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Ecological and Health Risk Assessment in Road Dust Samples from Various Land Use of Düzce City Center: Towards the Sustainable Urban Development

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Abstract Urban environmental risks are related to dynamic and long-term cross-processes arising from complex interconnected relationships. Although they have various sources, trace metals' ability to accumulate is relatively high compared to other pollutants. Therefore, for this reason, heavy metals can be found in high amounts in cities, especially in road dust. The targets of the present study are to appoint the levels and sources of trace metals in road dust samples collected from eleven areas in the Düzce city center. Because of their potential health risks, the five heavy metals (Cd, Cr, Cu, Ni, and Pb) are the most commonly studied pollutants. The inhalation of them through the mouth and nose is almost negligible; however, ingestion is a higher potential health risk for children. The hazard index (HI) and geoaccumulation index (I_{geo}) are powerful tools used to assess the level of risk. Factors governing possible contamination mean values were evaluated in the following order: Pb (56.07 mg/kg) > Cu (43.45 mg/kg) > Ni (30.05 mg/kg) > Cr (26.58 mg/kg) > Cd (4.33 mg/kg). The noncarcinogenic risks of Pb poses are relatively higher than those posed by the other four metals for both children and adults. However, HI values of Cd, Pb, and Ni in children were 1.25–1.61, 2.93–3.74, and 1.00–1.14; Cd is 1.05–2.56. The HI values for children are relatively higher than for adults. This paper provides the most significant contribution to road dust is atmospheric deposition by industrial activities and traffic density. Regarding Pb, while I_{geo} is 0.66 in park areas and 0.61 in forest areas, it reaches 0.96 on highways. While Ni is calculated for I_{geo} as 0.52 in forest area, it gets 0.97 in industrial factory surroundings. The findings reveal the multidimensional results of land use policies regarding sustainable urban development. The stochastic model obtained is vital, especially in disadvantaged groups.

Keywords Ecological risk index · Health monitoring · Metal pollution · Spatial modeling · Sustainable cities · Urban monitoring

1 Introduction

Monitoring the health of societies to protect public health has become a critical issue for sustainable communities. The World Health Organization (WHO) states that 7 million premature deaths occur

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annually due to exposure to indoor and outdoor air pollution (WHO, 2013). In developing countries, exposure to air pollution is relatively lower than that in other countries. There are multidimensional factors that reduce urban air quality. But road dust is the primary source of atmospheric particles. (Haynes et al., 2020; Isinkaralar, 2022a, b). It is one of the most crucial issues of heavy metal contamination and ensures the rapid decline in an atmospheric deposition has many anthropogenic sources of complex air quality (Kelly & Fussell, 2019; Lima et al., 2023). Air pollution caused by atmospheric particles is seriously concentrated in urban areas due to complex interactions with the effect of transnational dynamics depending on emission intensity and meteorological conditions (Ambade et al., 2022; Isinkaralar & Varol, 2023).

Human activities in urban areas are all the significant reasons for heavy metal pollution in road dust. Therefore, an in-depth look at the fine particle of dust on road surfaces contributes to various sizes of particulate matter (PM) through the air, leading to human health through inhalation. Therefore, in recent years, dust formation mechanisms have gradually been used for various activities such as urban transformation, construction, and heavy traffic (Wang et al., 2020). Most studies of dust and its source have compared annual levels in settlements to identify which is more critical (Rajaram et al., 2014; Shahab et al., 2022). Heavy metals released from these areas accumulate in the water, soil, and atmosphere (Wei et al., 2021). Urban air pollution has become more critical due to industry and economic activities being more concentrated in cities (Han et al., 2023; Lin & Zhu, 2018). This is a personal responsibility to repress and reduce of increase in emissions.

Heavy metal pollution has emerged significantly in urban environments due to rapid urbanization and industrialization (Wei et al., 2010; Jiang et al., 2018). Even though heavy metals are one of the most critical air pollutants, they have invariably been deemed merely a common issue in urban environments (Jia et al., 2020). These toxic elements cause severe contamination and can readily accumulate in the background. Owing to the exposure time and concentration, it is known that the accumulations harm every level of the ecosystem, especially humans, through various pathways (Chenery et al., 2020; Isinkaralar et al., 2022, 2023). Accumulation levels show undesirable responses at higher concentrations in the vital system and are easily deposited in tissues. Heavy metals can also cause bioaccumulation; thus, their calculation and risk assessment is critical in the environmental systems (Barsova et al., 2019). Therefore, the source and amount of toxic elements must be determined for contaminated sites, including traffic, because it has the principal source. It has been calculated as the leading mobile source of heavy metal emissions depending on density and congestion (Hwang et al., 2016). It also contributes to the roadside greenbelts about traffic emissions, energy generation in the industry, and burning fossil fuels for house-heating purposes (Istanbullu et al., 2023; Krupnova et al., 2020). The higher the number of these sources, the more emissions released to the environment increase, and their accumulation in the environment is widespread (Salazar-Rojas et al., 2023; Shahab et al., 2020). Road dust is a source and a swamp of pollutants in the atmosphere. Industrial emissions, natural sources, and coal combustion are attributed to air pollution by suspending particles into the atmosphere (Deng et al., 2017; Qin et al., 2021). Atmospheric pollutants, accumulating in dry and wet precipitation areas, can get on roads and urban environments (Jia et al., 2021). These pollutants from different sources can easily pass from urban regions to humans (Keshavarzi et al., 2015; Khpalwak et al., 2019). For this reason, to protect the health of people living in cities with high population density, it is necessary to determine the background contamination caused by heavy metals, monitor these pollutants, and know their sources and emission amounts.

The focus of this paper was to define the ecological and health risk assessment by determining the heavy metal pollution in road dust collected from various locations determined in Düzce city center. The present report extensively studies urban road dust as follows: (i) to determine the current state of Cr, Cu, Cd, Ni, and Pb in road dust via relative bioavailability (RBA) due to the fact they were strongly associated with human influences; (ii) to provide the cumulative probabilities of hazard index (HI); (iii) to assess a critical index analysis of the environmental impact using the geo-accumulation index; (iv) to identify sources and spatial distribution of selected heavy metals; (v) to estimate health risk assessment of children and adults by the US-Environmental Protection Agency (US-EPA) health risk estimation model. In addition, the existence and possible future directions of investigations in urban air quality and human health have been analytically revealed.

2 Materials and Methods

2.1 Sampling Sites

Düzce city with a population of approximately 395,679 people (40°50′45.9″N 31°09′52.0″ E) is located in the north of the Türkiye (41°16′49.4″N 36°20′04.1″ E) and is varied in terms of physical geography. The climate of the city can vary during different seasons; the mean annual temperature, annual precipitation volume, relative humidity, and wind speed are + 11.7 °C, 1146 mm, ~75%, and ~3.8 m/s. A pronounced majority of northern and southerner winds and the dominant soil type is alluvial soil. The number of motor vehicles and industries is also proliferating, and environmental pollutants can accumulate considerable quantities of heavy metals and other pollutants recent observation as smog. Also, many industries such as glass, furniture, textile, pharmaceutical, metal profile, and pipe have been established in Düzce (Fig. 1).

According to the data obtained from six stations in the area, it was determined that there was a slight increase in all stations according to the measurement results of previous years. The main factor in the determination of the sampling places was aimed to be intense urban mobility. In this context, eleven different locations have been determined due to their strategic location as follows: (i) residential area, (ii) industrial area, (iii) main city roads with heavy traffic flow, (iv) city center with heavy traffic, and (v) forest area. The dense traffic poses road dust, including heavy metals, on the environment with different backgrounds. The pollution status

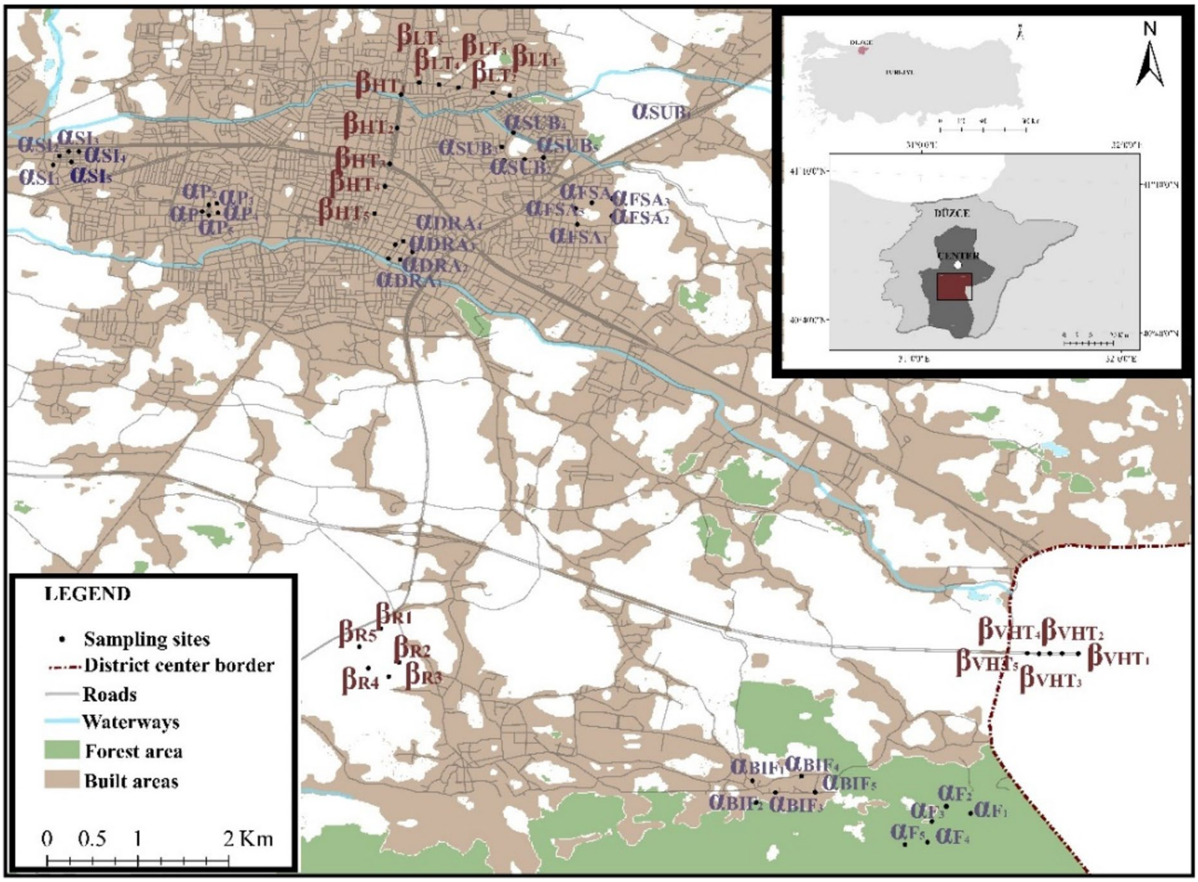

Fig. 1 Location map of sampling points

was examined for collecting road dust to determine sampling points. The longitude and latitude aimed to diversify the samples are summarized by choosing different homogeneous locations that accumulate on the roadside in Table 1.

2.2 In Vitro Digestion Test

Samples were obtained from the main streets in Düzce city during the dry winter season of 2022, which had in all five districts, including areas with 11 points. Samples were carefully prepared as follows: (i) the polyethylene brush, bottles, and beakers were cleaned with the hydrochloric acid solution overnight and then washed with deionized and fresh water at least four times to make sure any pollution; (ii) a total of 165 road dust samples in 1 m^2 of the road edge were swept using a soft polyethylene brush as approximately 200 g utilized powderless gloves; (iii) subsequently, the samples were collected into sealed polyethylene bags and labeled from RD1 to RD165. The RD1-165 was brought to the laboratory, where it dried in an oven at 75°C for 48 h until they were precisely deprived of any moisture, powdered, and sieved to remove large and unwanted particles of the < 75 μm diameter fraction, (iv) the particle size mainly selected due to their atmospheric deposition is easily transported by resuspension (Zhao & Li, 2013), (v) all the samples were kept at 4 °C until heavy metal content analysis.

Table 1 Sites ID and their description

Sites ID	Station label	Description
S1	αBIF	Industrial factory surroundings
S2	αSI	Small industry
S3	αDRA	Residential area
S4	αSUB	Suburb
S5	αFSA	Empty land in the settlement area
S6	αP	Park
S7	αF	Forest area
S8	βVHT	Highway
S9	βHT	Heavy Traffic
S10	βLT	Low heavy traffic—neighborhood
S11	βR	References

2.3 Analysis of Heavy Metals

Each road dust sample was elaborated to analyze the heavy metals content via four main steps: (a) 1 ± 0.02 g aliquot of dry dust was weighed and dissolved in a ratio of 10:8:2 (v/v) of nitric acid (35%, HNO_3), perchloric acid (70%, $HClO_4$), and sulfuric acid (98%, H_2SO_4); stirred at 60°C for 30 min, (b) the mixture was added to into a microwave oven at 220 °C for 60 min (USEPA 1995); (c) the solution filtered by vacuum pump using Whatman filter papers a pore size of 0.45-μm diameter; (d) after acid digestion, the digest samples were determined in triplicate for higher validity by inductively coupled plasma-optical emission spectrometry (ICP-OES, SpectroBlue, Spectro, Germany), and the current concentration of Cd, Cr, Cu, Ni, and Pb were considered during all procedures for multiplying the diluted factor. This study used all the chemicals and reagents of analytical grade.

2.4 Quality Control and Statistical Analysis

The quality control (QC) was approved throughout the analysis to block any contribution, and the devices were calibrated regularly by calibration standards ($R^2 \geq 0.988$). A method blank and replication of samples were investigated for all experiments. The extent of recovery for four metals was obtained with an SD of less than 5%, and trace amounts were monitored for total heavy metals in the blanks. Also, the instrumental detection limits for Cd, Cr, Cu, Ni, and Pb were obtained as 0.036, 0.028, 0.024, 0.047, and 0.019 μg/g, respectively.

To identify the nexus, heavy metal in road dust and their possible correlation was performed using statistical methods during the observed and original variables. The correlation matrix and principal component analysis correlated five heavy metals and apportioned natural versus anthropogenic parameters for similar Cd, Cr, Cu, Ni, and Pb values in road dust. The commercial statistics software package was used for F value, error rate, and thus the difference of the factors by SPSS version 23.0 (IBM Corp., Armonk, NY, USA) for Windows at the 95% confidence level.

2.5 Geo-accumulation Index and Health Risk Assessment Model

The most commonly applied quantitative index that can be computed to make evaluations of road dust is the geo-accumulation index (I_{geo}) which was initially defined by Müller (1969). They easily depose on surface soil (Charzyński et al., 2017), $PM_{2.5}$, and PM_{10} (Kong et al., 2012) as the intensity of anthropogenic contaminant. According to the formula widely used by Zhang et al. (2012) and Zhu et al. (2013), the I_{geo} main parameter was used to assess the pollution level of urban dust contamination in the following expression with Eq. (1).

$$Igeo = log_2\left(\frac{c_n}{1.5Bn}\right) \tag{1}$$

C_n represents dust samples' concentration, and B_n reflects background concentration values. *K* value represents a constant coefficient (defined to be 1.5). The *I*geo values are the corresponding exposure pollution in the seven classes as follows: (a) *I*geo values <0 for no pollution, (b) between 0 and 1 for low, (c) between 1 and 2 for moderate, (d) between 2 and 3 for above medium, (e) between 3 and 4 for high; (f) between 4 and 5 for above high, and (g) >5 for extremely contamination.

In this research, the exposure quantity was calculated using the USEPA method to examine the health effects of road dust containing heavy metals (USEPA, 1989; 1996; 2002). Demonstrating that road dust directly or indirectly affects people living in residences, commercial areas, and public transportation areas; direct ingestion (*ADD*ing) in Eq. 2 via Enrichment Facttor (EF) by Sutherland (2000), inhalation (*ADD*inh) in Eq. 3, and dermal contact absorption (*ADD*dermal in Eq. 4) were calculated. The hazard quotient (HQ), based on non-cancer toxic risk, was found by dividing the average daily dose (ADD) by the reference dose for each exposure route. The HI numerical values were found to calculate the risks that are not carcinogenic but pose a risk from the sum of the HQ values. If this value exceeds 1, it is a potential risk and emphasizes that it has no carcinogenic effect. Besides the total concentrations of the heavy metals found, relative bioavailability (RBA) was considered in all calculations.

where *C* is associated with the concentration of heavy metals (mg/kg); IngR is the ingestion rate; EF is the exposure frequency; ED is the exposure duration; BW is the human body weight; and AT is the average exposure time (ED × 365) in Eq. (2).

$$\mathrm{ADD_{ing}} = C \times \frac{\mathrm{IngR \times EF \times ED}}{\mathrm{BW \times AT}} \times 10^{-6} \tag{2}$$

where PEF is the particle emission factor, and InhR is the inhalation rate in Eq. (3).

$$\mathrm{ADD_{inh}} = C \times \frac{\mathrm{InhR \times EF \times ED}}{\mathrm{PEF \times BW \times AT}} \tag{3}$$

where SL and SA are the skin adherence factor and exposed skin area, and ABS is the dermal absorption factor in Eq. (4).

$$\mathrm{ADD_{dermal}} = C \times \frac{\mathrm{SL \times SA \times ABS \times EF \times ED}}{\mathrm{BW \times AT}} \times 10^{-6} \tag{4}$$

where RBA shows the contents of the bioavailable fraction of pollution in Eq. (5).

$$\mathrm{HQ_{ing}} = \frac{\mathrm{ADD}_{ing} \times \mathrm{RBA}}{\mathrm{RfD}_{ing}} \tag{5}$$

$$HQ_{\mathrm{inh}} = \frac{\mathrm{ADD}_{inh}}{\mathrm{RfD}_{inh}} \tag{6}$$

$$HQ_{\mathrm{dermal}} = \frac{\mathrm{ADD}_{dermal}}{\mathrm{RfD}_{dermal}} \tag{7}$$

$$HI \sum_{1}^{i} HQ \tag{8}$$

$$LADD_{inh} = \frac{C \times \mathrm{EF}}{\mathrm{PEF \times AT}} \times \left(\frac{InhR_{child} \times ED_{child}}{BW_{child}} + \frac{InhR_{adult} \times ED_{adult}}{BW_{adult}}\right) \tag{9}$$

3 Results

3.1 Concentrations of Heavy Metals in Street Dust

The evidence in Table 2 shows the heavy metal concentration in road dust in different regions in Düzce, where the distribution is approximately log-normal. The absolute heavy metal concentrations in the road dust decrease in the order of Pb > Ni > Cu > Cd > Cr, and the concentration of Cr, Cu, Cd, Ni, and Pb ranged from 18.78 to 32.63, 35.83 to 205.07, 2.51 to 55, 14.89 to 365.31, and 11.81 to 705.56 mg/kg, respectively.

Table 2 Heavy metals in street dust from several locations (mg/kg)

Elements	Mean	Median	Min	Max	StDev	Skewness	Kurtosis	Background in soil	$I_{geo(mean)}$
Cr	25.59	24.49	18.78	32.63	18.39	0.129	4.61	17.60	0.01
Cu	44.29	40.16	35.83	205.07	245.23	6.073	36.04	19.33	0.58
Cd	41.46	42.02	2.51	55	6.74	-4.67	25.97	0.08	5.17
Ni	288.86	289.59	14.89	365.31	26.68	-2.84	15.10	11.24	0.83
Pb	532.33	537.86	11.81	705.56	75	-3.92	21.20	19.46	0.94

Table 3 I_{geo} values in each studied site

Locations	Cr	Ni	Cu	Cd	Pb
S1	0.17	0.97	0.71	5.35	1.12
S2	0.04	0.87	0.58	5.23	0.99
S3	−0.01	0.83	0.52	5.16	0.94
S4	0.05	0.89	0.59	5.23	1.00
S5	0.01	0.84	0.53	5.20	0.95
S6	0.02	0.64	0.54	5.20	0.66
S7	−0.02	0.52	0.50	5.13	0.61
S8	0.02	0.84	0.54	5.20	0.96
S9	−0.03	0.79	0.48	5.13	0.90
S10	−0.08	0.72	0.94	4.98	0.77
S11	−0.10	0.74	0.41	5.06	0.83

Mean I_{geo} values of Cr, Cu, Cd, Ni, and Pb were 0.01, 0.58, 5.17, 0.83, and 0.94, respectively. According to the I_{geo} index classification, the monitored site is unpolluted if I_{geo} values are smaller than 0. All average site values for Cr can say almost unpolluted, and I_{geo} values between 0 and 1 show unpolluted to moderately polluted; it can be said that pollution has virtually started to occur for Ni and Pb. The highest index value of Cd might be attributed to anthropogenic activities in all sites.

When examining all regions, S1 was found to be relatively high compared to other areas. The maximum I_{geo} values of Cr, Ni, Cu, Cd, and Pb in S1 were 0.17, 0.97, 0.71, 5.35, and 1.12, respectively. Among the heavy metals, Cd, which draws attention compared to the others, has been determined to have the highest pollutant rates, between 4.98 and 5.35. However, the I_{geo} values of Cr were lower than 1, proposing that the corresponding metal did not contaminate S1 and S11 (Table 3).

3.2 Spatial Distribution and Statistics

Spatial distributions of Cr, Ni, Cu, Cd, and Pb concentrations in the road dust in Düzce city are separately shown in Fig. 2. The trends for Cr, Ni, Cu, Cd, and Pb are similar with higher concentrations in S1, and their contents in road dust correlate linearly. We believe that their emissions from industry and traffic are the primary sources of toxic metals in Düzce City. Table 4 demonstrates the correlation matrix results showing that Pb and Ni are accumulated brought to traffic-related pollution. The Cr, Ni, Cu, Cd, and Pb contribute significantly to the contamination of road dust, and the correlation analysis also shows significant correlations between them in road dust ($p < 0.01$). Cr, Ni, Cu, Cd, and Pb contents in road dust correlate linearly in accumulations. This suggests they strongly depose suspended particles, atmosphere aerosol, and precipitation in urban road dust.

3.3 Human Health Risk Assessment of Heavy Metals

Table 5 demonstrates oral ingestion (HQ_{ing}), dermal contact (HQ_{dermal}), and inhalation (HQ_{inh}) values that were found to evaluate noncarcinogenic health risks in Cu. The toxicity values used in risk calculations for the inhalation route that are the corresponding oral reference doses and slope factors. The assumption that deserves inhalation; it is important to the absorption of the particle-bound toxicants which will result in similar health effects as if the particles had been ingested (De Miguel et al., 2007; Zheng et al., 2010). The total was calculated using RBA to determine exposure levels, and the HQ values for each were found separately as $HQ_{ing} > HQ_{dermal} > HQ_{inh}$. This sorting is steady with the findings of former results (Hu et al., 2011; Tang et al., 2017; Hou et al., 2019).

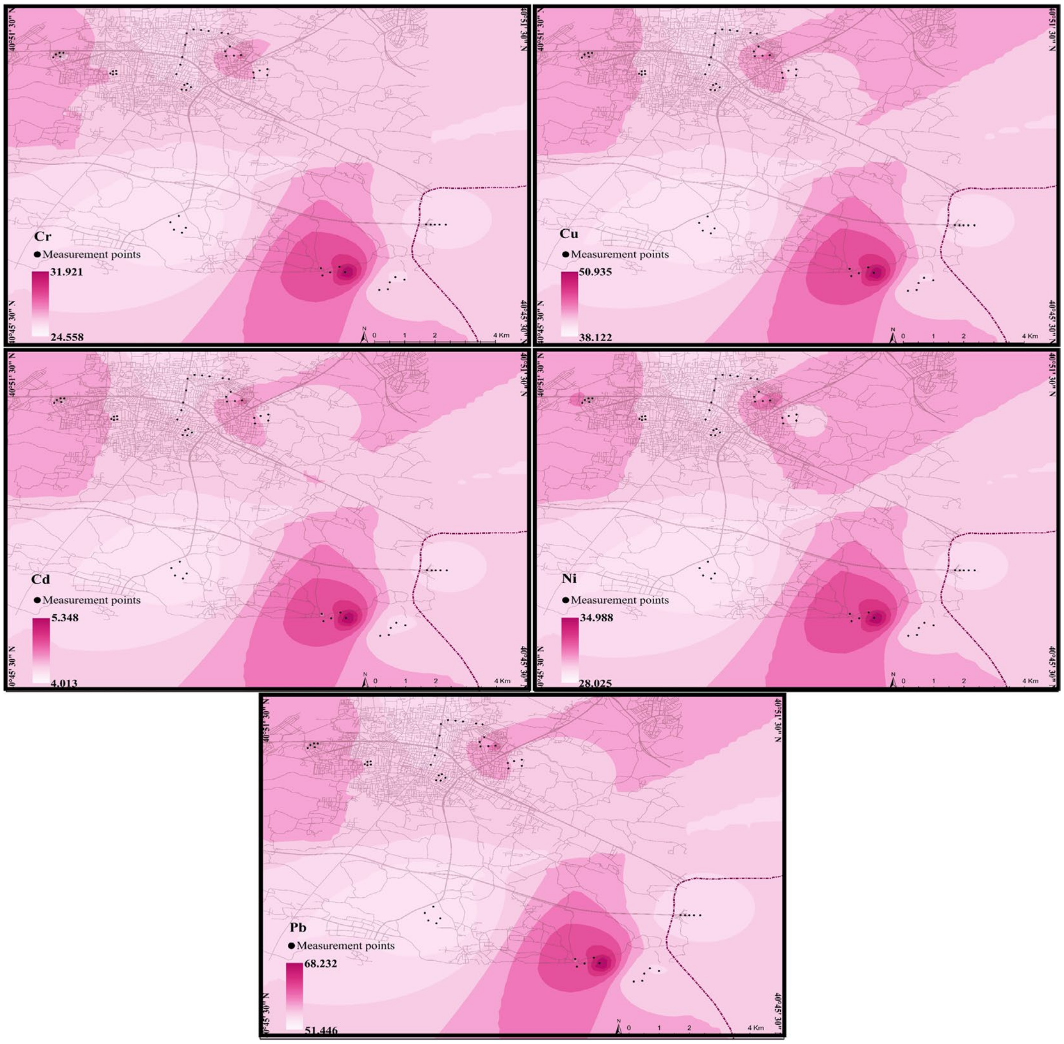

Fig. 2 Heavy metal spatial distribution in road dust (mg/kg)

Table 4 Correlation coefficients results of heavy metals of road dust samples

	Cr	Ni	Cu	Cd	Pb
Cr	1	0.973**	0.987**	0.988**	0.987**
Ni		1	0.977**	0.975**	0.975**
Cu			1	0.991**	0.989**
Cd				1	0.988**
Pb					1

**Significant correlation at the 0.01 level (two-tailed)

Table 6 represents HQ_{ing}, HQ_{dermal}, and HQ_{inh} values that were found to evaluate noncarcinogenic health risks in Cr. This suggests that children and adults in Düzce are exposed to potential health risks from Cu and Cr in road dust (HI < 1).

Table 7 represents HQ_{ing}, HQ_{dermal}, and HQ_{inh} values that were found to evaluate noncarcinogenic health risks in Cd. The probability for the HI values of Cd ranged from 1.25 to 1.61 in all sites, Pb pollution 2.93 to 3.74 in all locations, and Ni pollution 1.00 to 1.14 excluding S10 and S11.

Tables 8 and 9 show that HQ_{ing}, HQ_{dermal}, and HQ_{inh} values were found to evaluate noncarcinogenic health risks in Pb and Ni. Reference doses for Pb have been taken from the WHO's (1993) Guidelines for Drinking Water Quality. The HI values of Pb were higher than those of Cu, Cr, Cd, and Ni for both

Table 5 Hazard quotient and risk for Cu in locations

Elements	Locations	Children				Adult				$LADD_{inh}$
		HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI	HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI	
Cu	S1	1.55E-01	1.78E-07	4.86E-05	1.55E-01	2.55E-02	1.03E-07	1.14E-05	2.55E-02	1.13E-01
	S2	1.42E-01	1.63E-07	4.44E-05	1.42E-01	1.17E-02	9.37E-08	1.04E-05	1.17E-02	1.03E-01
	S3	1.36E-01	1.56E-07	4.25E-05	1.36E-01	1.12E-02	8.98E-08	9.97E-06	1.12E-02	9.88E-02
	S4	1.42E-01	1.63E-07	4.45E-05	1.42E-01	1.17E-02	9.39E-08	1.04E-05	1.17E-02	1.03E-01
	S5	1.37E-01	1.57E-07	4.30E-05	1.37E-01	1.13E-02	9.07E-08	1.01E-05	1.13E-02	9.98E-02
	S6	1.38E-01	1.58E-07	4.32E-05	1.38E-01	1.13E-02	9.11E-08	1.01E-05	1.13E-02	1.00E-01
	S7	1.34E-01	1.53E-07	4.18E-05	1.34E-01	1.10E-02	8.83E-08	9.80E-06	1.10E-02	9.72E-02
	S8	1.38E-01	1.58E-07	4.32E-05	1.38E-01	1.13E-02	9.11E-08	1.01E-05	1.13E-02	1.00E-01
	S9	1.32E-01	1.52E-07	4.14E-05	1.32E-01	1.09E-02	8.75E-08	9.70E-06	1.09E-02	9.62E-02
	S10	1.82E-01	2.09E-07	5.70E-05	1.82E-01	1.50E-02	1.2E-07	1.33E-05	1.50E-02	1.32E-01
	S11	1.26E-01	1.45E-07	3.95E-05	1.26E-01	1.04E-02	8.34E-08	9.25E-06	1.04E-02	9.17E-02

Table 6 Hazard quotient and risk for Cr in locations

Elements	Locations	Children				Adult				$LADD_{inh}$
		HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI	HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI	
Cr	S1	2.54E-01	1.56E-06	6.10E-02	3.15E-01	4.38E-02	1.56E-06	6.10E-02	1.05E-01	7.08E-02
	S2	2.32E-01	1.43E-06	5.56E-02	2.87E-01	2.00E-02	1.43E-06	5.56E-02	7.56E-02	6.46E-02
	S3	2.24E-01	1.38E-06	5.38E-02	2.78E-01	1.93E-02	1.38E-06	5.38E-02	7.31E-02	6.25E-02
	S4	2.33E-01	1.44E-06	5.61E-02	2.89E-01	2.01E-02	1.44E-06	5.61E-02	7.62E-02	6.51E-02
	S5	2.27E-01	1.39E-06	5.44E-02	2.81E-01	1.95E-02	1.39E-06	5.44E-02	7.40E-02	6.32E-02
	S6	2.28E-01	1.4E-06	5.48E-02	2.83E-01	1.97E-02	1.4E-06	5.48E-02	7.45E-02	6.37E-02
	S7	2.22E-01	1.37E-06	5.34E-02	2.76E-01	1.92E-02	1.37E-06	5.34E-02	7.26E-02	6.20E-02
	S8	2.28E-01	1.4E-06	5.48E-02	2.83E-01	1.97E-02	1.4E-06	5.48E-02	7.45E-02	6.37E-02
	S9	2.20E-01	1.35E-06	5.28E-02	2.73E-01	1.90E-02	1.35E-06	5.28E-02	7.17E-02	6.13E-02
	S10	2.12E-01	1.3E-06	5.09E-02	2.63E-01	1.83E-02	1.3E-06	5.09E-02	6.92E-02	5.92E-02
	S11	2.10E-01	1.29E-06	5.05E-02	2.61E-01	1.81E-02	1.29E-06	5.05E-02	6.87E-02	5.87E-02

Table 7 Hazard quotient and risk for Cd in locations

Elements	Locations	Children				Adult				$LADD_{inh}$
		HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI	HQ_{ing}	HQ_{inh}	HQ_{dermal}	HI	
Cd	S1	1.60E+00	7.34E-07	6.01E-03	1.61E+00	2.55E+00	7.34E-07	1.37E-02	2.56E+00	1.16E-02
	S2	1.47E+00	6.74E-07	5.52E-03	1.48E+00	1.17E+00	6.74E-07	1.25E-02	1.18E+00	1.07E-02
	S3	1.40E+00	6.44E-07	5.28E-03	1.41E+00	1.12E+00	6.44E-07	1.20E-02	1.13E+00	1.02E-02
	S4	1.47E+00	6.74E-07	5.52E-03	1.48E+00	1.17E+00	6.74E-07	1.25E-02	1.18E+00	1.07E-02
	S5	1.44E+00	6.59E-07	5.40E-03	1.44E+00	1.13E+00	6.59E-07	1.21E-02	1.14E+00	1.05E-02
	S6	1.44E+00	6.59E-07	5.40E-03	1.44E+00	1.13E+00	6.59E-07	1.21E-02	1.14E+00	1.05E-02
	S7	1.37E+00	6.29E-07	5.16E-03	1.38E+00	1.10E+00	6.29E-07	1.18E-02	1.11E+00	9.98E-03
	S8	1.44E+00	6.59E-07	5.40E-03	1.44E+00	1.13E+00	6.59E-07	1.21E-02	1.14E+00	1.05E-02
	S9	1.37E+00	6.29E-07	5.16E-03	1.38E+00	1.09E+00	6.29E-07	1.16E-02	1.10E+00	9.98E-03
	S10	1.24E+00	5.7E-07	4.66E-03	1.25E+00	1.50E+00	5.7E-07	1.60E-02	1.51E+00	9.03E-03
	S11	1.31E+00	6E-07	4.91E-03	1.31E+00	1.04E+00	6E-07	1.11E-02	1.05E+00	9.50E-03

Table 8 Hazard quotient and risk for Pb in locations

Elements	Locations	Children				Adult				LADD$_{inh}$
		HQ$_{ing}$	HQ$_{inh}$	HQ$_{dermal}$	HI	HQ$_{ing}$	HQ$_{inh}$	HQ$_{dermal}$	HI	
Pb	S1	3.74E+00	2.72E-06	1.48E-03	3.74E+00	6.15E-01	2.72E-06	3.48E-04	6.15E-01	1.51E-01
	S2	3.42E+00	2.49E-06	1.36E-03	3.42E+00	2.81E-01	2.49E-06	3.18E-04	2.81E-01	1.38E-01
	S3	3.30E+00	2.4E-06	1.31E-03	3.30E+00	2.71E-01	2.4E-06	3.07E-04	2.71E-01	1.33E-01
	S4	3.43E+00	2.5E-06	1.36E-03	3.43E+00	2.82E-01	2.5E-06	3.19E-04	2.82E-01	1.39E-01
	S5	3.33E+00	2.42E-06	1.32E-03	3.33E+00	2.73E-01	2.42E-06	3.09E-04	2.74E-01	1.34E-01
	S6	3.33E+00	2.42E-06	1.32E-03	3.33E+00	2.74E-01	2.42E-06	3.10E-04	2.74E-01	1.34E-01
	S7	3.24E+00	2.36E-06	1.29E-03	3.24E+00	2.66E-01	2.36E-06	3.01E-04	2.66E-01	1.31E-01
	S8	3.33E+00	2.42E-06	1.32E-03	3.33E+00	2.74E-01	2.42E-06	3.10E-04	2.74E-01	1.34E-01
	S9	3.20E+00	2.33E-06	1.27E-03	3.20E+00	2.63E-01	2.33E-06	2.98E-04	2.64E-01	1.29E-01
	S10	2.93E+00	2.13E-06	1.16E-03	2.93E+00	2.41E-01	2.13E-06	2.73E-04	2.41E-01	1.18E-01
	S11	3.06E+00	2.23E-06	1.22E-03	3.06E+00	2.52E-01	2.23E-06	2.85E-04	2.52E-01	1.24E-01

Table 9 Hazard quotient and risk for Ni in locations

Elements	Locations	Children				Adult				LADD$_{inh}$
		HQ$_{ing}$	HQ$_{inh}$	HQ$_{dermal}$	HI	HQ$_{ing}$	HQ$_{inh}$	HQ$_{dermal}$	HI	
Ni	S1	1.14E+00	2.41E-07	7.52E-05	1.14E+00	1.82E-02	1.39E-07	1.89E-06	1.82E-02	7.86E-02
	S2	1.06E+00	2.25E-07	7.02E-05	1.06E+00	8.49E-03	1.3E-07	1.76E-06	8.49E-03	7.34E-02
	S3	1.03E+00	2.18E-07	6.82E-05	1.03E+00	8.24E-03	1.26E-07	1.71E-06	8.24E-03	7.13E-02
	S4	1.07E+00	2.27E-07	7.09E-05	1.07E+00	8.57E-03	1.31E-07	1.78E-06	8.57E-03	7.41E-02
	S5	1.04E+00	2.2E-07	6.86E-05	1.04E+00	8.29E-03	1.27E-07	1.72E-06	8.30E-03	7.18E-02
	S6	1.04E+00	2.2E-07	6.86E-05	1.04E+00	8.29E-03	1.27E-07	1.72E-06	8.30E-03	7.18E-02
	S7	1.02E+00	2.16E-07	6.75E-05	1.02E+00	8.16E-03	1.25E-07	1.69E-06	8.16E-03	7.06E-02
	S8	1.04E+00	2.2E-07	6.86E-05	1.04E+00	8.29E-03	1.27E-07	1.72E-06	8.30E-03	7.18E-02
	S9	1.00E+00	2.12E-07	6.64E-05	1.00E+00	8.02E-03	1.22E-07	1.67E-06	8.02E-03	6.94E-02
	S10	9.53E-01	2.02E-07	6.30E-05	9.53E-01	7.61E-03	1.16E-07	1.58E-06	7.61E-03	6.58E-02
	S11	9.67E-01	2.04E-07	6.39E-05	9.67E-01	7.72E-03	1.18E-07	1.60E-06	7.72E-03	6.68E-02

children and adults. Cu (1.26E-01–1.82E-01 for children) and Cr (2.61E-01–3.15 E-01 for children) were found to pose no risk for children and adults due to the HI values for Cu (1.00E-01–9.98E-02 for an adult), and Cr (5.87E-02–7.08E-02 for an adult) was lower than 1 in all sites. Although Pb, Ni, and Cd are not dangerous to adults, there appears to be a risk for Cd in children due to HI > 1. The HI values indicated that Cd, Pb, and Cr pollution should be paid more attention to, especially for children.

The findings revealed that the HI values for all the studied metals in all sites for children exceeded the HI > 1, indicating that Ni metal has considered a carcinogenic risk to children from exposure to road dust in Table 9.

In general, according to the table risk assessment results, it is seen that children face more risks than adults. From a causal perspective, similar results were obtained by Ferreira-Baptista and De Miguel (2005) and Hu et al. (2016) in a health risk assessment of heavy metals in street dust. The non-cancer risk of HQ$_{inh}$ and HQ$_{dermal}$ would pose a lower risk than HQ$_{ing}$. Thus, inhalation of resuspended particles through the mouth and nose is almost negligible compared with the other routes of exposure.

4 Discussion

The results of our study confirmed that the harmful effects of Cd, Cr, Cu, Ni, and Pb metals were found in high concentrations in road dust by adhering to PMs (PM_1, $PM_{2.5}$, and PM_{10}) in several areas. Particles are transported to the atmosphere due to the lack of periodic maintenance of the vehicles in the city, the removal of the fossil fuels they use without complete combustion, the abrasions in the engine parts, and the wear of the brake pads and tire particles (Yayla et al., 2022; Sulhan et al., 2023). Afterward, the rapid urbanization and economic development of the local urban ecosystem and citizens have increased the formation of toxic metals with their bioavailability and toxicity (Isinkaralar, 2023).

Then, its attachment to PM causes it to be transported and deposited with them. For the priority areas, emissions for heating purposes, using coal and fossil fuels, are seen as the main source in residential areas. In the industrial zone, according to the types of production, leakages from the process and the chimney are seen as sources of pollution. Toxic metals, which can be detected in areas such as dense residential areas and residential areas, adversely affect the health of all segments of society, including children at a high rate. If the exposure value of adults is compared with the exposure threshold value of children, it is seen that they accumulate more than adults (Wei et al., 2015). Numerous studies have investigated the relationship between heavy metal concentrations in road dust and health risk assessment by traffic activities (Duong & Lee, 2011; Hwang et al., 2016; Budai & Clement, 2018; Bartholomew et al., 2020). Khan and Shah (2023) collected topsoil from highways and roadsides to demonstrate metal content in Lahore soil during the winter of 2017 and summer of 2018. Their distribution was affected by anthropogenic inputs to assess the following trend during summer and winter. Heidari et al. (2021) also assessed the ecological and health risk in the road dust of Bandar Abbas City, Iran, for As, Cd, Co, Cr, Cu, Mn, Ni, Pb, and Zn. Source apportionment determined critical heavy metal source by the PMF model output into Monte Carlo simulation. They found that the ecological and health risk related to road dust polluted with heavy metals with leakage, fuel combustion, fertilizers, traffic emission, and others. Qadeer et al. (2020) studied Cu, Ni, Cd, Pb, and Zn in road dust of Lahore and Faisalabad in Pakistan. They found dominant metals in which Zn and Pb average values were 95.5 and 56.8 mg/kg in Lahore and 90.4 and 49.5 mg/kg in Faisalabad. Similar to our study, Pb was highest in S1 form industrial activities and indicated risk assessment exceeded the permissible limit. Rahman et al. (2019) collected 88 street dust which analyzed Pb, Cd, Zn, Cr, Ni, As, Mn, and Cu contents in samples of Dhaka City. Also, they calculated the hazard index on children and adults, and Cr (1.04) was a little more than the safe level one. There against, HI for Cr was observed to be lower than one in our study. This study indicated that ingestion of dust particles seems to be the major exposure route for Cd, Pb, and Ni to children considering non-cancer risk, which is similar to the reported findings by Kamani et al. (2017), Cai and Li (2019), and Zgłobicki et al. (2019). Broadly, our analysis provided that hand and mouth intake was the primary source of exposure way for both children and adults. This is consistent with the research of Zhaoyong et al. (2019) about the health risks of selected metals which performed a statistical analysis of As, Cu, Hg, Cd, Pb, Ni, Cr, Co, Zn, and Mn, which calculated hazard quotient (HQ), HI values, and the I_{geo} for 58 cities in 28 provinces of China between 2000 and 2018. They showed the ranges of heavy metals from 0.02 to 3407.2 mg/kg among the selected cities. In addition, the average values exceeded the background value for all metals due to the industries and traffic emissions.

The ADD_{ing} (mouth intake) values of Cu, Hg, Cd, Pb, Zn, As, Ni, Cr, Co, and Mn were determined for children > adults. The study by Sadeghdoust et al. (2020) was on human health risks and potential ecological risks for the toxic metals in street dust from Dezful, Iran. Thirty points were determined to investigate the metal uptake form ingestion > dermal contact > inhalation and found values from 0.4 to 224 mg/g depending on traffic and population density. A similar study was also accomplished by Xiao et al. (2020) on the human health risk of road dust samples. They used the carcinogenic risk (RI), HI, and HQ for toxic metals from anthropogenic activities. The Cd, Pb, Sb, and Zn were detected more in the samples than the environmental background values of Liaoning and China. Depending on different anthropogenic activities, some metals had strong correlations, such as Pb–Zn and Sn–Cu. By comparing other metals, Cd values were 10.9 times higher than background values with moderate to very high potential ecological risk. Roy et al. (2022) reviewed Pb, Zn, Cu, Ni, Cd, Cr, Mn, and Fe concentrations in road dust samples on a global scale. They compared the road dust pollution trend in samples from different continents and estimated potential ecological and human health risks. The review study has reported the contamination of heavy metals from several sources in many cities, which negatively impacts children and adults. Kabir et al. (2022) reported spatial distribution and contamination level of road dust for ecological and human health of toxic heavy metals in Kushtia district, Bangladesh. All collected dust samples were evaluated to represent the cancer risk with three main pathways: the HI and HQ. The spatial distribution maps showed that traffic, industrial, agricultural applications, and atmospheric deposition have continuously polluted road dust with heavy metals. The results showed that unplanned urbanization and industrialization might greatly emit toxic metals to ecological and human health due to increased traffic volume, industry, and population. The distribution of metals is also dominant in road dust from coal and fuel combustion of various activities and some metal planting industries and electroplating that continue to pollute aberrantly.

5 Conclusion

City centers are areas where emissions are dominated by vehicle density and dense populations are at risk. Therefore, health risk assessment in urban centers is a critical issue. Trace metals are among the components that make up air pollution for inhalable particulate matter. Our results confirm the adverse effects of toxic metals with road dust on the human health of motor vehicles, exhaust emissions, industrial leakage, geogenic influences, and anthropogenic activities. The concentrations of toxic metals in the road dust from the hot points depended on their spatial characteristics, such as residence and vehicle volume, wind condition, and atmospheric dispersion. Pb, Ni, and Cu concentrations were higher than background levels. They had a very high degree of motor vehicles with diesel exhaust emissions, brake abrasion, fuel combustion, tire wear, and the corrosion and demolition of vehicle pieces. Traffic status (density, emissions, vehicle speeds, fuel type, atmospheric conditions, and dispersion) were substantial factors in determining the pollution grade of heavy metals in road dust. Enhanced comprehensive investigations are required to confirm the probability of cancer risk due to long-term seasonal exposure to Pb Ni and Cu from road dust in the workspace.

Author Contribution Kaan Isinkaralar: conceptualization, software, writing original draft, processing analysis, interpretation, formal analysis. Oznur Isinkaralar: conceptualization, software, writing original draft, processing analysis, interpretation, formal analysis, review and editing. Emine Pirinç Bayraktar: processing analysis, interpretation, data curation, software, formal analysis, review and editing.

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

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

References

Ambade, B., Kumar, A., Kumar, A., & Sahu, L. K. (2022). Temporal variability of atmospheric particulate-bound polycyclic aromatic hydrocarbons (PAHs) over central east India: Sources and carcinogenic risk assessment. *Air Quality. Atmosphere & Health, 15*(1), 115–130. https://doi.org/10.1007/s11869-021-01089-5

Barsova, N., Yakimenko, O., Tolpeshta, I., & Motuzova, G. (2019). Current state and dynamics of heavy metal soil pollution in Russian Federation—A review. *Environmental Pollution, 249*, 200–207. https://doi.org/10.1016/j.envpol.2019.03.020

Bartholomew, C. J., Li, N., Li, Y., Dai, W., Nibagwire, D., & Guo, T. (2020). Characteristics and health risk assessment of heavy metals in street dust for children in Jinhua, China. *Environmental Science and Pollution Research, 27*(5), 5042–5055. https://doi.org/10.1007/s11356-019-07144-0

Budai, P., & Clement, A. (2018). Spatial distribution patterns of four traffic-emitted heavy metals in urban road dust and the resuspension of brake-emitted particles: Findings of a field study. *Transportation Research Part D: Transport and Environment, 62*, 179–185. https://doi.org/10.1016/j.trd.2018.02.014

Cai, K., & Li, C. (2019). Street dust heavy metal pollution source apportionment and sustainable management in a typical city—Shijiazhuang, China. *International Journal of Environmental Research and Public Health, 16*(14), 2625. https://doi.org/10.3390/ijerph16142625

Charzyński, P., Plak, A., & Hanaka, A. (2017). Influence of the soil sealing on the geoaccumulation index of heavy metals and various pollution factors. *Environmental Science and Pollution Research, 24*(5), 4801–4811. https://doi.org/10.1007/s11356-016-8209-5

Chenery, S., Sarkar, S. K., Chatterjee, M., Marriott, A. L., & Watts, M. J. (2020). Heavy metals in urban road dusts from Kolkata and Bengaluru, India: Implications for human health. *Environmental Geochemistry and Health, 42*(9), 2627–2643. https://doi.org/10.1007/s10653-019-00467-4

De Miguel, E., Iribarren, I., Chacon, E., Ordonez, A., & Charlesworth, S. (2007). Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). *Chemosphere, 66*(3), 505–513. https://doi.org/10.1016/j.chemosphere.2006.05.065

Deng, W., Li, X., An, Z., Yang, L., Hou, K., & Zhang, Y. (2017). Identification of sources of metal in the agricultural soils of the Guanzhong Plain, northwest China. *Environmental Toxicology and Chemistry, 36*(6), 1510–1516. https://doi.org/10.1002/etc.3704

Duong, T. T., & Lee, B. K. (2011). Determining contamination level of heavy metals in road dust from busy traffic areas with different characteristics. *Journal of Environmental Management, 92*(3), 554–562. https://doi.org/10.1016/j.jenvman.2010.09.010

Ferreira-Baptista, L., & De Miguel, E. (2005). Geochemistry and risk assessment of street dust in Luanda, Angola: A tropical urban environment. *Atmospheric Environment, 39*(25), 4501–4512. https://doi.org/10.1016/j.atmosenv.2005.03.026

Han, Q., Wang, M., Xu, X., Li, M., Liu, Y., Zhang, C., Li, S., & Wang, M. (2023). Health risk assessment of heavy metals in road dust from the fourth-tier industrial city in central China based on Monte Carlo simulation and bioaccessibility. *Ecotoxicology and Environmental Safety, 252*, 114627. https://doi.org/10.1016/j.ecoenv.2023.114627

Haynes, H. M., Taylor, K. G., Rothwell, J., & Byrne, P. (2020). Characterisation of road-dust sediment in urban systems: A review of a global challenge. *Journal of Soils and Sediments, 20*(12), 4194–4217. https://doi.org/10.1007/s11368-020-02804-y

Heidari, M., Darijani, T., & Alipour, V. (2021). Heavy metal pollution of road dust in a city and its highly polluted suburb; quantitative source apportionment and source-specific ecological and health risk assessment. *Chemosphere, 273*, 129656. https://doi.org/10.1016/j.chemosphere.2021.129656

Hou, S., Zheng, N., Tang, L., Ji, X., Li, Y., & Hua, X. (2019). Pollution characteristics, sources, and health risk assessment of human exposure to Cu, Zn, Cd and Pb pollution in urban street dust across China between 2009 and 2018. *Environment International, 128*, 430–437. https://doi.org/10.1016/j.envint.2019.04.046

Hu, X., Zhang, Y., Luo, J., Wang, T., Lian, H., & Ding, Z. (2011). Bioaccessibility and health risk of arsenic, mercury and other metals in urban street dusts from a mega-city, Nanjing, China. *Environmental Pollution, 159*(5), 1215–1221. https://doi.org/10.1016/j.envpol.2011.01.037

Hu, B., Liu, B., Zhou, J., Guo, J., Sun, Z., Meng, W., Guo, X., & Duan, J. (2016). Health risk assessment on heavy metals in urban street dust of Tianjin based on trapezoidal fuzzy numbers. *Human and Ecological Risk Assessment: An International Journal, 22*(3), 678–692. https://doi.org/10.1080/10807039.2015.1104625

Hwang, H. M., Fiala, M. J., Park, D., & Wade, T. L. (2016). Review of pollutants in urban road dust and stormwater runoff: Part 1. Heavy metals released from vehicles. *International Journal of Urban Sciences, 20*(3), 334–360. https://doi.org/10.1080/12265934.2016.1193041

Isinkaralar, K. (2022a). Atmospheric deposition of Pb and Cd in the Cedrus atlantica for environmental biomonitoring. *Landscape and Ecological Engineering*. https://doi.org/10.1007/s11355-022-00503-z

Isinkaralar, K. (2022b). Temporal variability of trace metal evidence in Cupressus arizonica, Platanus orientalis, and Robinia pseudoacacia as pollution-resistant species at an industrial site. *Water, Air, & Soil Pollution, 233*(7), 1–12. https://doi.org/10.1007/s11270-022-05743-1

Isinkaralar, O. (2023). Bioclimatic comfort in urban planning and modeling spatial change during 2020–2100 according to climate change scenarios in Kocaeli, Türkiye. *International Journal of Environmental Science and Technology, 20*(7), 7775–7786. https://doi.org/10.1007/s13762-023-04992-9

Isinkaralar, O., & Varol, C. (2023). A cellular automata-based approach for spatio-temporal modeling of the city center as a complex system: The case of Kastamonu, Türkiye. *Cities, 132*, 104073. https://doi.org/10.1016/j.cities.2022.104073

Isinkaralar, K., Koc, I., Erdem, R., & Sevik, H. (2022). Atmospheric Cd, Cr, and Zn deposition in several landscape plants in Mersin, Türkiye. *Water, Air, & Soil Pollution, 233*(4), 1–10. https://doi.org/10.1007/s11270-022-05607-8

Isinkaralar, K., Isinkaralar, O., Koç, İ., Özel, H. B., Şevik, H. (2023). Assessing the possibility of airborne bismuth accumulation and spatial distribution in an urban area by tree bark: A case study in Düzce, Türkiye. *Biomass Conversion and Biorefinery*, 1–12. https://doi.org/10.1007/s13399-023-04399-z

Istanbullu, S. N., Sevik, H., Isinkaralar, K., & Isinkaralar, O. (2023). Spatial distribution of heavy metal contamination in road dust samples from an urban environment in Samsun, Türkiye. *Bulletin of Environmental Contamination and Toxicology, 110*(4), 78. https://doi.org/10.1007/s00128-023-03720-w

Jia, X., Fu, T., Hu, B., Shi, Z., Zhou, L., & Zhu, Y. (2020). Identification of the potential risk areas for soil heavy metal pollution based on the source-sink theory. *Journal of Hazardous Materials, 393*, 122424. https://doi.org/10.1016/j.jhazmat.2020.122424

Jia, M., Zhou, D., Lu, S., & Yu, J. (2021). Assessment of foliar dust particle retention and toxic metal accumulation ability of fifteen roadside tree species: Relationship and mechanism. *Atmospheric Pollution Research, 12*(1), 36–45. https://doi.org/10.1016/j.apr.2020.08.003

Jiang, Y., Shi, L., Guang, A. L., Mu, Z., Zhan, H., & Wu, Y. (2018). Contamination levels and human health risk assessment of toxic heavy metals in street dust in an industrial city in Northwest China. *Environmental Geochemistry and Health, 40*(5), 2007–2020. https://doi.org/10.1007/s10653-017-0028-1

Kabir, M. H., Kormoker, T., Shammi, R. S., Tusher, T. R., Islam, M. S., Khan, R., Omor, M. Z. U., Sarker, M. E., Yeasmin, M., & Idris, A. M. (2022). A comprehensive assessment of heavy metal contamination in road dusts along a hectic national highway of Bangladesh: Spatial distribution, sources of contamination, ecological and human health risks. *Toxin Reviews, 41*(3), 860–879. https://doi.org/10.1080/15569543.2021.1952436

Kamani, H., Mahvi, A. H., Seyedsalehi, M., Jaafari, J., Hoseini, M., Safari, G. H., Dalvand, A., Aslani, H., Mirzaei, N., & Ashrafi, S. D. (2017). Contamination and ecological risk assessment of heavy metals in street dust of Tehran, Iran. *International Journal of Environmental Science and Technology, 14*, 2675–2682. https://doi.org/10.1007/s13762-017-1327-x

Kelly, F. J., & Fussell, J. C. (2019). Improving indoor air quality. health and performance within environments where people live. travel. learn and work. *Atmospheric Environment., 200*, 90–109. https://doi.org/10.1016/j.atmosenv.2018.11.058

Keshavarzi, B., Tazarvi, Z., Rajabzadeh, M. A., & Najmeddin, A. (2015). Chemical speciation, human health risk assessment and pollution level of selected heavy metals in urban street dust of Shiraz, Iran. *Atmospheric Environment, 119*, 1–10. https://doi.org/10.1016/j.atmosenv.2015.08.001

Khan, Y. K., & Shah, M. H. (2023). Sequential extraction of selected metals to assess their mobility, pollution status and health risk in roadside soil. *Environmental Monitoring and Assessment, 195*(5), 552. https://doi.org/10.1007/s10661-023-11129-5

Khpalwak, W., Jadoon, W. A., Abdel-Dayem, S. M., & Sakugawa, H. (2019). Polycyclic aromatic hydrocarbons in urban road dust, Afghanistan: Implications for human health. *Chemosphere, 218*, 517–526. https://doi.org/10.1016/j.chemosphere.2018.11.087

Kong, S., Lu, B., Ji, Y., Zhao, X., Bai, Z., Xu, Y., & Jiang, H. (2012). Risk assessment of heavy metals in road and soil dusts within PM 25, PM 10 and PM 100 fractions in Dongying city Shandong, Province, China. *Journal of Environmental Monitoring, 14*(3), 791–803. https://doi.org/10.1039/C1EM10555H

Krupnova, T. G., Rakova, O. V., Gavrilkina, S. V., Antoshkina, E. G., Baranov, E. O., & Yakimova, O. N. (2020). Road dust trace elements contamination, sources, dispersed composition, and human health risk in Chelyabinsk, Russia. *Chemosphere, 261*, 127799. https://doi.org/10.1016/j.chemosphere.2020.127799

Lima, L. H. V., do Nascimento, C. W. A., da Silva, F. B. V., Araújo, P. R. M. (2023). Baseline concentrations, source apportionment, and probabilistic risk assessment of heavy metals in urban street dust in Northeast Brazil. *Science of The Total Environment*, *858*, 159750. https://doi.org/10.1016/j.scitotenv.2022.159750

Lin, B., & Zhu, J. (2018). Changes in urban air quality during urbanization in China. *Journal of Cleaner Production, 188*, 312–321. https://doi.org/10.1016/j.jclepro.2018.03.293

Müller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. *The Journal of Geology, 2*, 108–118.

Qadeer, A., Saqib, Z. A., Ajmal, Z., Xing, C., Khalil, S. K., Usman, M., Huang, Y., Bashir, S., Ahmad, Z., Ahmed, S., Thebo, K. H., & Liu, M. (2020). Concentrations, pollution indices and health risk assessment of heavy metals in road dust from two urbanized cities of Pakistan: Comparing two sampling methods for heavy metals concentration. *Sustainable Cities and Society, 53*, 101959. https://doi.org/10.1016/j.scs.2019.101959

Qin, G., Niu, Z., Yu, J., Li, Z., Ma, J., & Xiang, P. (2021). Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. *Chemosphere, 267*, 129205. https://doi.org/10.1016/j.chemosphere.2020.129205

Rahman, M. S., Khan, M. D. H., Jolly, Y. N., Kabir, J., Akter, S., & Salam, A. (2019). Assessing risk to human health for heavy metal contamination through street dust in the Southeast Asian Megacity: Dhaka, Bangladesh. *Science of the Total Environment, 660*, 1610–1622. https://doi.org/10.1016/j.scitotenv.2018.12.425

Rajaram, B. S., Suryawanshi, P. V., Bhanarkar, A. D., & Rao, C. V. C. (2014). Heavy metals contamination in road dust in Delhi city, India. *Environmental Earth Sciences, 72*, 3929–3938. https://doi.org/10.1007/s12665-014-3281-y

Roy, S., Gupta, S. K., Prakash, J., Habib, G., & Kumar, P. (2022). A global perspective of the current state of heavy metal contamination in road dust. *Environmental Science and Pollution Research, 29*, 33230–33251. https://doi.org/10.1007/s11356-022-18583-7

Sadeghdoust, F., Ghanavati, N., Nazarpour, A., Babaenejad, T., & Watts, M. J. (2020). Hazard, ecological, and human health risk assessment of heavy metals in street dust in Dezful, Iran. *Arabian Journal of Geosciences, 13*, 1–14. https://doi.org/10.1007/s12517-020-05915-5

Salazar-Rojas, T., Cejudo-Ruiz, F. R., & Calvo-Brenes, G. (2023). Assessing magnetic properties of biomonitors and road dust as a screening method for air pollution monitoring. *Chemosphere, 310*, 136795. https://doi.org/10.1016/j.chemosphere.2022.136795

Shahab, A., Zhang, H., Ullah, H., Rashid, A., Rad, S., Li, J., & Xiao, H. (2020). Pollution characteristics and toxicity of potentially toxic elements in road dust of a tourist city, Guilin, China: Ecological and health risk assessment☆. *Environmental Pollution, 266*, 115419. https://doi.org/10.1016/j.envpol.2020.115419

Shahab, A., Hui, Z., Rad, S., Xiao, H., Siddique, J., Huang, L. L., Ullah, H., Rashid, A., Taha, M. R., Zada, N. (2022). A comprehensive review on pollution status and associated health risk assessment of human exposure to selected heavy metals in road dust across different cities of the world. *Environmental Geochemistry and Health*, 1–22. https://doi.org/10.1007/s10653-022-01255-3

Sulhan, O. F., Sevik, H., & Isinkaralar, K. (2023). Assessment of Cr and Zn deposition on Picea pungens Engelm in. urban air of Ankara, Türkiye. *Environment, Development and Sustainability, 25*(5), 4365–4384. https://doi.org/10.1007/s10668-022-02647-2

Sutherland, R. A. (2000). Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. *Environmental*

Geology, 39(6), 611–627. https://doi.org/10.1007/s002540050473

Tang, Z., Chai, M., Cheng, J., Jin, J., Yang, Y., Nie, Z., Huang, Q., & Li, Y. (2017). Contamination and health risks of heavy metals in street dust from a coal-mining city in eastern China. *Ecotoxicology and Environmental Safety, 138*, 83–91. https://doi.org/10.1016/j.ecoenv.2016.11.003

US Environmental Protection Agency (EPA) (1989) US EPA Risk Assessment Guidance for Superfund, Vol I: Human Health Evaluation Manual. EPA/540/1–89/002 Office of Solid Waste and Emergency Response, Washington.

US Environmental Protection Agency (EPA) (1995) Method 3052: Microwave assisted acid digestion of siliceous and organically based matrices. In USEPA-SW-846 (Ed.). Test methods for evaluating solid waste (3rd ed.). Washington. DC: US Environmental Protection Agency.

US Environmental Protection Agency (EPA) (1996) Soil screening guidance: Technical background document. Office of Solid Waste and Emergency Response (EPA/540/R-95/128).

US Environmental Protection Agency (EPA) 2002 Supplemental guidance for developing soil screening levels for superfund sites. OSWER 9355. 4–24. Office of Emergency and Remedial Response, Washington.

Wang, X., Liu, E., Lin, Q., Liu, L., Yuan, H., & Li, Z. (2020). Occurrence, sources and health risks of toxic metal (loid) s in road dust from a mega city (Nanjing) in China. *Environmental Pollution, 263*, 114518. https://doi.org/10.1016/j.envpol.2020.114518

Wei, B., Jiang, F., Li, X., & Mu, S. (2010). Contamination levels assessment of potential toxic metals in road dust deposited in different types of urban environment. *Environmental Earth Sciences, 61*(6), 1187–1196. https://doi.org/10.1007/s12665-009-0441-6

Wei, X., Gao, B., Wang, P., Zhou, H., & Lu, J. (2015). Pollution characteristics and health risk assessment of heavy metals in street dusts from different functional areas in Beijing, China. *Ecotoxicology and Environmental Safety, 112*, 186–192. https://doi.org/10.1016/j.ecoenv.2014.11.005

Wei, Z., Van Le, Q., Peng, W., Yang, Y., Yang, H., Gu, H., Lam, S. S., & Sonne, C. (2021). A review on phytoremediation of contaminants in air, water and soil. *Journal of Hazardous Materials, 403*, 123658. https://doi.org/10.1016/j.jhazmat.2020.123658

World Health Organization (1993) WHO Guidelines for Drinking Water Quality (second ed), Recommendations, vol. I, WHO, Geneva.

World Health Organization, (2013). Health risks of air pollution in Europe—HRAPIE: Recommendations of concentration-response functions for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide. World Health Organization. Retrieved from http://www.euro.who.int.

Xiao, Q., Zong, Y., Malik, Z., & Lu, S. (2020). Source identification and risk assessment of heavy metals in road dust of steel industrial city (Anshan), Liaoning, Northeast China. *Human and Ecological Risk Assessment: An International Journal, 26*(5), 1359–1378. https://doi.org/10.1080/10807039.2019.1578946

Yayla, E. E., Sevik, H., & Isinkaralar, K. (2022). Detection of landscape species as a low-cost biomonitoring study: Cr, Mn, and Zn pollution in an urban air quality. *Environmental Monitoring and Assessment, 194*(10), 687. https://doi.org/10.1007/s10661-022-10356-6

Zgłobicki, W., Telecka, M., & Skupiński, S. (2019). Assessment of short-term changes in street dust pollution with heavy metals in Lublin (E Poland)—Levels. sources and risks. *Environmental Science and Pollution Research, 26*(34), 35049–35060. https://doi.org/10.1007/s11356-019-06496-x

Zhang, Y., Hu, X., & Yu, T. (2012). Distribution and risk assessment of metals in sediments from Taihu Lake, China using multivariate statistics and multiple tools. *Bulletin of Environmental Contamination and Toxicology, 89*, 1009–1015. https://doi.org/10.1007/s00128-012-0784-7

Zhao, H., & Li, X. (2013). Understanding the relationship between heavy metals in road-deposited sediments and washoff particles in urban stormwater using simulated rainfall. *Journal of Hazardous Materials, 246*, 267–276. https://doi.org/10.1016/j.jhazmat.2012.12.035

Zhaoyong, Z., Mamat, A., & Simayi, Z. (2019). Pollution assessment and health risks evaluation of (metalloid) heavy metals in urban street dust of 58 cities in China. *Environmental Science and Pollution Research, 26*, 126–140. https://doi.org/10.1007/s11356-018-3555-0

Zheng, N., Liu, J., Wang, Q., & Liang, Z. (2010). Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China. *Science of the Total Environment, 408*(4), 726–733. https://doi.org/10.1016/j.scitotenv.2009.10.075

Zhu, Z., Sun, G., Bi, X., Li, Z., & Yu, G. (2013). Identification of trace metal pollution in urban dust from kindergartens using magnetic, geochemical and lead isotopic analyses. *Atmospheric Environment, 77*, 9–15. https://doi.org/10.1016/j.atmosenv.2013.04.053