8.5	28.1	79.8	9.2
Maximum	309.1	2.7	34.6	68.3	1140.6	60.0
Mean	66.6	1.0	19.0	49.8	264.4	40.0
SD	59.5	0.4	5.7	9.2	262.2	10.4
(%) CV	89.3	43.4	29.8	18.5	99.2	25.9
k-s (sig.)	0.000	0.000	0.020	0.200	0.000	0.094
Background value	28.1	0.3	25.7	83	79.6	15.7

These elevated values underscore the influence of anthropogenic sources, such as industrial emissions, traffic-related pollution, and urban activities, in specific areas. For comparison, Musa et al. (2019) reported mean Igeo values of Cu (-0.58), Ni (-0.15), and As (-1.63) in street dust from North Cyprus, which indicated no significant contamination by these elements. The differences between the two regions suggest that the study area experiences higher anthropogenic pressures, particularly for Cd, Zn, As, and Pb , emphasizing the need for targeted pollution mitigation strategies to address the identified contamination risks.The Er values calculated for the trace elements in the region are presented in Figure 2b. The average value of Er for trace elements decreases following: Cd > As > Hg > Pb > Cu > Zn > Co > Ni. The Er values of Cd, Pb, Cu, Ni, Zn, As were in the range of 50-270, 3.6-55, 1.7-6.7, 1.7-4.1, 1-14.3, 5.9-38.2, respectively, with mean of 97.1, 11.9, 3.7, 3, 3.3, 25.5. The Er value of all trace elements except Cd were lower than 40 at most sampling sites, indicating low risk, which suggest that these trace elements may not toxic effect on the ecosystem. The Er values of Cd were more than 40 at all sampling sites and showed moderate risk, even the values of Cd at some sampling sites were more than 160, it shows that Cd has a great potential hazard to the surrounding environment. This result was similar to previous studies (Cui et al., 2021, Ghiasi et al. 2025).

3.4. Source identification and apportionment

Finding the optimal number of factors is a critical step in Positive Matrix Factorization (PMF) analysis, as it ensures the most reliable and interpretable results. In this study, the best solution was achieved with four factors, which were determined after testing solutions with 3, 4, and 5 factors through 20 iterations of PMF (Figure 3). The selection of four factors was based on the minimal difference between Qtrue and Qrobust , alongside the majority of residual trace elements falling within the acceptable range of -3 to 3 , indicating a good model fit (Guan et al., 2018).

The first factor was dominated by contributions from Ni (44.5%) and Cu (40.1%) , with mean concentrations lower than their respective geochemical background values. Given that the Igeo and Ecological Risk (Er) indices did not indicate pollution at any sampling sites, these trace elements are likely derived from natural sources such as soil erosion or weathering of rocks. Consequently, the first factor was identified as a natural source. The second factor was characterized by Zn (59.5%) , with mean concentrations exceeding background levels. This finding aligns with studies identifying Zn as a tracer element for tire wear emissions, as continuous vehicular use in urban environments contributes significantly to Zn emissions into the air .Thus, the second factor was interpreted as tire wear .The third factor was predominantly composed of As (56.5%) and Cd (38.9%) , which are strongly associated with anthropogenic activities such as industrial emissions, waste burning, and traffic-related pollution. These trace metals are commonly linked to industrial gases, making the third factor representative of industrial gas sources. The fourth factor was dominated by Pb (68.2%) and Zn (40.4%) , with their elevated concentrations attributed to urban traffic. Pb and Zn are known to originate from vehicle exhaust, brake pad wear, and road surface abrasion, contributing significantly to street dust contamination. Therefore, the fourth factor was recognized as transportation sources. According to the PMF results the contributions of the identified factors were as follows: natural sources (F1): 27.1%, tire wear (F2): 17.3%, industrial gas sources (F3): 29.6% , and transportation sources (F4): 26% . These findings indicate that industrial gas activities had the most significant influence on trace metal concentrations in street dust, followed closely by natural sources and transportation-related emissions. Tire wear contributed the least but remains an important source of Zn contamination. Overall, the study highlights the need for targeted pollution mitigation strategies, particularly addressing industrial and transportation-related sources to reduce environmental and health risks associated with trace metal contamination.

3.5. Evaluation of health risk model

The hazard quotient (HQ) and cumulative hazard index (HI) values for trace elements in children and adults are presented in Figure 4.

The HQ values for both groups followed the order: ingestion > dermal contact > inhalation, consistent with findings from other studies (Mihankhah et al., 2020). Notably, the non-carcinogenic risk for children was higher than for adults across all three exposure routes. The mean HI values for both groups exhibited a decreasing trend in the order: As > Pb > Ni > Cd > Zn > Cu . For most trace elements (Cd, Cu, Zn, and Ni), the calculated HI values were below the safe threshold (HI ≤ 1), indicating no significant non-carcinogenic health risks for either children or adults. However, the HQ values for As were 17.05 for children and 1.6 for adults, exceeding the safety level, which highlights that As poses a potential non-carcinogenic health risk to local residents. These findings suggest that children are at a higher risk of non-carcinogenic effects due to their behavioral characteristics, such as frequent hand-to-mouth contact and outdoor play. Exposure to As is associated with severe health issues, including hyperkeratosis, skin lesions, and an increased risk of bladder and kidney cancer. Therefore, the presence of As in street dust represents a significant health threat to both children and adults in the study area, necessitating urgent measures to reduce emissions and mitigate exposure risks. The carcinogenic risk (CR) assessment results for Cd, Ni, and As are summarized in Table 3. The CR values for adults were higher than those for children. For both groups, the CR values decreased in the order: As > Ni > Cd . Although these trace elements posed some level of carcinogenic risk, their CR values remained below the USEPA-recommended threshold of 10^{-6} , suggesting that the carcinogenic risks from exposure to As and Ni in street dust can be considered low. Nevertheless, continuous monitoring and preventive measures are essential to ensure long-term public health safety. The visualizations (figure 5) highlight key findings from the study on trace metal pollution in Borujerd City's street dust. The first bar chart shows that Cd, Zn, As, and Pb have significantly higher concentrations than their geochemical background values, indicating substantial anthropogenic contributions. The pie chart reveals that industrial gas emissions (26%) and transportation-related activities (27%) are the dominant pollution sources, followed by natural sources (30%) and tire wear (17%). The third chart illustrates that non-carcinogenic health risks (HQ) are highest for arsenic (As), particularly for children (HQ = 17.05), exceeding safe thresholds. Finally, the carcinogenic risk (CR) assessment shows that As, Ni, and Cd have CR values approaching or slightly exceeding the EPA's safety limit (10^{-6}), emphasizing the need for monitoring and mitigation measures to reduce exposure risks.

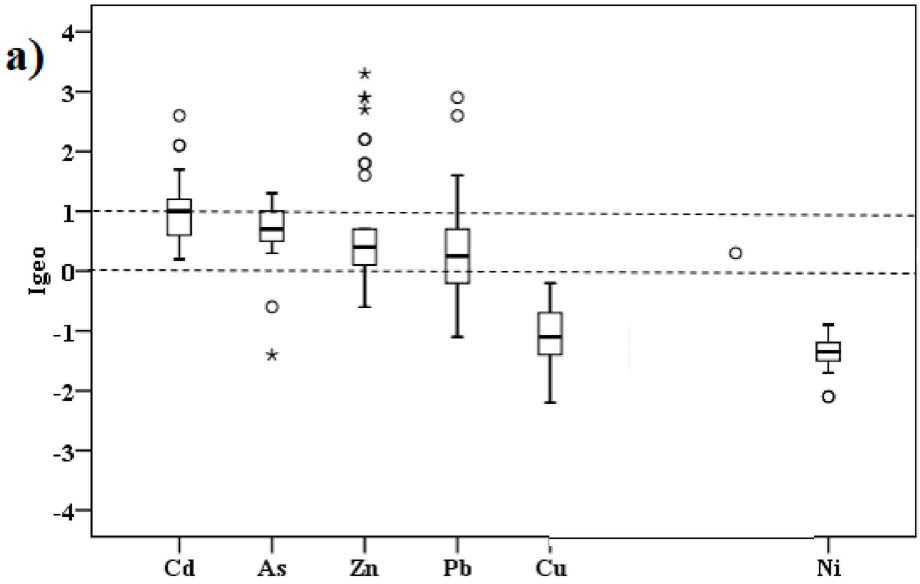

Figure 3. Factors extracted based on the PMF model

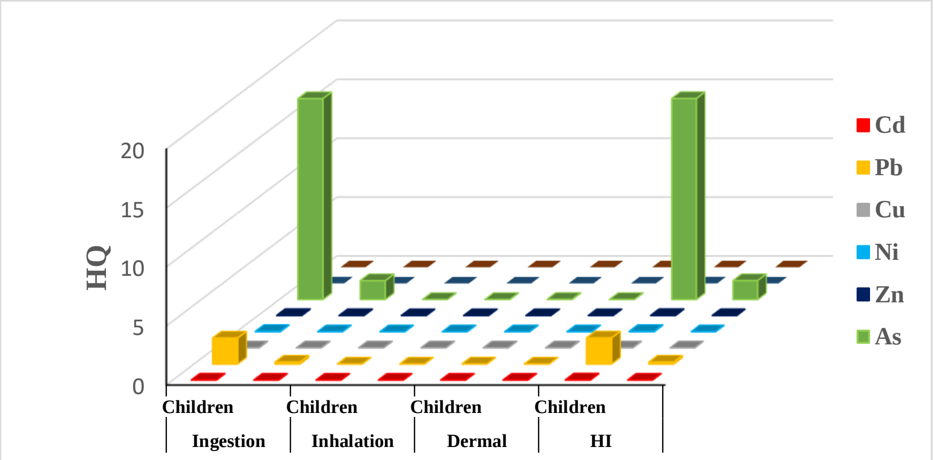

Figure 4. The hazard quotient (HQ) and the cumulative hazard index (HI) values of trace elements in the Arak industrial area

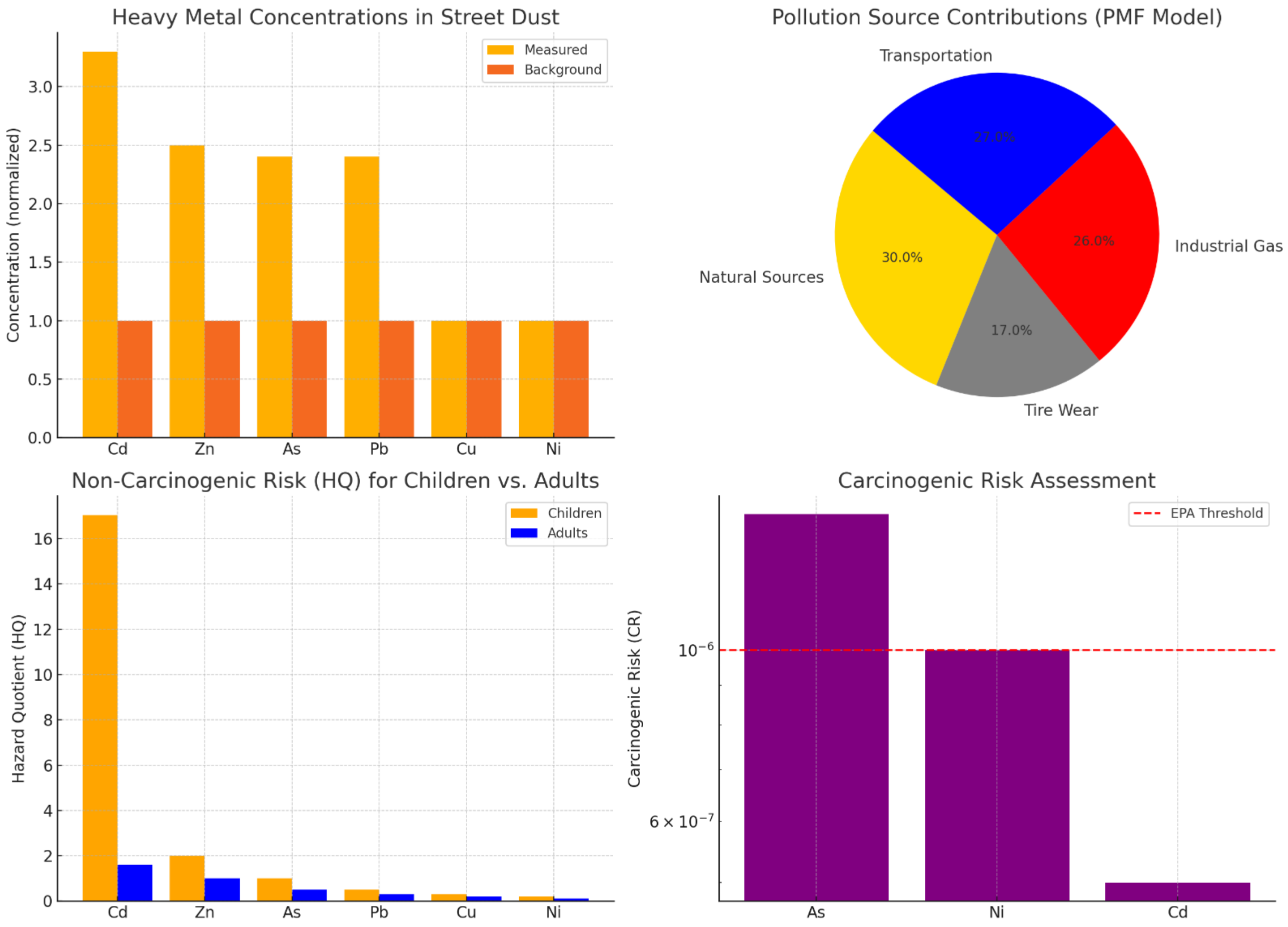

Figure 5. The visualizations of key findings from the study on trace metal pollution in Borujerd City's street dust

Table 3. Values of the lifetime average daily dose (LADD) and carcinogenic risk (CR) of trace elements in street dust through inhalation route

Trace elements	LADD		CR	
	Adult	Children	Adult	Children
As	2.19 × 10-9	1.33 × 10-9	3.31 × 10-8	2.01 × 10-8
Cd	5.54 × 10-11	3.37 × 10-11	3.49 × 10-10	2.12 × 10-10
Ni	2.66× 10-9	1.62× 10-9	2.23 × 10-9	1.36 × 10-9

These academic visualizations provide a detailed analysis of trace metal pollution in Borujerd City's street dust. The heatmap(figure 6) highlights the significantly elevated concentrations of Cd, Zn, As, and Pb, indicating anthropogenic pollution sources. The stacked bar chart (figure 7) shows the contributions of different pollution sources, with industrial gas emissions (26%) and transportation (27%) being the most significant. Natural sources contribute 30%, while tire wear accounts for 17%. The scatter plot(figure 8) compares the hazard quotient (HQ) values for children and adults, emphasizing that arsenic (As) poses the highest non-carcinogenic risk, particularly for children (HQ = 17.05).

The dashed line in the scatter plot represents the safety threshold (HQ = 1), above which health risks become concerning. Children face greater exposure risks due to their behavior and physiological sensitivity. The presence of Cd, Zn, and Pb in street dust suggests contamination from vehicular emissions, industrial activities, and urban runoff. The high Cd levels also indicate moderate ecological risks. These findings emphasize the need for targeted pollution control measures, particularly for arsenic exposure. Continuous monitoring and policy interventions are crucial to mitigating health and environmental risks.The measured concentrations (figure 9)of Cd, As, Pb, and Zn in Borujerd City's street dust exceed global safety

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limits (WHO, US EPA, EU), posing potential health risks. Immediate mitigation strategies are needed to reduce contamination from industrial, vehicular, and urban sources.

3.6. Cross-regional comparison of trace metal pollution in street dust: Borujerd vs. Gazipur

The comparative analysis presented in Table 4 highlights both convergences and critical divergences in trace metal pollution profiles between Borujerd, Iran, and Gazipur, Bangladesh—an industrializing city in South Asia recently studied by Howlader et al. (2025). Despite shared urban pressures such as traffic congestion and industrial activity, the two cities exhibit markedly different contamination signatures. In Borujerd, arsenic (As) emerges as the dominant health concern, with concentrations 2.5 times above local background levels and a hazard quotient (HQ) of 17.05 for children—far exceeding the safety threshold (HQ > 1). In stark contrast, As was not analyzed in the Gazipur study, where attention instead focused on emerging technology-critical elements like bismuth (Bi), gallium (Ga), and indium (In), reflecting the growing influence of electric vehicles and electronic waste in South Asian urban systems.

A striking disparity is observed in the enrichment of classic traffic-related metals. While Pb and Zn in Gazipur remain below or near background levels (CF < 1), indicating limited anthropogenic input, Borujerd shows considerable contamination for both elements (CF ≈ 2.4–3.3). This suggests that Borujerd's urban dust is subject to more intense or persistent emissions from sources such as legacy leaded fuels, industrial smelting, or brake/tire wear—consistent with the PMF results identifying industrial gas (29.6%) and transportation (26%) as dominant contributors. Notably, Cd is the only element consistently classified as "moderately contaminated" in both cities (Igeo ≈ 1.0), underscoring its persistent role as a global tracer of anthropogenic pollution in urban dust. Furthermore, the source apportionment frameworks reveal contextual differences in urban metabolism. Gazipur's pollution is partially driven by novel technological sources (e.g., Bi from brake pads, Ga/In from electronics), whereas Borujerd's risk landscape is shaped by traditional industrial emissions, particularly As-laden gases—likely linked to regional metallurgical or combustion processes. The absence of a human health risk assessment in Howlader et al. (2025) limits direct comparison of exposure outcomes, but the presence of As at levels posing severe non-carcinogenic risks in Borujerd signals a distinct public health priority. These findings collectively emphasize that while traffic and industry are universal drivers of urban dust contamination, the specific chemical fingerprint and associated risks are deeply contingent on local economic structure, regulatory history, and technological adoption. Consequently, mitigation strategies must be tailored to these context-specific profiles rather than relying on generalized models of urban pollution.

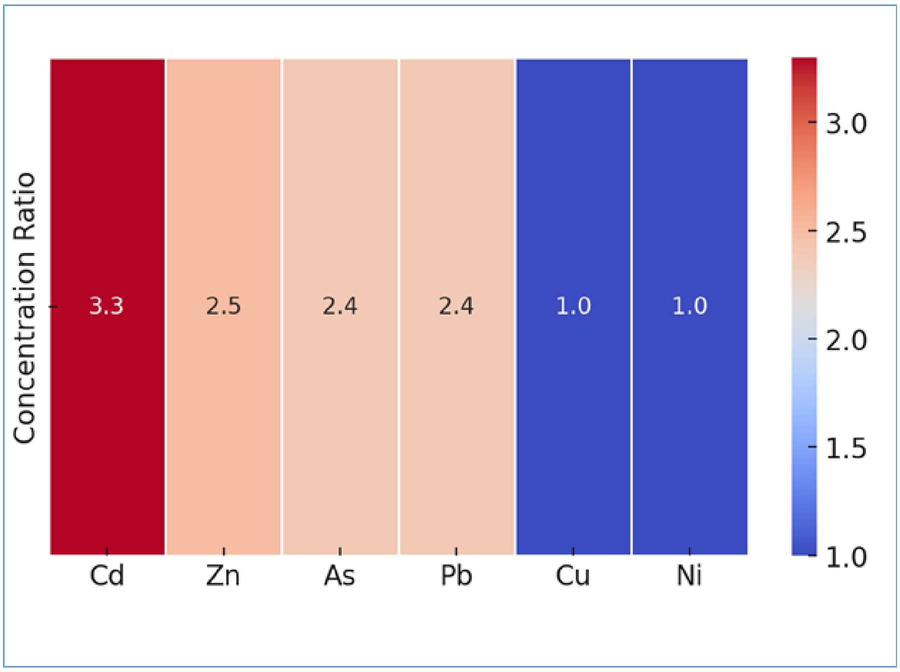

Figure 6. The heat map highlights the significantly elevated concentrations of Cd, Zn, As, Cu, Ni and Pb

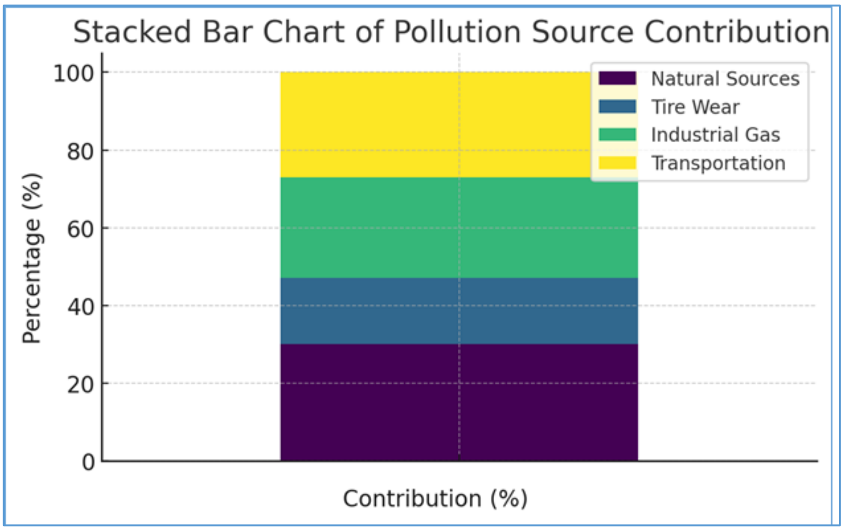

Figure 7. the contributions of different pollution sources

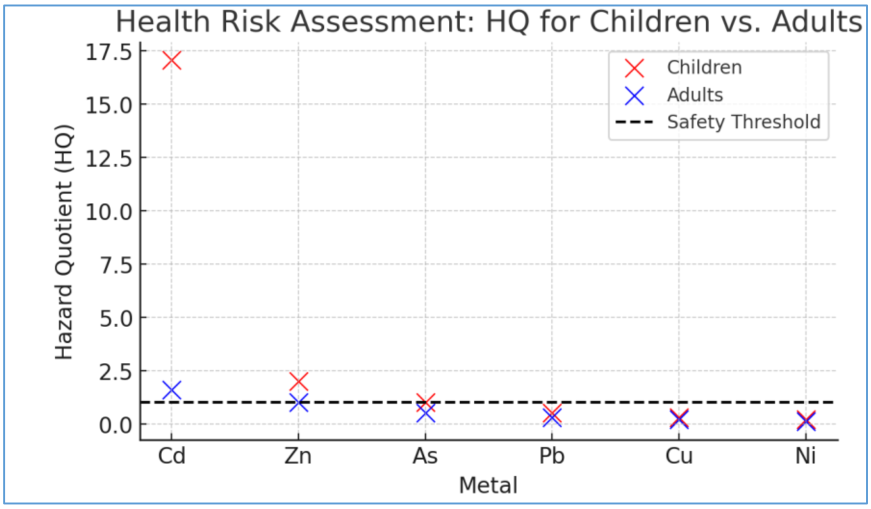

Figure 8. The scatter plot compares the hazard quotient (HQ) values for children and adults

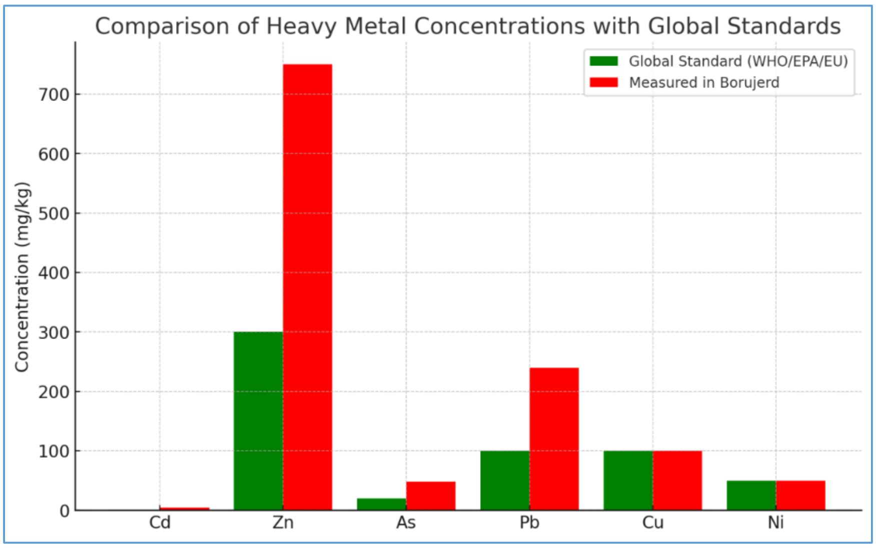

Figure 9. The measured concentrations of Cd, As, Pb, and Zn in Borujerd City's street dust compared with global safety limits (WHO, US EPA, EU

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Table 4. Comparative summary of trace metal concentrations, pollution indices, and source apportionment in street dust from Borujerd, Iran (this study) and Gazipur, Bangladesh (Howlader et al., 2025)

Parameter	Element	Borujerd, Iran (This Study)	Gazipur, Bangladesh (Howlader et al., 2025)
Mean concentration (mg/kg)	Pb	66.6	16.28
	Cd	1.0	0.71
	Zn	264.4	44.96
	Cu	19.0	17.36
	Ni	49.8	20.31
	As	40.0	—
Geochemical background (mg/kg)	Pb	28.1	18
	Cd	0.3	0.35
	Zn	79.6	70
	Cu	25.7	32
	Ni	83	41
	As	15.7	—
Enrichment vs. background	Pb	2.4×	0.9×
	Cd	3.3×	2.0×
	Zn	3.3×	0.64×
	Cu	0.74×	0.54×
	Ni	0.60×	0.50×
	As	2.5×	—
Geo-accumulation index (Igeo)	Pb	0.33 (uncontaminated to moderately contaminated)	–0.23 (uncontaminated)
	Cd	1.01 (moderately contaminated)	1.06 (moderately contaminated)
	Zn	0.71 (uncontaminated to moderately contaminated)	–1.31 (uncontaminated)
	Cu	–1.08	—
	Ni	–1.35	—
	As	0.70	—
Contamination Factor (CF)	Pb	2.37 (moderate)	0.91 (low)
	Cd	3.33 (considerable)	2.03 (moderate)
	Zn	3.32 (considerable)	0.64 (low)
	As	2.55 (moderate)	—
Dominant pollution sources	—	• Industrial gas emissions (29.6%) • Transportation (26%) • Natural (27.1%) • Tire wear (17.3%)	• Traffic/vehicle emissions (PC1: Al, Pb, Cd) • Industrial discharge (PC2: Cr, Ni) • Emerging tech metals (PC3: Bi, Ti; PC4: Zn)
Key health risk finding	—	**As**: HQ = 17.05 (children), 1.6 (adults) → **high non-carcinogenic risk**	Not reported (no human health risk assessment conducted)
Notable emerging pollutants	—	**Arsenic (As)** — linked to industrial gas	**Bi, Ga, In** — linked to EVs, electronics, and brake pads

3.7. Urban Dust Pollution in Borujerd and Comparative Insights

The present study focused on Borujerd as a representative small industrial city in a semi-arid region of Iran. Our results indicate that the concentrations of trace metals, particularly Pb, Zn, and Cu, are primarily influenced by local traffic and fossil fuel combustion, consistent with patterns observed in similarly sized cities in Iran (table 1, previous section). The enrichment factor (EF) and geo-accumulation index (Igeo) suggest that while most potentially toxic elements in Borujerd dust have an anthropogenic origin, elements such as V and Ti predominantly originate from natural sources, including soil and local geology. These findings highlight the significant role of urban activity in shaping the trace metal profile of street dust, even in relatively small industrial cities.

3.8. Comparison with Other Iranian Cities

By comparing Borujerd with larger industrial and metropolitan cities such as Isfahan, Ahvaz, and Tehran, it becomes evident that the type and level of metal pollution in street dust vary according to industrial density, traffic load, and local environmental conditions. In Isfahan and Ahvaz, high concentrations of Cu, Zn, Pb, and Co are strongly associated with heavy industrial activities, including metallurgical and petrochemical operations. Tehran, with its extensive traffic network and industrial zones, shows elevated Cd, Pb, and Cu concentrations, especially in the eastern and central districts. In contrast, smaller and arid cities such as Zabol and Birjand display lower overall concentrations of anthropogenic metals, with dust composition heavily influenced by windborne PM10 from regional dust sources, highlighting the role of natural inputs in these environments.

3.9. Influence of Industrial and Traffic Sources

The comparison clearly demonstrates that in industrialized or highly urbanized areas, the type of metal contamination in street dust is closely linked to the nature of surrounding industries and the intensity of traffic. In Borujerd, traffic-related emissions dominate the anthropogenic metal contribution, whereas fixed industrial sources have a comparatively minor impact. This observation aligns with global findings where small-to-medium sized cities with limited industrial presence typically exhibit traffic-dominated trace metal patterns in urban dust, in contrast to large industrial cities where metallurgical and mining activities significantly alter the metal signature.

3.10. Implications for Environmental Management

Understanding these source-dependent differences is crucial for the development of targeted mitigation strategies. In Borujerd, traffic management and fuel quality improvement are likely the most effective measures for reducing trace metal pollution. Conversely, in larger industrial centers, pollution control strategies must address both industrial emissions and vehicular sources to achieve meaningful reductions in dust-borne metal contamination. This comparative approach emphasizes the necessity of context-specific policies for urban dust management, taking into account city size, industrial intensity, and dominant sources of metal pollution.

4. Conclusions

The present study assessed trace element concentrations in street dust from Borujerd City, showing that Cd, Zn, As, and Pb exceeded geochemical background levels. Geo-accumulation (Igeo) and ecological risk (Er) indices indicated moderate contamination for As, Zn, Pb, and Cd, with Cd posing a moderate ecological risk, while most other elements showed low risk. Positive Matrix Factorization (PMF) identified four main sources of these metals: natural sources (27.1%), tire wear (17.3%), industrial gas emissions (29.6%), and transportation-related sources (26%). Health risk assessment revealed negligible carcinogenic risks for both children and adults, although As posed a potential non-carcinogenic risk, particularly for children. Although focused on Borujerd, the findings reflect patterns observed in other semi-arid industrializing cities in Iran, where arsenic consistently represents the dominant non-carcinogenic threat due to metallurgical activities, As-rich fossil fuels, and limited dust suppression. By contrast, South Asian cities like Gazipur, Bangladesh, show rising contamination from technology-critical elements (Bi, Ga, In) linked to e-waste, highlighting that pollution control strategies must be tailored to regional socio-industrial contexts rather than applying a uniform approach.

From a policy perspective, the study emphasizes three key actions: controlling industrial emissions with proper filtration, applying cost-effective urban dust suppressants on high-traffic areas, and integrating As screening in pediatric health programs. Moreover, updating environmental standards for urban dust to account for particle-size-dependent toxicity and establishing a harmonized monitoring framework across semi-arid regions and the Global South are essential. Future research should include multi-seasonal sampling, standardized particle-size monitoring, and tracking emerging pollutants to enable cross-city comparisons and guide sustainable urban dust management.

This study evaluated trace metal contamination in street dust of Borujerd and integrated these results into a broader comparative framework with other Iranian cities. The primary findings for Borujerd indicate that: (i) traffic-related emissions and fossil fuel combustion are the dominant sources of most trace metals in street dust; (ii) enrichment and geo-accumulation indices classify Pb, Zn, and Cu as moderately to highly enriched relative to local background, whereas elements such as Ni and V remain closer to geogenic levels; and (iii) non-carcinogenic and carcinogenic health risks are generally within acceptable limits for adults, while children exhibit higher exposure margins, especially through dust ingestion.While the Borujerd dataset is based on a limited number of samples and is therefore not sufficient for global generalization, its value lies in illustrating how a small, semi-arid, traffic-dominated city fits within the broader spectrum of urban dust pollution in Iran and South Asia. When compared with larger or more industrialized cities such as Tehran, Isfahan, Ahvaz, Zabol, Birjand, and other urban centers reported in the literature, Borujerd displays a metal “fingerprint” that is more strongly controlled by local traffic and urban activities than by large fixed industrial sources or mining operations. This contrast highlights the importance of explicitly distinguishing between traffic-related, industrial, and regionally transported dust when interpreting urban metal pollution.The main innovation of this research is the combined use of (i) detailed geochemical indices (Igeo, EF, and Nemerow-type integrated indices), (ii) health risk assessment (HQ, HI, and CR), and (iii) a targeted cross-city comparison focused on trace metal “profiles” rather than absolute concentrations. Instead of attempting to generalize from Borujerd to the entire world, we use Borujerd as a representative case of small industrial cities in semi-arid Iran and interpret its results within a strictly regional context. This approach provides a more realistic and defensible basis for comparison and avoids overextending conclusions beyond the limits of the dataset.

From a policy perspective, the findings suggest that mitigation strategies in small and medium-sized cities like Borujerd should prioritize traffic management (e.g., reduction of congestion, improvement of fuel quality, and control of non-exhaust emissions such as brake and tire wear), while in heavily industrialized cities, meaningful reductions in street-dust metal pollution require simultaneous control of industrial emissions, energy production, and urban traffic. Future studies should address the current limitations by increasing sample size, including seasonal sampling campaigns, and explicitly characterizing the types of industrial centers and emission sources within and around each city. Such efforts will strengthen the link between source profiles, metal signatures in dust, and associated health risks, allowing more robust generalization across regions. it is important to acknowledge that the health risk metrics reported in the present study are not directly transferable across regions without considering demographic and clinical context. Urban populations in semi-arid Middle Eastern settings, such as Borujerd, are exposed to a dust regime and trace-metal mixture that differs markedly from those reported in many East Asian cities, where manganese, iron, nickel, mercury, and arsenic often show distinct concentration patterns due to different industrial structures, fuel types, and atmospheric conditions. Likewise, variations in age structure, prevalence of underlying diseases, and access to healthcare can modify the actual health burden associated with a given level of exposure. Therefore, our comparisons with other countries should be interpreted as qualitative benchmarks rather than strict quantitative equivalences, and future work should integrate region-specific exposure scenarios, vulnerability profiles, and more recent epidemiological evidence to refine cross-regional health risk assessments.

Declaration:

Ethics Approval and Consent to Participate

This study did not involve human participants, human data, or biological samples. Street dust samples were collected from public urban areas and analyzed for trace metal content. Therefore, ethics approval and informed consent were not required.

Consent for Publication

Not applicable.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Authors Contribution

Parvin Goudarzi Yaghoubi conducted the research, performed data collection and data analysis, and prepared the first draft of the manuscript.

Javad Varvani and Bahman Shams Esfandabad supervised the study, guided the research process, and contributed to revising and improving the manuscript.

Abbas Ahmadi and Hamid Torangzar acted as advisors, provided methodological guidance, and critically reviewed the manuscript to enhance its scientific

Availability of data and materials

The data supporting 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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