



Assessment of Societal Health Risks: Spatial Distribution and Potential Hazards of Toxic Metals in Street Dust Across Diverse Communities

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Abstract On a global scale, the urban design of city centers is a topic of discussion concerning various aspects such development and its impact on public health. This research examines the health effects of urban agglomeration in city centers with compact, close development. In this work, the potentially toxic metals in street dust were studied by collecting and measuring street dust samples, measuring trace metal concentrations, and using index assessment, spatial analysis, correlation analysis, and health risk assessment models. Eskişehir, located in the part of Central Anatolia close to the Aegean region, west Türkiye, has been widely recognized as one of the most popular, known for having many narrow and old buildings in urban environments. The present paper investigates the atmospheric dust-related chemical speciation, urban environmental pollution, and human health risks in Eskişehir City by studying 66 dust

samples collected at 11 points in the selected streets in August 2023. the study found that the concentrations of trace elements followed the order $Cr > Ni > Pb > Cd > Cu$. The primary source of these high levels is believed to be traffic-related contamination involving Cd, Pb, and Ni. The assessment of non-carcinogenic health risks has shown that the significant sources of potential toxic metals exposure for both children and adults are i) through ingestion and ii) dermal contact. The Hazard index (HI) for selected metals decreased in the order $Cr > Pb > Ni > Cd > Cu$ for both children and adults without imposing possible non-carcinogenic risk ($HI < 1$). On the contrary, Cr posed cancer risks above the safety threshold ($> 10^{-4}$) through ingestion. Based on the available findings, Eskişehir still suffers from considerable environmental and ecological degradation and severe health risks due to street dust contamination. However, while high pollution was detected in the city center, where there is commercial land use, low values were observed in the region, rich with the water surface, bicycle paths, landscape design, and where traffic is slowed down.

Keywords Human exposure · urban modeling · land use · spatial distribution · land management

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1 Introduction

Urban environments face mounting challenges due to population growth, industrialization, vehicular emissions, and energy demands. These stressors negatively

impact air quality, urban expansion, and sustainable development in cities (Bernardino et al., 2019; Wang et al., 2018). This issue has transcended regional, city, or country boundaries and has become a global concern (Goudie, 2014). As climate change intensifies, it has been reported that over 7 million lives have been lost, primarily due to respiratory infections, heart and lung diseases, and lung cancer (An et al., 2018; Combes & Franchineau, 2019). Exposure to urban pollutants has become inevitable in societies that fail to prioritize and implement planned urbanization (Zeng et al., 2020). Urban pollution affecting air, water, and noise has emerged as a significant threat to public health (Jaafari et al., 2021). Human health and ecosystems are exposed to hazardous substances (Aguilera et al., 2021). Numerous advanced techniques and integrated risk functions have been developed to assess the global disease burden of fine particulate matter (PM_{2.5}) from cities' anthropogenic sources (Adewumi, 2022). However, their adoption remains limited (Fang et al., 2015; Liu et al., 2016). Many of these pollutants can be attributed to traffic and related emissions, adversely affecting city air quality through carbon emissions, aerosols, particulate matter, and toxic metals (Bolorani et al., 2021).

City centers, characterized by concentrated services and populations, serve as commercial hubs (Trujillo-González et al., 2016). These areas are influenced by intricate dynamics interconnected at various levels (Liang et al., 2019). Consequently, the development of sustainable city centers has gained significant attention (Yu et al., 2013). The sustainability challenge has rekindled interest in urban land use patterns and city structures' compactness or sprawling nature. As a result, urban planning research now focuses on managing growth following sustainability goals and maintaining the relationships established within city centers (Weber et al., 2014).

Pollutants in the urban environment are predominantly anthropogenic, such as vehicular exhaust, industrial emissions, and coal-burning activities. However, they can originate from both natural and anthropogenic sources, either directly or indirectly (Zhao et al., 2021). They were released into the outdoor environment, attached to PMs, and traveled long distances with them. Among them are elements that bioaccumulate and have high toxicity on ecosystems and human health, depending on the concentration. As the release of pollutants continues to increase, their concentrations

increase in the region, posing a net health risk to residents (Xie et al., 2019). The combined effects on human health due to the increased diversity of pollutants and their non-dispersive presence is a reason, among many others, for the migration of residents to a more tranquil and pollutant-free area. Toxic metals can be found in street dust in urban environments that have deteriorated the urban air quality and endangered living organisms and human health via inhalation, ingestion, and skin contact (Acosta et al., 2015).

During the summer months, when there is little or no rainfall, the accumulated dust increases, and the amount of toxic metals increases; they are carried to a considerable distance by the wind due to the durability of the gaps (Qadeer et al., 2020). Particularly in Eskişehir, intense accumulation and transport occur throughout the year in cities where precipitation is low but urbanization is intense. According to data from Türkiye's Meteorology Offices, during 2023, the lowest and highest PM₁₀ values recorded were 6.92 and 146.31 µg/m³, respectively. Some days, they demonstrated that the daily mean value surpassed 336 µg/m³, with over 10% of the days exceeding the hazardous health limit set by the United States Environmental Protection Agency (US EPA, 2008). During the summer, when there is little or no rainfall, dust and toxic metals increase. They are carried to a considerable distance by the wind due to the durability of the gaps. This is why the rates of cardiovascular and respiratory diseases and lung cancer are increasing in survivors. The street dust particles are highly connected with toxic metals. This problem has attracted global attention through the local governments, which need to continuously monitor the region's toxic air pollutants level to assess ecological and health hazards. Effective spatial planning and sustainable land management can have significant impacts on the potential transfer of heavy metals from contaminated soils to humans. In this context, while the compact or sprawling structure of the city center is being discussed, the kind of threat posed to health by single-centered, compact settlements should be known. The current literature review shows that road dust is widely used for heavy metal monitoring. The network between identifying heavy metal sources and health risk assessment is strong in Fig. 1. Therefore, road dust was chosen as an indicator for health risk assessment.

This study comprehensively investigates street dust trace metal concentrations, contamination levels, and

pollution sources in Eskişehir, assessing ecological risks through multiple pollution/ecological indices. It further evaluates potential non-carcinogenic and carcinogenic risks for children and adults due to long-term exposure to toxic metals in street dust. Focusing on high-traffic streets, this research offers unique insights into pollution levels and ecological/human health risks associated with metal pollution. It distinguishes itself from prior Eskişehir studies and establishes a vital database on environmental pollution and its impact on inhabitants' health. Analyzing the city center's spatial structure and discussing land use and health risks across various age groups completes the research.

2 Literature Review

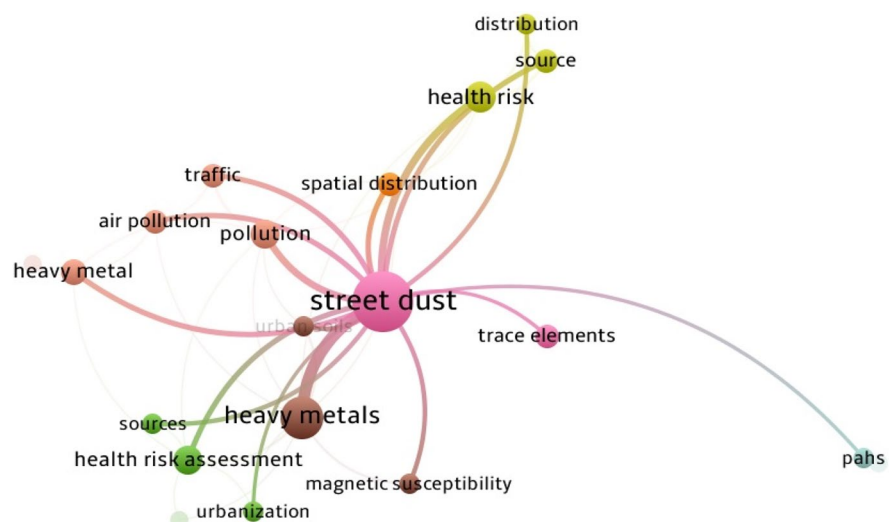
The framework of potentially toxic metals in street dust by vehicular emission, engine corrosion, and interruption of air streams is used to research environmental literary endeavors. Potentially toxic metals in street dust are a cognitive extension of the standard urban air quality that assumes various elements influencing environmental health (Li et al., 2016). Urbanization, population, wealth, and technology are commonly considered arguments for examining their contribution to urban air quality (Dehghani et al., 2017; Jiang et al., 2018). As a result, this current research aims to confirm the effects of population growth, economic growth, green economy, and

energy consumption on environmental degradation. Overall, this paper aims to affirm the effects of population growth, urbanization, economic growth, and energy consumption on urban air quality degradation.

The potentially toxic metals in street dust explain how urban emissions impact urban air quality deterioration. Saeedi et al. (2012) revealed the high ecological risk of street dust samples by traffic and related activities. After that, a sizable body of studies appeared to examine the occurrence of ecological and health risk assessment (Acosta et al., 2014; Musa et al., 2019; Tang et al., 2013; Urrutia-Goyes et al., 2018). Their experimental evidence demonstrated that income has various effects on urban air degradation. Zheng et al. (2010), Wang et al. (2012), and Rajaram et al. (2014) have shown that rapid urbanization and traffic emission leads to urban air degradation in several regions. This phenomenon supports the potentially toxic metals, demonstrating a deposition on biomass. Their findings revealed an accumulation, showing rapid urbanization and its emission are incredibly connected. Increased urban activities will boost existing emissions mobility and worsen ecology and health.

Many scholars have explored the correlation between densely populated streets and health risks (Du et al., 2013; Duong & Lee, 2011; Han et al., 2014). Apeagyei et al. (2011) highlighted that motor vehicle traffic significantly elevates heavy metal concentrations, increasing metal pollution and declining human health. Similarly, Li et al.

Fig. 1 "Visualizing Networks: Street Dust Representation through Link-based Analysis using Vosviewer Software in Bibliographic Studies"



(2013) and Elom et al. (2014) investigated the relationship between toxic metal deposition in the human body via street dust. They found that urban street dust poses substantial health risks to humans. The growing human and vehicular populations in cities, alongside the expansion of industrialization, have resulted in increased waste generation. Although alternative road routes used by urban centers to combat overcrowding have reduced traffic, the accumulation of traffic-induced toxic substances could not be prevented. Although the accumulation of toxic substances has been reduced on the roads intended to be pedestrianized, they remain in the environment for long periods without decomposing. Many studies have been conducted on the adverse effects of toxic substances on human health by Han et al. (2016), and Ladonin and Mikhaylova (2020). In the results, the concentration, source, distribution pattern, degree of pollution, and risk assessment of heavy metals from various anthropogenic sources pointed to the use of motor vehicles, especially traffic, leakages in industrial processes, and various other activities. Table 1 emphasizes the aspects those studies focus on determining the impact of toxic metals on ecology and human health.

3 Material and Methods

This study comprises a five-phase approach, illustrated in Fig. 2. The research design was initially established, followed by land use assessment and sample collection in the study area. Subsequently, the findings were assessed through comprehensive analyses at three distinct levels: heavy metal concentrations, correlation examination, and health risk evaluation. The risk assessment was tailored to consider land use, statistical data, and age group demographics.

3.1 Study Area

Eskişehir is situated in the northwestern of Türkiye, covering approximately 2678 km² and a population of 807,068 habitants according to Turkish Statistical Institute (TÜİK), (2022) in Fig. 3. This city is the most populated area because it has an Organized Industrial Zone. Agricultural activities are relatively

limited, so their contribution to atmospheric pollution is insignificant. Its climate is severe continental and extremely fragile to wind erosion/dust emissions; also, average rainfall is generally low during the summer and autumn. The characteristics of annual average temperature and precipitation of 21.9 °C and 15 mm typically occur in August.

3.2 Street Dust Sampling

In August 2023, a total of 66 street dust samples were collected from 11 bustling, high-traffic streets with dense populations. These areas experience heavy vehicular congestion at traffic lights. A 0.5 square meter frame, polyethylene brush (5.6 cm), and a plastic hand shovel were used at each site to gather the samples. The collected samples were then placed in bags for transportation to the laboratory.

Upon reaching the lab, the street dust samples underwent drying at 50°C for 48 hours, followed by sieving with 100-micrometer sieves. This process yielded 0.5 grams of each dust sample, which were then separated for the analysis of toxic metal concentrations. Since background values were unavailable, the continental upper crust values Rudnick and Gao (2003) reported were employed as references. An aqua regia extraction method was used in conjunction with SpectroBlue atomic emission spectrometry (ICP-OES, Germany), which features a SpectroBlue plasma source to analyze the toxic metal concentrations.

3.3 Chemical Analysis

This research concentrated on the determination of 5 toxic elements, including Cd, Cr, Cu, Ni, and Pb. All chemicals and reagents were purchased from Sigma-Aldrich and used as analytical grades. The wet digestion technique was applied with aqua regia-HCl (37%) / HNO₃ (69%), 3:1 (v/v) for 60 min at 80°C and then, they were washed with deionized water, filtered through a Whatman filter, were dried and analyzed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Ishtiaq et al., 2018). A blank sample was prepared for each group during digestion for quality assurance/quality control (QA/QC). At the same time, the calibration curve was plotted by using five standards for the accuracy of the extraction and dust assessment method. All samples were processed and inspected in three replicates.

Table 1 Historical Research on Toxic Metals and Urban Emissions

Authors	Country	Methodology	Selected metals	Proxy measured of biomonitoring	Urbanization dimensions	Do related sources examine?
Wei et al. (2015)	Four different functional regions in Beijing, China	Concentrations, distribution, accumulation, and health risk assessment	Cr, Ni, Cu, Zn, Cd and Pb	One hundred fifty-four street dust samples	Urban areas, Heavy-density traffic areas, educational area	Anthropogenic sources and background values
Kamani et al. (2015)	City and suburban in Zahedan, Iran	Potential associated health effects risks	Cd, Cr, Cu, Ni, Pb, and Zn	Seventy-eight street dust samples	Commercial, high traffic, industrial, urban park, and residential	Background levels
Kim et al. (2016)	Three different sites in Seoul and in Jeon-guep, south area of South Korea	Mental health survey	Al, Na, Mg, K, Ca, Mn, Li, Cr, Fe, Co, Ni, Cu, Zn, As, Cd, Pb and Mo	Eight samples	Food marketplaces, heavy traffic areas and rural area	Background elemental concentrations
Gope et al. (2017)	Fifteen different sites, medium-sized industrial in Asansol, Eastern India	Ecological and health risk index	Zn, Cd, Pb, and Cu	Fifteen street dust samples	Rapid, unprecedented, non-sustainable industrialization and urbanization areas, including national highways, busy traffic zones, industrial areas, residential areas and sensitive area	Background value
Alsbou and Al-Khashman (2018)	The entrance of the Wadi Musa City (Ain Musa site) to the At-Taybeh area, Petra region in Jordan	Ecological risk	Cd, Cu, Fe, Pb, and Zn	Fifty-five street dust samples	vehicular traffic densities was not close to specific pollution source fields	Background levels
Zgłobicki et al. (2019)	Lublin, Poland	Environmental pollution and potential ecological risk	Cd, Cr, Cu, Ni, Pb and Zn	Sixty-eight sites	Varying intensity of motor vehicle traffic in transport routes, residential districts, retail and service centers, and industrial areas	Geochemical background
Castillo-Nava et al. (2020)	Monterrey Metropolitan Area in Nuevo Leon, Mexico	Potential ecological index	Pb, Cd and Zn	Forty-one samples of street dust	Anthropogenic activity	Background values from soil near the study area

Table 1 (continued)

Authors	Country	Methodology	Selected metals	Proxy measured of biomonitoring	Urbanization dimensions	Do related sources examine?
Malakootian et al. (2021)	Kerman, Iran	Source apportionment of elements, pollution assessment, and Potential ecological health risk assessment	Al, Mn, Zn, Cu, V, Pb, Cr, Ni, Li, As, Co, Mo, Sb, Cd, Ag	Thirty-five street dust samples	A dense network of streets and many mining industries	A non-industrial area was selected as the background point
Isinkaralar et al. (2024)	Düzce, Türkiye	Relative bioavailability, environmental pollution and health risk assessment	Cd, Cr, Cu, Ni, and Pb	One hundred sixty-five dust samples	Residential area, industrial area, main city roads with heavy traffic flow, and city center	Forest areas were used as background values.

3.4 Statistical Analysis

In order to establish the relationship between toxic metals in street dust and their potential origins, a comprehensive analysis was conducted using the Pearson correlation coefficient and cluster analysis. These methods were implemented with the help of the statistical software package SPSS version 22.0. The Pearson correlation coefficient is a widely recognized metric in environmental research, as it measures the relative strength of the association between two trace metals. During this analysis, the standard deviation (S.D.) was calculated for each dust sample. The results demonstrated good precision, as the relative standard deviation was within 5% (S.D. < 5%). This indicates that the detection limits for the concentration of metals such as Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), and Lead (Pb) were accurately measured at 0.02, 0.09, 0.020, 0.015, and 0.09 mg/kg, respectively.

3.5 Pollution Indices

Here, the potential ecological and human health risks caused by toxic metals in street dust gathered from several points in the Eskişehir were analyzed through standard indexes, which are explained as follows Hakanson (1980): i) Enrichment Factor (*EF*) is commonly applied to evaluate the contamination level and to trace the origin and sources of certain elements contained in street dust, ii) Ecological Risk Index (*RI*) describes the degree of contamination of each metal based on their adverse environmental risk (Laniyan & Adewumi, 2019), and iii) Health Risk Assessment model by US EPA (1989, 2001, 2011) associated with toxic metals for both adults and children was calculated through Hazard Index (*HI*) and hazard quotient (*HQ*).

$$EF : \frac{(Ci/Cr)_{Samples}}{(Ci/Cr)_{Baseline}} \quad (1)$$

$$RI : \sum_{i=1}^n E_i \quad (2)$$

$$E_i : T_i f_i \quad (3)$$

$$f_i : C_i/B_i \quad (4)$$

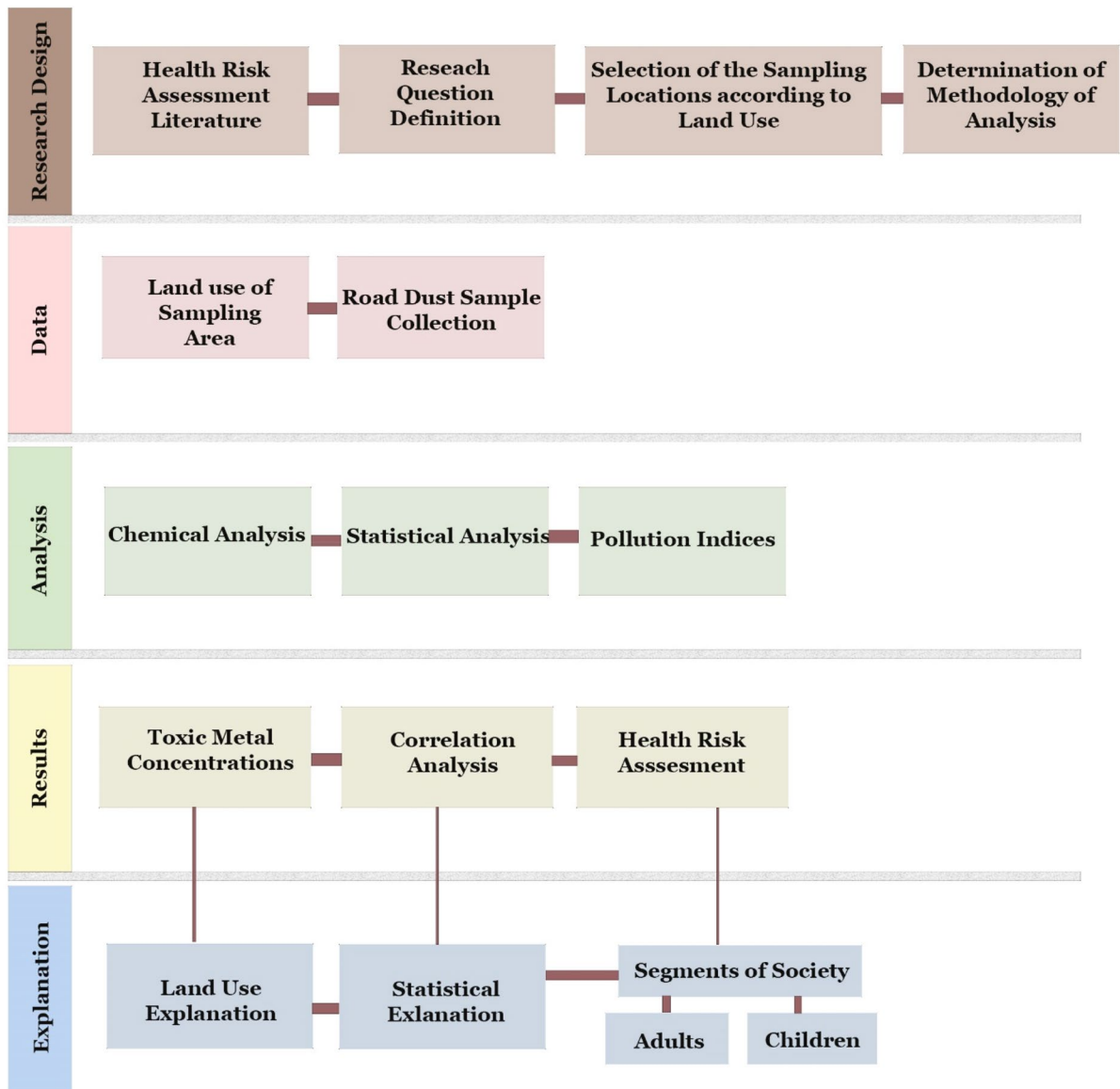


Fig. 2 Stages of the research

$$D_{Ing} : \frac{IngRxEFxED}{BWxAT} \times 10^{-6} \quad (5)$$

$$D_{Inh} : C \times \frac{InhRxEFxED}{PEFxBWxAT} \quad (6)$$

$$D_{Der} : C \times \frac{SLxSxABSxEFxED}{BWxAT} \times 10^{-6} \quad (7)$$

$$HI : \{ (HQ_{Ing}) + (HQ_{Inh}) + (HQ_{der}) \} : \left\{ \left(\frac{D_{Ing}}{R_f D_{Ing}} \right) + \left(\frac{D_{Inh}}{R_f D_{Inh}} \right) + \left(\frac{D_{Der}}{R_f D_{Der}} \right) \right\} \quad (8)$$

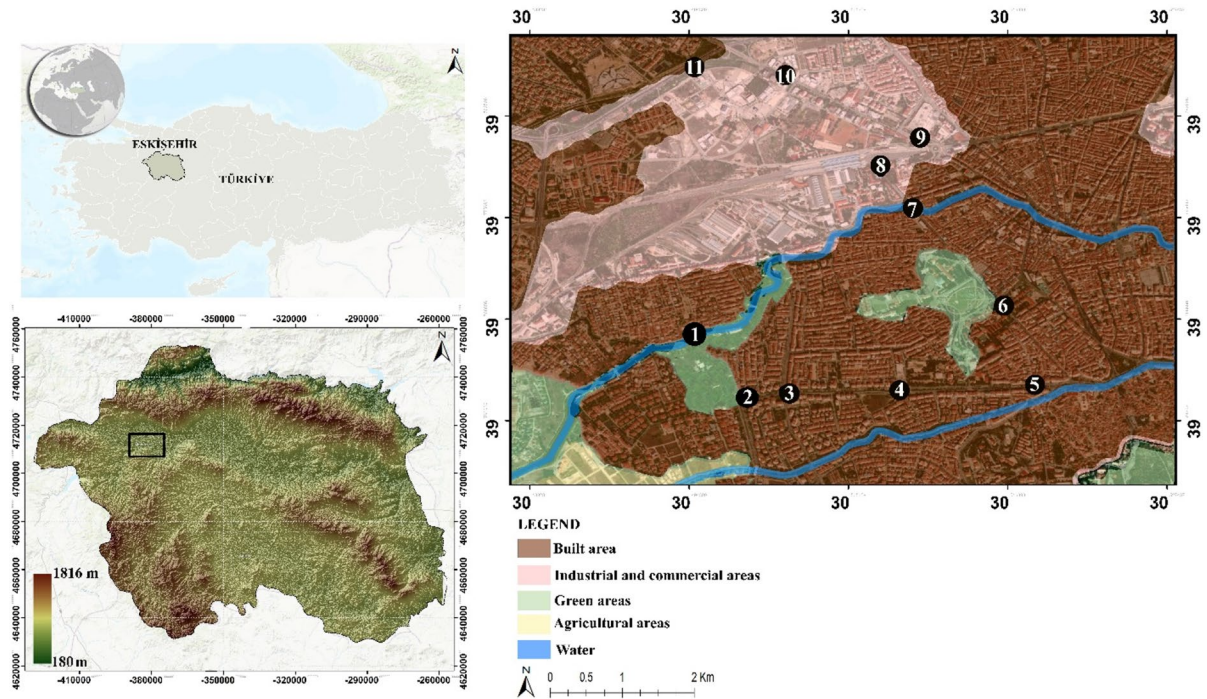


Fig. 3 The location of the sampling points in Eskişehir

Here C_i is the concentration of heavy metals (i , $\text{mg}\cdot\text{kg}^{-1}$), and C_r is the concentration of the reference metal (r , $\text{mg}\cdot\text{kg}^{-1}$). The EF value is smaller than one, which means that the element mainly comes from the crust and other natural sources, while an EF larger than 1 implies that it is affected by both human and natural factors. The EF s are categorized for enrichment level as the minimum (1-2), moderate (2-5), significant (5-20), very high (20-40), and extremely strong (>40) (Ekwere & Edet, 2021). E_i is the potential ecological risk factor of metal i , and T_i is the metal toxic factor. f_i is the metal pollution factor of metal i , which equals the amount of metal i in the sample (C_i) divided by its B_i ; reference value for metals, C_i is the content of metals in street dust. Classification levels were determined as low (<150), moderate (150-300), high (300-600), severe (>600) for RI and low (<40), moderate (40-80), high (80-160), serious (160-320), severe (>320) for E_i . The Eq. (5-7) were calculated health risk by exposure pathways which were used some standard values as flows: $IngR_{child}$ and $IngR_{adult}$ are 100 and 200 $\text{mg}\cdot\text{day}^{-1}$ for the children and adult ingestion rate (US EPA, 2011); Inh_{child} and Inh_{adult} are 20 and 7.6 $\text{m}^3\cdot\text{day}^{-1}$ for the children and adult

inhalation rate (US EPA, 2009); PEF_{child} and PEF_{adult} are $1.36\text{E}+09\text{ m}^3\cdot\text{kg}^{-1}$ for the children and adults particle emission factor (US EPA, 2002); SL_{child} and SL_{adult} are 0.2 and 0.7 $\text{mg}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$ for the children and adult skin adherence factor (US EPA, 2002); SA_{child} and SA_{adult} are 2800 and 5700 cm^2 for the children and adult exposed skin area (US EPA, 2004); ABS_{child} and ABS_{adult} are the dermal absorption factor and same value as 0.001 for Cd (US EPA, 2004); EF_{child} and EF_{adult} in Eq. (5) are the exposure frequency as 350 $\text{day}\cdot\text{yr}^{-1}$ (); ED_{child} and ED_{adult} are 6 and 24 year for the children and adult exposure duration; BW_{child} and BW_{adult} are 15 and 70 kg for the children and adult body weight (US EPA, 2001); AT_{child} and AT_{adult} are the same value as $ED \times 365$ day for non-cancer the averaging time and 70×365 day for cancer the averaging time. The HQ is expressed as the ratio between the average daily dosage (ADD) received through several pathways (D_{ing} , D_{inh} , and D_{der}) and the reference dose (RfD) $\text{mg}/\text{kg}/\text{day}$ for a given toxic metal. The $HI > 1$ means probable non-carcinogenic activity of toxic metals; $HI < 1$ suggests no health risk. However, carcinogenic risk ($CR > 1 \times 10^{-4}$) and acceptable level ($1 \times 10^{-6} < CR < 1 \times 10^{-4}$) indicate the risk of

toxic metal in street dust that 1 in 10,000 people can get any cancer as a consequence of a lifetime of exposure to carcinogenic hazards. Also, all variables are used as a guide in the human health risk assessment model based on US EPA (1989, 2001, 2007). Eq. (8) expresses reference dose by different exposure pathways, in which R_fD_{Ing} , R_fD_{Inh} , and R_fD_{Der} are varied, and the range value from 6.00E-05 to 1.20E-02 for the toxic metal.

4 Results

4.1 Toxic Metal Concentration in Street Dust

Table 2 gives the descriptive statistics of Cd, Cr, Cu, Ni, and Pb concentrations obtained from 66 street dust samples gathered from eleven points on Eskişehir Street. The trace elements examined in previous studies for Cr, Ni, Cu, Pb, and Cd ranged from 224 mg/kg for Cr to 0.51 mg/kg for Cd. The overall high Pb levels are due to the high traffic density and industrial activities in Eskişehir compared to other cities. A recent study revealed higher average Cd, Cu, and Pb concentrations in Eskişehir than outdoors. The mean concentrations of Cd, Ni, and Pb have exceeded the values recorded for the Upper Continental Crust. There was no considerable variation in concentrations between streets and sampling days, suggesting a higher contamination risk from anthropogenic activities. Eskişehir has a unique characteristic combination of elemental compositions. In these selected points, observed values may not reflect actual natural and anthropogenic diversities for all sites of Eskişehir. The skewness values for the Cr, Ni, Cu, Pb, and Cd were largely positive, indicating that the means were higher than the median, suggesting the presence of high pollution events and the temporal nature of the highest concentrations between sampling points. The arithmetic mean contents of Cr, Ni, Cu, Pb, and Cd in the street dust of Eskişehir street dust decrease in the order $Cr > Ni > Pb > Cu > Cd$. Except for Cd, all trace metal levels exhibited major standard deviations. It demonstrates the great diversity of amounts in street dust. The skewness values of Cr, Cu, Pb, and Cd, except Ni, are higher than unity, which indicates that these elements are highly positively skewed towards low concentrations.

Spatial distribution assessment is an assisted tool for determining the polluted and non-polluted zones

Table 2 The descriptive statistics of Cr, Ni, Cu, Pb, and Cd (mg kg^{-1}) in street dust samples

Sampling points	Cr	Cu	Cd	Ni	Pb
1	22.83	16.00	0.76	32.33	17.83
2	47.00	35.17	1.41	47.17	35.67
3	47.67	35.83	3.07	48.00	38.83
4	36.83	35.67	2.46	43.33	39.50
5	59.50	55.67	2.39	55.83	56.67
6	63.00	34.83	2.38	57.50	48.83
7	79.17	37.33	3.62	60.83	61.17
8	94.67	38.50	3.79	49.83	55.33
9	50.00	37.00	2.40	57.83	53.50
10	55.50	34.17	4.18	40.33	51.17
11	46.83	27.17	1.88	40.00	39.67
Mean	54.81	35.21	2.56	48.45	45.28
SD	27.94	14.49	1.31	16.04	17.81
CV (%)	50.98	41.15	51.17	33.11	39.33
Skewness	0.87	0.44	0.52	0.18	0.28
Kurtosis	0.52	-0.27	-0.20	-0.51	-0.13

in a defined field on ArcGIS spatial map. In the current work site, spatial distribution patterns of Cr, Ni, Cu, Pb, and Cd in road dust are depicted in Fig. 4.

4.2 Correlation Analysis

Figure 5a displays dendrogram results in four clusters: i) Ni-Pb ii) Pb and Cu; iii) Cr; and iv) Cu and Cd, which are fully consistent with the correlation results. However, clusters 3 and 4 seem to come together relatively higher, probably indicating a common source. Pearson's correlation coefficients between metals represent common origin with potential natural and anthropogenic sources in Fig. 5b. It can be seen that Cr, Ni, Cu, Pb, and Cd had significant positive correlations with each other. Pb-Cr and Pb-Ni showed significantly strong correlations, $r: 0.56^{**}$ and $r: 0.51^{**}$ because they represented vehicular traffic-related emissions. Similarly, Ni and Cu had positive correlations with $r: 0.54^{**}$, whereas Cu only had a slight correlation with Cd ($r: 0.11$) due to Cd and Cu having different sources. This suggests that Cd and Cu are partly derived from a natural source (local soil), whereas Pb, Ni, and Cr are mainly impacted by traffic and industrial operations.

According to EF values, EF value of Cr, and Cu smaller than 1 implies no enrichment, while EF value of Cd is 1-2, representing deficiency to minimal

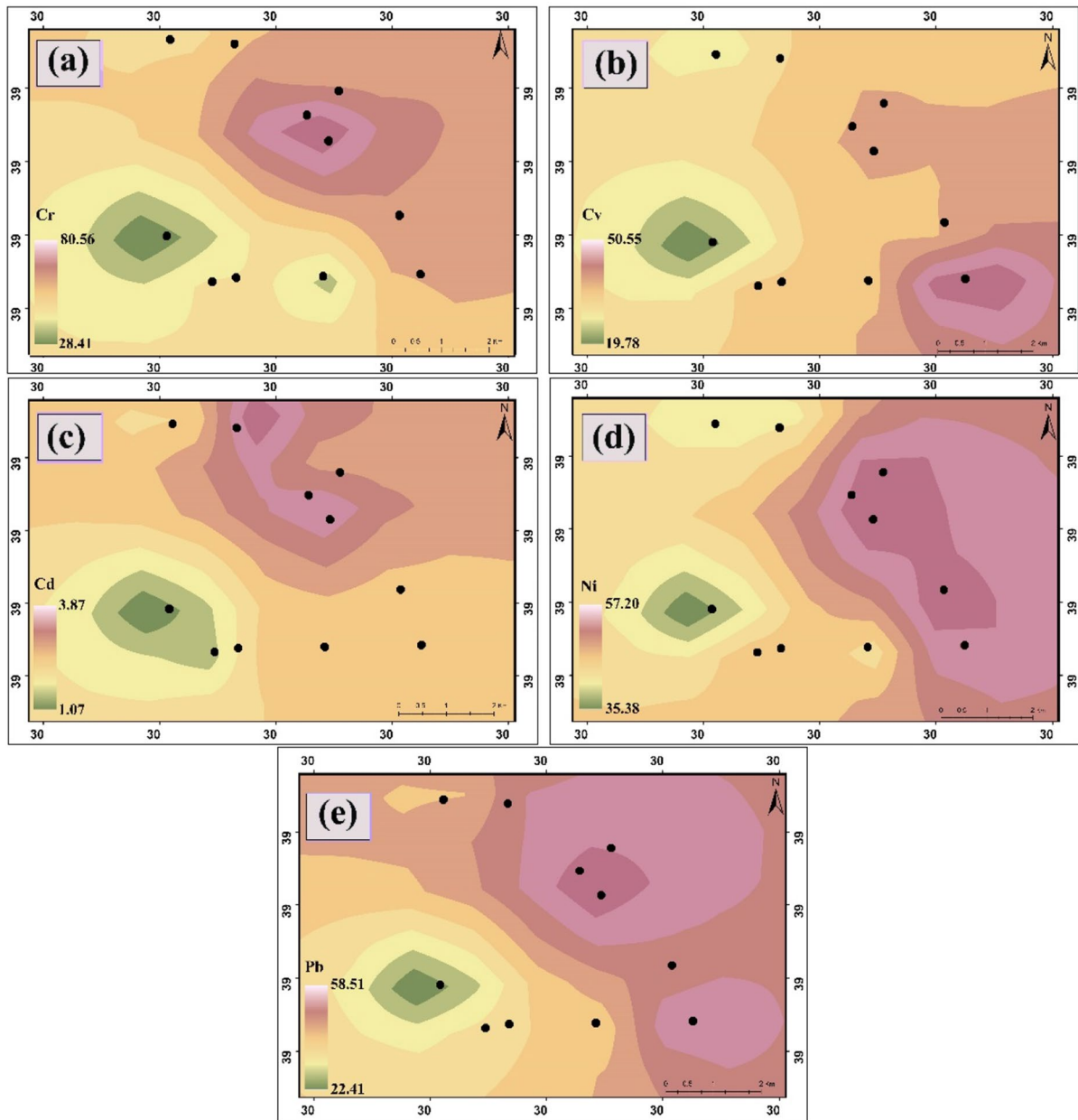


Fig. 4 Spatio-temporal distribution of (a): Cr, (b): Cu, (c): Cd, (d): Ni, and (e): Pb in the street dust for different land-use types in Eskişehir

enrichment. The *EF* values of Pb and Ni were determined as moderate enrichment due to their values calculated between 2 and 5.

4.3 Health Risk Assessment

The study of street dust environmental risks and pollution factors is of major importance, giving

insight into emission sources and assisting decision-making for resilient cities. The *EF* of selected toxic metals was calculated to assess the degree of contamination of street dust, which obtained mean *EF* values for Cu and Cd below 1.5. Their values represent deficiency to minimal enrichment based on their *EF* values, whereas the *EF* values showed moderate enrichment for Cd and Pb and significant

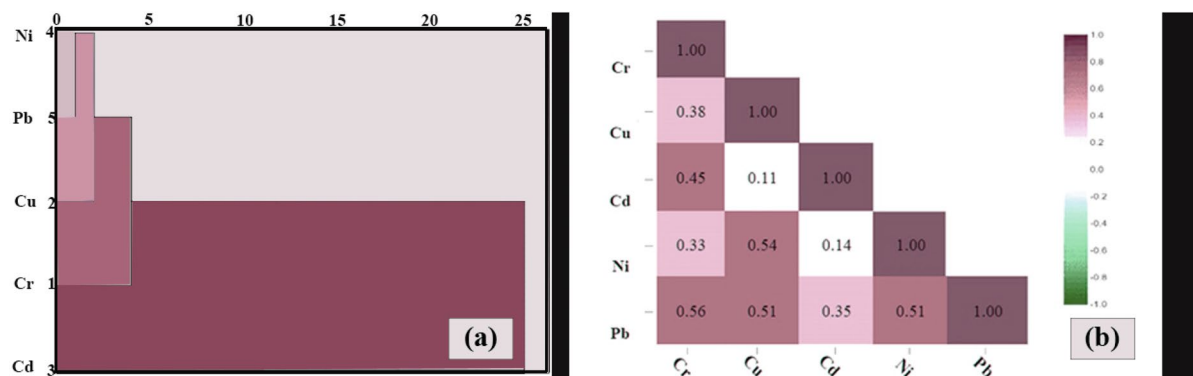


Fig. 5 (a): Dendrogram showing clustering and (b): Matrix of Pearson correlation coefficient values of toxic metals concentrations in street dust. **. Correlation is significant at the 0.01 level (2-tailed)

enrichment for Ni. Traffic-generated emissions in Eskişehir City and other urban facilities, such as construction and household activities, can be the main sources of anthropogenic emissions. Cd and Cu could be partly released from vehicular, although fossil-fuel combustion may also contribute to their levels. Table 3 shows that non-carcinogenic health risks were calculated for Cr, Ni, Cu, Pb, and Cd. The highest HQ_{ing} was estimated for Ni and Pb in children ($1.67E+00$ and $2.67E+00$), although these values were found for adults ($1.41E-02$ and $2.27E-01$), which means that low potential to cause non-carcinogenic risk ($HQ < 1$). The HQ_{ing} values for Cu were also high and comparable to Cu's, with averages of $1.15E-01$ for children and Pb $2.27E-01$ for adults. Ni presented the highest risk values regarding the inhalation and dermal contact

pathways, thus being recognized as the most hazardous element.

5 Discussion

In terms of the spatial distribution of toxic metals, the sampling sites were chosen from urban environments to represent diverse global locations. The research by Mehmood et al. (2019), Ciarkowska et al. (2019), and Silva et al. (2021) has focused on toxic metals from industrial or factory sources and vehicular traffic in cities. Pb, Ni, and Cd exhibited higher concentrations in this context than other metals. However, these concentrations were still lower than those in the Upper Continental Crust. On the contrary, the concentrations of anthropogenic-related elements such as Zn,

Table 3 The mean value of daily dose and hazard indices in toxic metal of street dust

Elements	D_{Ing}	D_{Inh}	D_{Der}	HQ_{Ing}	HQ_{Inh}	HQ_{Der}	HI
Adults							
Cd	$7.10E-05$	$2.23E-10$	$7.41E-09$	$7.10E-02$	$3.86E-07$	$7.41E-04$	$7.18E-02$
Cr	$1.20E-04$	$4.73E-09$	$1.58E-07$	$4.18E-02$	$2.87E-06$	$1.12E-01$	$1.54E-01$
Cu	$3.94E-04$	$3.04E-09$	$1.01E-07$	$9.84E-03$	$7.60E-08$	$8.44E-06$	$9.85E-03$
Ni	$2.91E-04$	$4.19E-09$	$1.39E-07$	$1.41E-02$	$2.03E-07$	$2.76E-06$	$1.41E-02$
Pb	$7.94E-04$	$3.91E-09$	$1.30E-07$	$2.27E-01$	$1.94E-06$	$2.48E-04$	$2.27E-01$
Children							
Cd	$8.41E-04$	$3.86E-10$	$3.16E-08$	$8.41E-01$	$3.86E-07$	$3.16E-03$	$8.45E-01$
Cr	$1.54E-02$	$8.22E-09$	$6.73E-07$	$4.67E-01$	$2.87E-06$	$1.12E-01$	$5.79E-01$
Cu	$4.60E-03$	$5.28E-09$	$4.32E-07$	$1.15E-01$	$1.32E-07$	$3.60E-05$	$1.15E-01$
Ni	$3.33E-03$	$7.26E-09$	$5.95E-07$	$1.67E+00$	$3.53E-07$	$1.10E-04$	$1.67E+00$
Pb	$9.33E-03$	$6.79E-09$	$5.56E-07$	$2.67E+00$	$1.94E-06$	$1.06E-03$	$2.67E+00$

Cu, Co, and Pb in the street dust samples were comparatively lower than those detected in atmospheric or street dust samples collected in other cities. This can be attributed to Eskişehir's lower population density, reduced vehicular emissions, and the absence of significant industrial zones (as mentioned in Shabanda et al., 2019 and Hanfi et al., 2020). The street dust was significantly enriched with Pb and Ni and moderately enriched with Cd due to heavier traffic density, higher population, and industrial activity (Pan et al., 2018). Although Pb has been stopped being used as an additive in petrol and gasoline worldwide, Pb emissions may still be related to the industrial sector and traffic, similar to other urban sites (Huang et al., 2022). Pan et al. (2017) noted that the current toxic metal concentrations for outdoor and indoor dust were significantly higher than those recently reported in the city.

Trace elements in street dust are considerably higher than in airborne dust because street dust is an important sink for pollutants and heavy metals in the urban environment (Mahato et al., 2023; Nezat et al., 2017). As such, while suspended dust polluted with urban pollution and heavy metals accumulates in the streets, only a proportion can be re-suspended into the atmosphere due to wind, traffic, and other human activities (Bisht et al., 2022; Luo et al., 2019). Additionally, the highly relevant relationship between Ni and Cr indicates that they presumably derive from similar geogenic sources and are influenced by anthropogenic sources, such as the traffic sector tire and brake wear (Rahman et al., 2019; Wahab et al., 2020). Wei et al. (2021) exhibited that brake materials contained Cu elements and existed in the atmosphere. Related research defined by Shen et al. (2018) and Chen et al. (2019) that Cu can be emitted into the urban environment due to wear of the car's oil pump, corrosion of metal parts in contact with the oil, and engine wear. Many health risk assessment investigations about street dust deposition, a considerable part of Ni, Fe, Cr, and Co in the atmosphere comes from lithogenic sinks by Bartholomew et al. (2020), Dat et al. (2021), and Delgado-Iniesta et al. (2022). Similar to this paper, Marín Sanleandro et al. (2018) reported that the *EF* values for Pb and Ni show significant enrichment due to traffic-related contamination. Previous research investigating pollution and ecological risk indices for street dust in urban environments has also reported higher pollution levels and risk index values due to the more significant deposition of hazardous metals

in the street rather than in airborne dust by Budai and Clement (2018); and Nargis et al. (2022). The seasonal variation of the content of toxic and poisonous metals, multiannual trends, and different sizes of street dust require further research. Roy et al. (2022) emphasized that although general trends for certain toxic metals in street dust are maintained, individual indices show slightly different pollution levels. The problem of improving the method of calculating the index requires further work. Urban centers contain urban functions that serve the city as a whole. Therefore, traditional urban centers have a high density of buildings and population. This density increases towards the city center and decreases towards the periphery. However, city centers have frequently contained connections and nodes designed with human scale in the past. Due to this road network and urban morphology, the road patterns are connected at short intervals.

Due to vehicular traffic frequently slowing down and stopping, the exhaust emissions of fossil fuel-consuming motor vehicles increase due to their stop-and-go movements. This leads to the release of toxic elements into the external environment, as technical components are responsible for enabling vehicles to stop and start wearing out. These stop-and-go movements also contribute to adverse effects on public health. Moreover, studies have indicated that such traffic patterns can indirectly decrease gross national income.

6 Conclusions

In the research area, residential zones with low densities featured water surfaces, parks, and alternative transportation systems to fossil fuels, exhibiting lower pollution risks. In contrast, commercial areas with high motor vehicle usage presented a higher risk of urban pollution based on heavy metals and health hazards. Extensive research has focused on distributing common trace metals in street dust, such as Cr, Ni, Cu, Pb, Cd, and Ni. A total of 66 samples were collected from diverse locations, including parks, traffic lights, and high-traffic areas. Strong correlations between Ni and Pb suggest similar geogenic origins influenced by anthropogenic factors like traffic, residential, and commercial emissions. Enrichment factor calculations highlight significant enrichment of Cd and moderate enrichment of Ni and Pb in street dust, posing a moderate ecological risk due to mean Ni and Pb contents. The primary contributors to severe

pollution and ecological risks are Pb and Ni, accounting for 68% of the total potential ecological risk. Moderate risks are associated with Cd, while vehicular emissions in the city center and the usage of brakes and engines providing stop-and-go movements contribute to the consistently high concentrations of Cd and Pb. Assessment of the non-carcinogenic human health risk demonstrated that the ingestion exposure route posed much greater health risks than inhalation and skin contact. Since the HI values of the Cr, Ni, Cu, Pb, and Cd were lower than the safe level ($HI < 1$), the non-carcinogenic health risks of targeted PTEs in Zabol atmospheric dust were generally low. Among the Ni, it exhibited the highest cancer risk through the inhalation pathway, although it was still below the safe limit of 10^{-4} —the carcinogenic risk related to street dust, considering the quantities of poisonous metals. There is an urgent need for urban management actions to mitigate the consequences of serious Pb, Ni, and Cd pollution, as well as the risk of Cr cancer. In urban areas, a detailed urban air quality control/plan is needed to assess the situation and select effective strategies to deal with the ecological and human health hazards of dust pollution. The findings provide a reference for urban management and the protection of residents' health in similar urban governments surrounding heavily trafficked streets.

Future research on urban traffic emissions is more comprehensive than previously, but certain strategies should be followed to ensure sustainable urban development. Based on the principle of sustainability, monocentric-multicentric urban growth models should be discussed separately. Alternative modes of transportation and public transport should be studied. Transportation systems powered by new energy sources should be targeted for a healthier urban model. Pedestrian-oriented designs should be presented to reduce vehicle and pedestrian density in the city center. Local governments can pursue policies such as taxation or pricing to limit the entry of vehicles using fossil fuels into the city center.

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

Declarations

Competing Interest The authors declare that they have no competing interests.

Ethics Approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Consent to Participate Not applicable.

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