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Geochemistry and health risk assessment of heavy metals pollution in urban dust of Sarvestan, Southern Iran

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Abstract
Urban dust is a significant source of heavy metals (HMs) pollution in urban areas, posing potential health risks to humans through inhalation, dermal absorption, and ingestion during long-term exposure. This study evaluates HMs pollution and human health risk assessment in urban street dust from Sarvestan city, located southeast of Shiraz in southern Iran. Street dust samples from ten stations were analyzed for HMs concentrations using ICP-OES. According to the grain size particle analysis, 12% of the particles were finer than 10 micrometers, indicating a high risk for silicosis. The mean concentrations of arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), copper (Cu), nickel (Ni), and zinc (Zn) were 3.46, 0.37, 43.4, 74.5, 92.3, 48.7, and 191.5 ppm, respectively. The geo-accumulation index (Igeo) and enrichment factor (EF) indicated a moderate level of pollution for Cd and a high level of enrichment for Cd, Pb, and As. The potential ecological risk factor (Er) showed the following decreasing order: Cd > As > Pb > Cu > Zn > Ni > Cr in Sarvestan street dust. The potential ecological risk index (RI) suggested a moderate risk based on the Er values of HMs. The non-carcinogenic risk/hazard index (HI) for children was within the acceptable range and higher than that for adults. The mean inhalation carcinogenic risk (Inh CR) value for both children and adults was negligible ($<1\times10^{-6}$). Children are particularly vulnerable to heavy metal exposure due to their lower body weight, higher inhalation and ingestion rates per unit body weight, hand-to-mouth behavior, and developing organ systems. This can lead to impaired cognitive development, neurological damage, and increased susceptibility to chronic diseases later in life. Therefore, assessing health risks specifically for children is not only crucial but also a priority in public health studies. This study, being the first of its kind in Sarvestan, aims to fill this critical knowledge gap by providing a quantitative health risk assessment for both children and adults, which is essential for formulating targeted public health policies and remediation strategies in this industrially developing region.

Keywords: Street dust, Heavy metals, Human health risk, Sarvestan.

Introduction

Dust, as a natural phenomenon in arid and semi-arid regions such as the Middle East and Iran, may have negative effects on human health, especially in urban areas. The dust phenomenon has widespread impacts on oceanic and terrestrial systems, global biochemical cycles, climate processes and air chemistry, air pollution, and human health (Engelbrecht & Derbyshire, 2010). Dust storms are different from air pollution caused by urban and industrial activities, which is a temporary and regional feature. Wind erosion plays a major role in the production of dust storms and occurs when strong, persistent winds are accompanied by erosion of dry, fine-grained, and loose soil. (Li et al., 2004; Yigiterhan et al., 2018). Dust particles are colloidal particles or larger, suspended in the air, and harmful to human health and other living organisms

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(McMurry et al., 2000).

Dust particles may have a wide range of compounds and elements depending on the source and route of transmission. Prolonged exposure to dust particles can cause lung and respiratory diseases such as pneumoconiosis (Godoi et al., 2008), as well as damage to the central nervous system, kidneys, liver, blood and even death (Wei et al., 2015).

Fine dust particles with high specific surface area is considered as a source of heavy metals (HMs) pollution. In addition, the effects of particle shape and mineralogy on the health has been highly considered (Wang et al., 2020). The dust mineralogy may lead to identification of the dust particles sources (Karimian Torghabeh et al., 2019). Heavy metals attached to dust can enter the human body through inhalation (inh), ingestion (ing) and dermal contact (derm).

Numerous studies have been conducted on urban dust and its effects on human health in Iran and around the world (Behravesh et al., 2015; Isinkaralar et al., 2024; Qader et al., 2026).

Among the studies conducted in Iran, dust in Khuzestan province, located in southwestern Iran and in vicinity of the studied province (Fars), has been considered as an environmental problem for several decades and its origin has been attributed to Iran's western neighbor, Iraq (Ghanavati, 2018). Despite numerous studies in the southwest of Iran, only a limited number of studies have been conducted in the south of Iran (Keshavarzi et al., 2015 on Shiraz street dust; Karimian Torghabeh et al., 2019 on Shiraz atmospheric dust), so in this study, Sarvestan region in the south of Iran is studied for the first time.

The aims of this study are to 1) determine HMs concentration in street dust samples collected from Sarvestan city in south Iran, 2) evaluate the pollution level of HMs using geo-accumulation index (I_{geo}) and enrichment factor (EF), and 3) assess the ecological and human health risk of HMs.

Geographical Location and Geology of the Study Area

Sarvestan city is located 80 km southeast of Shiraz in southern Iran (longitude: 53° 13'; latitude: 29° 17'; altitude: 1500 m). This city is located in the Sarvestan Plain and has an arid to semi-arid climate, low average rainfall, and high evaporation. Geologically, the region is located in the Zagros plain folded zone, and the surrounding rock units mainly consist of carbonate rocks, marls, and Quaternary alluvial sediments (Aghanabati, 2004). Sarvestan is in a relatively mountainous region between parallel mountain ranges in the South Zagros. The plain is generally covered by muddy deposits and partly by Quaternary alluvial sediments. The lithology of the Sarvestan region mainly comprises sedimentary rocks such as limestone and sandstone. In terms of climate conditions, this city is located between hot-dry and hot-humid regions.

Sarvestan, with a population of about 55,000 people and an area of 3,300 square kilometers, is one of the oil-rich areas of Fars Province (Figure 1 a and b). In recent years, the issue of oil exploitation in this region has become more significant. Currently, the National Drilling Company of Iran is drilling seven expansion wells in the Sarvestan and Saadat Abad oil fields. It is reported that three wells will be drilled in Sarvestan and four in Saadat Abad. Consequently, this city is affected by the production and transportation of oil and gas from the wells, which can contribute to pollution.

Materials and Methods

Dust Sampling

There are several methods for example glass trays (Karimian Torghabeh et al., 2020) and Siphon dust sampler (Rashki et al., 2012) for sampling dust. In this study, based on surveys and available maps, street dust sampling in Sarvestan city was conducted in October 2018 from ten relatively high-traffic locations, such as highway sides and gas stations. The samples were collected using clean brushes and plastic bags, and the tools used for each sample were washed with distilled water.

Chemical and Mineralogical Analysis of Dust Samples

The dust samples were passed through a 230-mesh sieve, and particles smaller than 63 micrometers were completely digested in a mixture of nitric acid, hydrochloric acid, and hydrofluoric acid. Particles smaller than 100 micrometers are easily suspended and can be inhaled through the nose or mouth (Ferreira-Baptista & De Miguel, 2005). After digestion, the sample solutions were sent to ZarAzma Company in Tehran for heavy metals concentration analysis using ICP-OES (Agilent model 735, United States).

Calculation of different environmental Indices

In this study, the potential ecological risk index (RI), geo-accumulation index (Igeo), enrichment factor (EF), and non-carcinogenic and carcinogenic risk indices of seven heavy metals (As, Cd, Cr, Cu, Ni, Pb, and Zn) were calculated in ten street dust samples from Sarvestan city.

Geo-accumulation index (I_{geo}); The I_{geo} is used to determine the level of pollution and to differentiate the impact of anthropogenic factors from natural ones, was first introduced by Müller (1969). This index is calculated from the following equation:

$$I_{geo} = \log_2(C_n/1.5B_n) \quad \text{(Müller, 1969)} \quad (1)$$

In which, C_n is the measured element concentration in the dust sample and B_n is the concentration of the element in the background. In this study, the average concentration of elements in the Upper Continental Crust (Taylor and McLennan., 1995) was used as the background concentration. A coefficient of 1.5 is also used to correct the effects of parent materials, and natural and anthropogenic fluctuations. This index is divided into seven levels such as $I_{geo} \leq 0$, uncontaminated (class 1); $0 < I_{geo} < 1$, uncontaminated to moderately contaminated (class 2); $1 < I_{geo} < 2$, moderately contaminated (class 3); $2 < I_{geo} < 3$, moderately to heavily contaminated (class 4); $3 < I_{geo} < 4$, heavily contaminated (class 5); $4 < I_{geo} < 5$, heavily to extremely contaminated (class 6); $5 \leq I_{geo}$, extremely contaminated (class 7) (Mullar, 1969) (Supplementary table 1).

Table 1. The factors that used for calculating human health risk in this study

Parameter	Unite	Children	Adults	References
IngR	mg/day	200	100	USEPA (2002)
InhR	m^3/day	7.6	20	USEPA (2002)
CF	kg/mg	1×10^{-6}	1×10^{-6}	
EF	day/year	365	365	Ferreira-Baptista & De Miguel (2005)
ED	year	6	24	Ferreira-Baptista & De Miguel (2005)
BW	kg	15	70	USEPA (2002)
AT	day	ED×365 70×365	ED×365 70×365	USEPA (1989)
PEF	m^3/kg	1.36×10^9	1.36×10^9	USEPA (2002)
SA	cm^2	2800	5700	USEPA (2002)
SL	$mg/cm^2.h$	0.2	0.07	USEPA (2002)
ABS	unitless	0.001	0.001	USEPA (2011)

Supplementary Table 1. Grades of EF, Igeo, E^i_r and RI

EF value	Degree of enrichment	Igeo class	Contamination level	E^i_r	Grads	RI	Ecological risk index
<2	minimal enrichment	<0	uncontaminated	< 40	low	<150	low
2-5	moderate enrichment	0-1	uncontaminated to moderately contaminated	40 – 80	moderate	150 – 300	moderate
5-20	significant enrichment	1-2	moderately contaminated	80 – 160	considerable	300 – 600	high
20-40	very highly enriched	2-3	moderately to heavily contaminated	160 – 320	high	≥ 600	very high
>40	extremely high enriched	3-4	heavily contaminated	≥ 320	very high		
		4-5	heavily to extremely contaminated				
		>5	extremely contaminated				

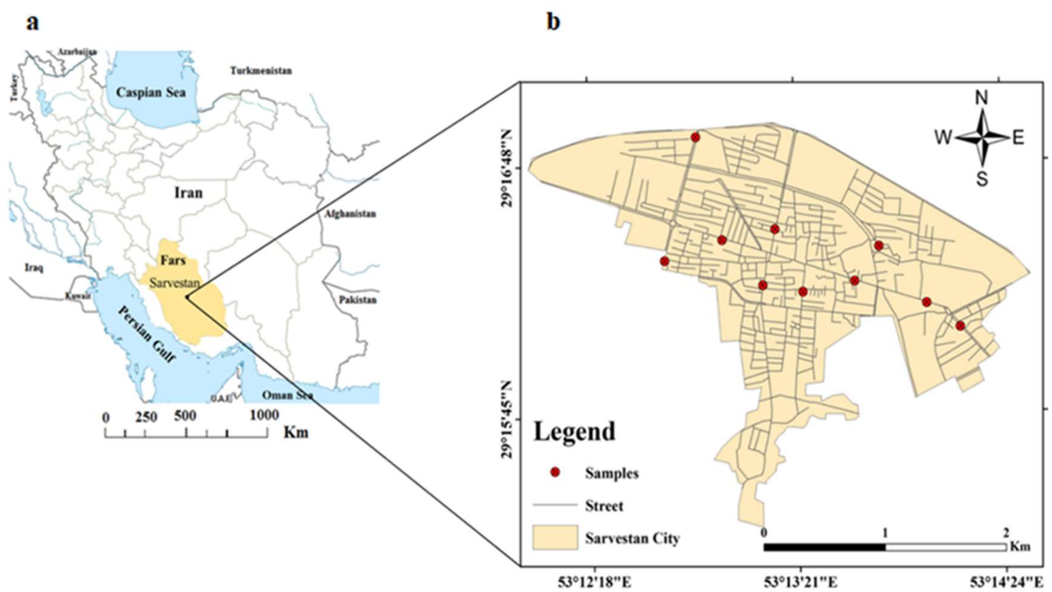

Figure 1. The map shown Fars province location (a) and points of street urban dust samples from Sarvestan city (b)

Enrichment factor (EF); This factor is used widly for environmental studies to determine the degree of HMs enrichment suggested by Buat-Menard and Chiselt in 1979 (Loska et al., 2003; Karimian Torghabeh et al., 2019; Taheri et al., 2021). The EF is calculated by the following equation:

$$EF= [C_n \text{ (sample)}/C_{ref} \text{ (sample)}]/[B_n \text{ (background)}/B_{ref} \text{ (background)}] \quad (2)$$

(Buat-Menard and Chiselt, 1979)

In which, C_n is the target element concentration in the dust sample, C_{ref} is the reference element concentration in the dust sample; B_n is the concentration of the element in the background content and B_{ref} is the concentration of the reference element in the background content. In this study, the Fe was considered as the reference element because it is more stable than other elements. The average concentration of elements in the Upper Continental Crust (Taylor & McLennan, 1995) has also been used as the background concentration. Enrichment factor (EF) values are divided into five levels such as EF≤2, minimal enrichment; EF=2–5, moderate enrichment; EF=5–20, significant enrichment; EF=20–40, very highly enriched and 40≥EF extremely high enriched (Buat-Ménard & Chesselet, 1979) (Supplementary table 1).

Calculation of ecological risk index; To calculate the potential ecological risk index (PERI, or RI) of HMs for the dust of Sarvestan city, three equations (Hakanson, 1980) were used as following:

$C^i{}_f = C^i{}_d / C^i{}_r$ (Hakanson, 1980) (3)

$E^i{}_r = T^i{}_r \times C^i{}_f$ (Hakanson, 1980) (4)

$RI = \Sigma E_r^i$ (Hakanson, 1980) (5)

In which, $C^i{}_f$ is the contamination factor for the considered HMs of dust sample, $C^i{}_d$ is the measured metal concentration, $C^i{}_r$ is the heavy metals background concentration, E_r^i is the potential ecological risk factor of each element, $T^i{}_r$ is the HMs toxicity factor (As=10, Cd=30, Cr=2, Cu=5, Ni=2, Pb=5 and Zn=1) (Hakanson, 1980; Luo et al., 2021), and RI is a risk index for all HMs. Hakanson (1980) presented $E_r^i < 40$, $40 \leq E_r^i < 80$, $80 \leq E_r^i < 160$, $160 \leq E_r^i < 320$ and $E_r^i \geq 320$ refer to low, moderate, considerable, high and very high potential ecological risk. Also, based on Hakanson (1980), RI<150 indicates low ecological risk; 150≤RI<300 is moderate; 300 ≤ RI < 600 refers to considerable and RI ≥ 600 very high ecological risk (Supplementary table 1).

calculation of health risk assessment; In this study, carcinogenic and non-carcinogenic risk assessment of exposure to HMs were performed based on method provided by the "US Environmental Protection Agency" (USEPA).

The people exposure to HMs is through three exposure routes (E) including ingestion, inhalation, and dermal contact. Average daily dose (ADD) of As, Cd, Pb, Cr, Ni, Zn, Cu elements via three routes were calculated using Equations 6 to 8.

$$ADD_{ing.} = \frac{C.IngR.CF.EF.ED}{BW.AT}$$ USEPA, 2002 and 1989 (6)

$$ADD_{inh.} = \frac{C.InhR.EF.\ ED}{PEF.\ BW.AT}$$ USEPA, 2002 and 1989 (7)

$$ADD_{derm.} = \frac{C.SA.CF.SL.ABS.EF.ED}{BW.AT}$$ USEPA, 2002 and 1989 (8)

Where, $ADD_{ing.}$, $ADD_{inh.}$ and $ADD_{derm.}$ are the mean daily absorption of metals (mg/kg.day) through swallowing, inhalation and dermal contact, respectively. The C represents the concentration of HMs in the dust (mg/kg), IngR is the rate of ingestion (mg/day) and InhR is the rate of inhalation (m^3/day). The CF represents conversion factor (kg/mg), EF is frequency of metal exposure (day/year); ED is duration of HMs exposure (year); BW is body weight of a person exposed to metals (kg); AT is average time of exposure to HMs (day), SA is the skin surface area exposed to dust (cm^2); SL is skin adhesion factor (mg/cm^2.day) and ABS is skin absorption factor (Table 1).

To determine non-carcinogenic risk, hazard quotient (HQ) for each element and exposure route and hazard index (HI) for all routes were calculated using equations 9 and 10.

$$HQ_E = \frac{AAD_E}{RfD}$$ (USEPA, 2002; Ferreira-Baptista and De Miguel, 2005) (9)

$$HI = \Sigma HQ_{ing+inh+der.}$$ (USEPA, 2002; Ferreira-Baptista and De Miguel, 2005) (10)

Where E refers to exposure route and RfD represents the reference dose of HMs for exposure routes (Supplementary table 3). This dose is determined by considering the children as a sensitive group. HQ is the amount of non-carcinogenic risk for an individual element in each uptake pathways. HI is an indicator of the non-carcinogenic risk for all three exposure pathways.

If the HQ > 1, there is concern about the potential non-carcinogenic risk.

Inhalation carcinogenic risk (Inh CR) for the HMs and exposure routs were calculated using equation 11.

$$InhCR_e = ADD_e.SF$$ USEPA, 2002 (11)

Cancer slope factor (SF) (mg/kg.day) for each metal provided in Supplementary table 1 (Qadeer et al., 2019). The USEPA sets the threshold for CR factor at 1×10^{-6} (USEPA, 2002; Ferreira-Baptista & De Miguel, 2005; Karimian Torghabeh et al., 2019).

Results and Discussion

HMs Concentration in Street Dust of Sarvestan City

The statistical summary of HMs (As, Cd, Cr, Pb, Cu, Ni, Zn) concentrations in Sarvestan street dust samples is shown in Table 2. The HMs concentrations in the samples varied from 2.7 to 4.4, with a mean (±SD) of 3.46 (0.61) for As, 0.33 to 0.44 with a mean of 0.37 (0.02) for Cd, 27 to 57 with a mean of 43.4 (8.65) for Cr, 13 to 176 with a mean of 74.5 (47.49) for Pb, 15 to 481 with a mean of 92.3 (132.82) for Cu, 32 to 63 with a mean of 48.7 (8.72) for Ni, and 54 to 352 with a mean of 191.5 (85.08) for Zn. Based on the median value, the decreasing order of HMs is as follows: Zn > Pb > Cu > Ni > Cr > As > Cd (Table 2 and Figure 2). The mean values of HMs in Sarvestan street dust were higher than the Upper Continental Crust (Taylor & McLennan, 1995; Keshavarzi et al., 2015; Isinkaralar et al., 2024).

The high levels of HMs in Sarvestan street dust can be attributed to anthropogenic activities such as vehicular traffic, construction, and industrial activities. Table 2 presents a comparison of the concentrations of HMs in this study area with those in Shiraz and other parts of the world. Figure 3 also shows the Concentration of HMs at sampling stations in Sarvestan city.

Table 2. Statistical summary of the HMs concentration in dust samples of Sarvestan city (mg/kg) and the mean value of HMs in other places street/road dust

Statistical parameter	Place	As	Cd	Cr	Pb	Cu	Ni	Zn	References
Min	Sarvestan (Iran)	2.7	0.33	27	13	15	32	54	This Study
Max		4.4	0.44	57	176	481	63	352	
Mean		3.46	0.37	43.4	74.5	92.3	48.7	191.5	
Median		3.65	0.38	45.5	67	47	48	210	
SD±		0.61	0.02	8.65	47.49	132.82	8.72	85.08	
Mean	Background (UCC)	1.5	0.098	35	20	25	44	71	Taylor & McLennan, 1995
	Shiraz (Iran)	6.58	0.5	67.16	115.71	136.34	77.52	403.46	Keshavarzi et al., 2015
	Mashhad (Iran)	-	-	47.37	133.12	68.36	105.37	254.34	Behravesh et al., 2015
	Tehran (Iran)	5.63	0.92	-	110.27	182.89	-	370.97	Taghavi et al., 2019
	Ahvaz (Iran)	6	0.3	57	86	45	58	999	Kianpor et al., 2019
	Dezful (Iran)	3	0.4	44	54	51	46	224	Sadeghdoust et al., 2020
	Rasht (Iran)	-	2.06	-	822.1	-	99.9	712.2	Alinia-Ahandani et al., 2021
	Birjand (Iran)	6.11	-	1.04	16.93	-	-	5.55	Farahi et al., 2024

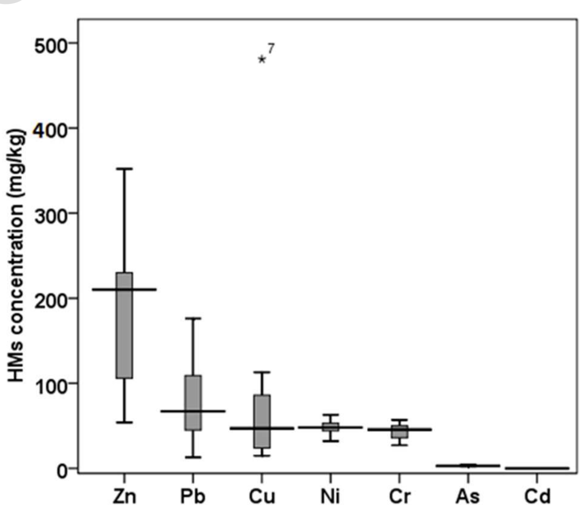

Figure 2. The box plot of HMs concentration in Sarvestan urban dust samples

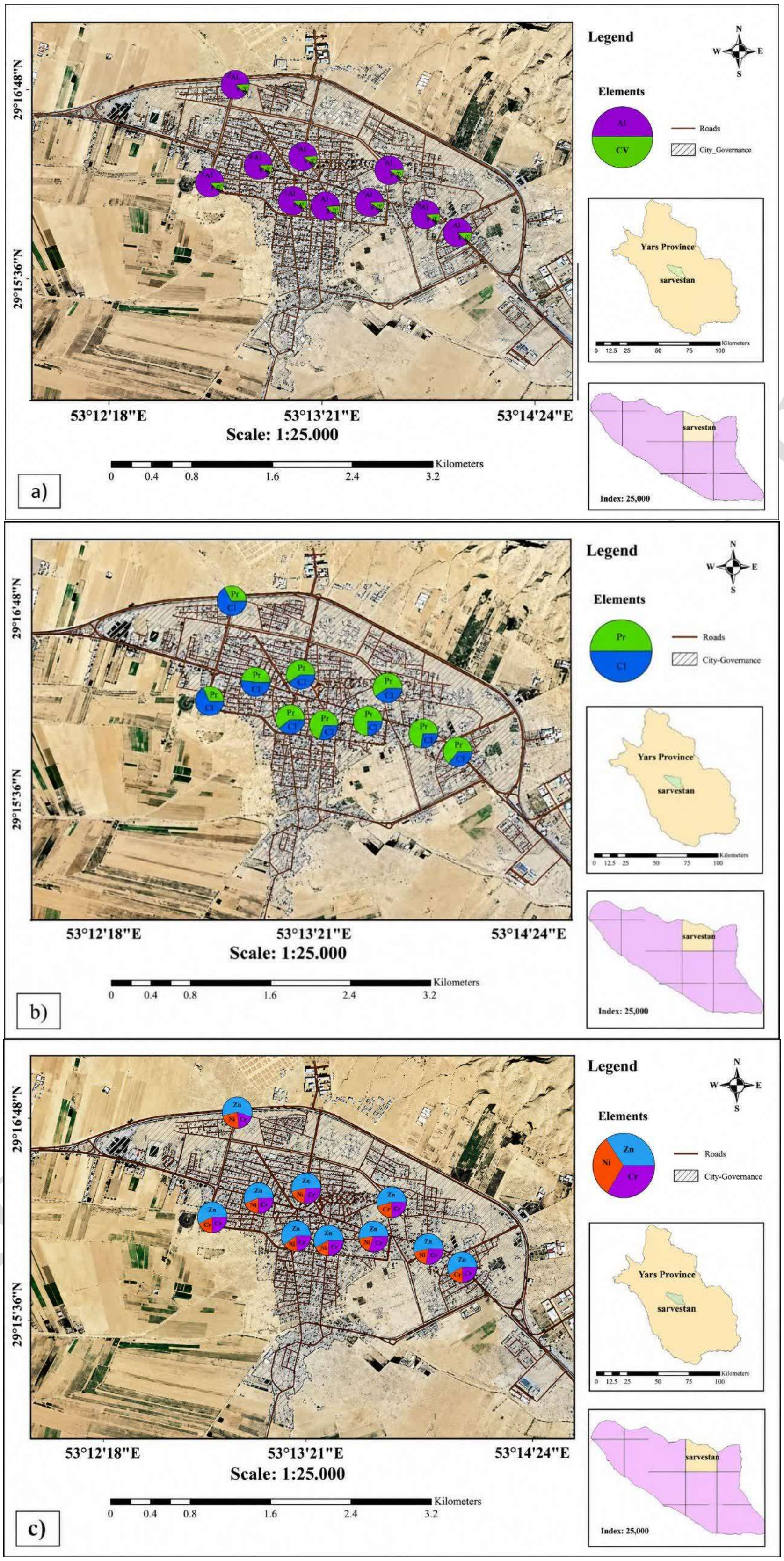

Figure 3. Concentration of HMs at sampling stations in Sarvestan city, a) As & Cd, b) Pb & Cr, c) Cu & Ni & Zn

Table 2 compares the concentration of heavy metals in different regions and their background values. Although the mean values of HMs in Sarvestan street dust were higher than the Upper Continental Crust, they were lower than those in large cities such as Tehran (Taghavi et al., 2019), Mashhad (Behravesh et al., 2015), and Shiraz (Keshavarzi et al., 2015). Interestingly, the Cu concentration in Sarvestan dust (10 stations) was higher than in some cities (Table 2). The source of the elevated Cu levels at these stations requires further discussion. The presence of an oil extraction company near Sarvestan, a city with a lower population and traffic compared to large cities like Tehran and Shiraz, could be a primary source of HMs entering the air and accumulating in street dust.

Additionally, given the proximity of battery manufacturing and automobile repair industries to Station 10, very high levels of heavy metals such as Cu, Pb, Cr, and As can be attributed to these industries (Sabouhi et al., 2016; Olaoye et al., 2016; Menkiti et al., 2017).

Geo-Accumulation Index (Igeo) and Enrichment Factor (EF);

The Igeo values in the studied dust samples were calculated based on the relevant equation. The results indicate that Cd has the highest average Igeo compared to other studied elements and represents a medium level of contamination based on the classification in Figure 4 (a: As, b: Cd, c: Cr, d: Pb, e: Cu, f: Ni, g: Zn). The elements As, Pb, Cu, and Zn exhibit unpolluted to moderately polluted levels, while Cr and Ni indicate an unpolluted status (Figure 4 and 5).

The bar graph of EF mean values for HMs is illustrated in Figure 6 and 7a. The highest mean EF value was observed for Cd, followed by Pb and As, which showed high enrichment. The EF mean values for Cr and Zn indicated moderate enrichment, while Cu and Ni exhibited minimal enrichment. In urban areas, Cd pollution is primarily associated with motor vehicles (Ghanavati, 2018), urban transportation, and smelting industries (Cui et al., 2019; Delgado-Iniesta et al., 2022; Rehman et al., 2025; Nazzal et al., 2025) (Figure 6 and 7a).

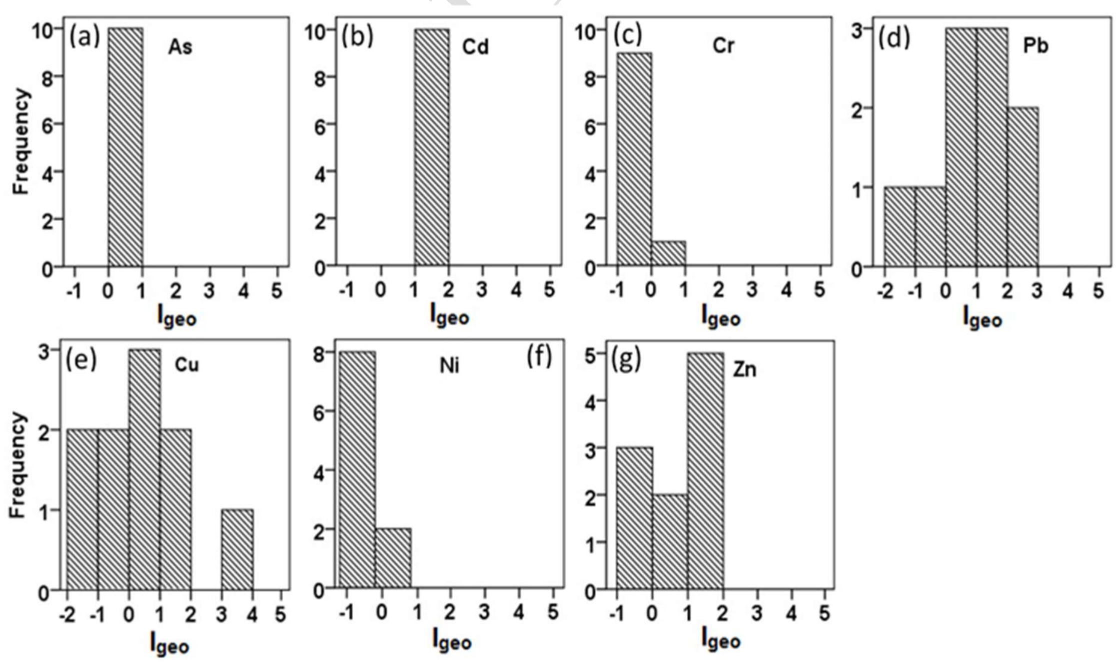

Figure 4. Histogram of HMs I_{geo} (a: As, b: Cd, c: Cr, d: Pb, e: Cu, f: Ni and g: Zn) levels in the street dust sample. In the x axis, $I_{geo} \leq 0$= uncontaminated (class 1); $0 < I_{geo} < 1$= uncontaminated to moderately contaminated (class 2); $1 < I_{geo} < 2$= moderately contaminated (class 3); $2 < I_{geo} < 3$= moderately to heavily contaminated (class 4); $3 < I_{geo} < 4$= heavily contaminated (class 5)

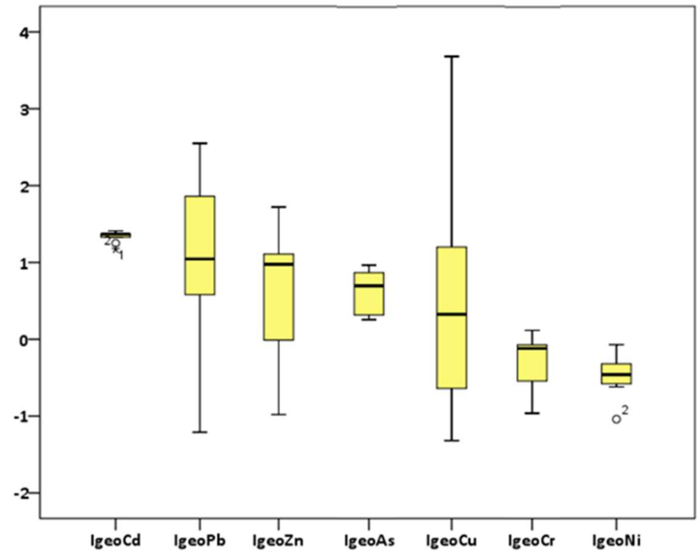

Figure 5. Box plot of Geo-accumulation index

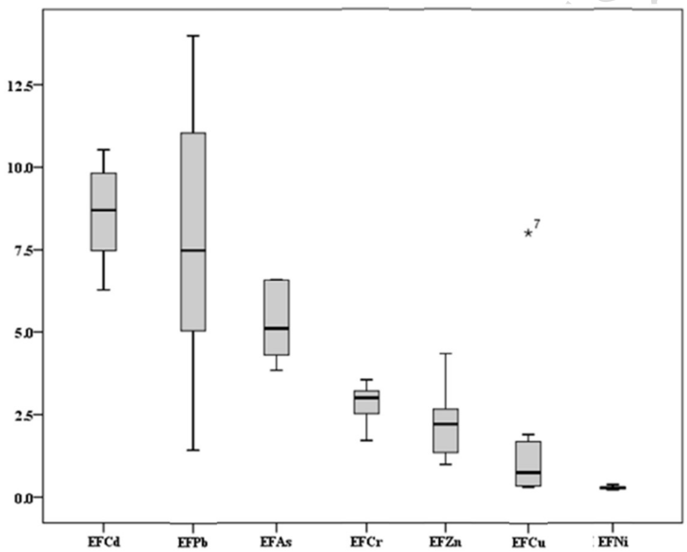

Figure 6. Box plots of Enrichment Factor

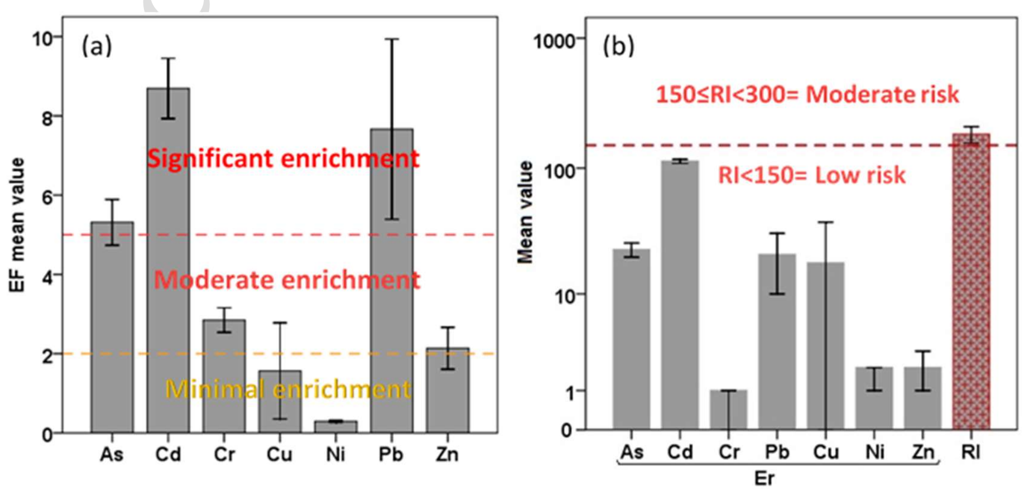

Figure 7. The bar graphs of EF (a), Er and RI (b) values of HMs in Sarvestan street dust

Potential Ecological Risk Factor and Index;

The potential ecological risk factor (Eri) and risk index (RI) of HMs in the studied dust samples were calculated based on Hakanson's (1980) method.

The results indicate that the Eri values for Cd in all 10 samples fall within the moderate contamination range (80-160). The Eri value for Pb exceeded 40 in 10% of the samples, indicating a relatively low level of contamination in the remaining samples. Additionally, Cu Eri in 10% of the samples was above 80, signifying a moderate level of pollution. The Eri values for the other HMs in the studied samples were below 40, indicating a low potential for contamination.

The RI for all elements in most dust samples indicates a moderate hazard level (150-300). However, in 30% of the samples, the RI values were 213.69, 258.99, and 209.56, respectively, showing the highest risk levels. The statistical results for Eri and RI are shown in Figure 7b.

Human Health Risk Assessment (HHRA);

The HHRA of heavy metals (HMs) in the dust samples was calculated based on three exposure pathways: ingestion, inhalation, and dermal absorption (Table 3 and Supplementary Table 2). The hazard quotient (HQ) levels of HMs in both children and adults followed the decreasing order: HQ_ing > HQ_derm > HQ_inh. The HQ levels in children were higher than those in adults across all pathways. In both age groups, the HQ_ing of HMs followed the ascending order: Pb > Cr > As > Ni > Cu > Zn > Cd.

The hazard index (HI) levels of HMs were less than 1 for both age groups. In the children's age group, the HI was higher than in the adult group. The highest HI level was associated with Pb (3.36×10^{-1}) in children. Therefore, according to Table 3, the HI levels of HMs do not pose significant health risks.

Table 3. The mean value of HQ $_{\text{(ing, inh. and derm)}}$, HI and Inh CR for children and adult exposure to Sarvestan street dust

HMs Parameters	As	Cd	Cr	Pb	Cu	Ni	Zn
				Children			
HQ_{ing}	1.53×10^{-1}	5.04×10^{-3}	1.92×10^{-1}	2.83×10^{-1}	3.07×10^{-2}	3.24×10^{-2}	8.51×10^{-3}
HQ_{inh}	4.28×10^{-6}	1.40×10^{-7}	5.65×10^{-4}	7.88×10^{-6}	8.55×10^{-7}	8.80×10^{-7}	2.37×10^{-7}
HQ_{derm}	1.05×10^{-3}	1.41×10^{-3}	2.70×10^{-2}	5.29×10^{-3}	2.87×10^{-4}	3.36×10^{-4}	1.19×10^{-4}
HI	1.54×10^{-1}	6.45×10^{-3}	2.20×10^{-1}	2.89×10^{-1}	3.10×10^{-2}	3.28×10^{-2}	8.63×10^{-3}
Inh CR	1.66×10^{-9}	7.60×10^{-11}	5.82×10^{-8}	-	-	1.30×10^{-9}	-
				Adults			
HQ_{ing}	1.64×10^{-2}	5.4×10^{-4}	2.06×10^{-2}	3.04×10^{-2}	3.29×10^{-3}	3.47×10^{-3}	9.11×10^{-4}
HQ_{inh}	2.41×10^{-6}	7.94×10^{-8}	3.18×10^{-4}	4.44×10^{-6}	4.82×10^{-7}	4.96×10^{-7}	1.34×10^{-7}
HQ_{derm}	1.60×10^{-4}	2.15×10^{-4}	4.12×10^{-3}	8.08×10^{-4}	4.38×10^{-5}	5.14×10^{-5}	1.81×10^{-5}
HI	1.66×10^{-2}	7.55×10^{-4}	2.51×10^{-2}	3.12×10^{-2}	3.34×10^{-3}	3.53×10^{-3}	9.30×10^{-4}
Inh CR	3.76×10^{-9}	1.71×10^{-10}	1.31×10^{-7}	-	-	2.94×10^{-9}	-

Supplementary Table 2. Daily dose and hazard indices of heavy metals in atmospheric dust for both children and adults

Elements		**ADD_{ing}**	**ADD_{inh}**	**ADD_{derm}**	**HQ_{ing}**	**HQ_{inh}**	**HQ_{derm}**	**HI**
Children								
As	Min	3.60E-05	1.01E-09	1.01E-07	1.20E-01	3.34E-06	8.20E-04	1.21E-01
	Max	5.87E-05	1.64E-09	1.64E-07	1.96E-01	5.45E-06	1.34E-03	1.97E-01
	Mean	4.61E-05	1.29E-09	1.29E-07	1.54E-01	4.28E-06	1.05E-03	1.55E-01
Cd	Min	4.40E-06	1.23E-10	1.23E-08	4.40E-03	1.23E-07	1.23E-03	5.63E-03
	Max	5.87E-06	1.64E-10	1.64E-08	5.87E-03	1.64E-07	1.64E-03	7.51E-03
	Mean	5.04E-06	1.41E-10	1.41E-08	5.04E-03	1.41E-07	1.41E-03	6.45E-03
Cr	Min	3.60E-04	1.01E-08	1.01E-06	1.20E-01	3.52E-04	1.68E-02	1.37E-01
	Max	7.60E-04	2.12E-08	2.13E-06	2.53E-01	7.42E-04	3.55E-02	2.90E-01
	Mean	5.79E-04	1.62E-08	1.62E-06	1.93E-01	5.65E-04	2.70E-02	2.20E-01
Pb	Min	1.73E-04	4.84E-09	4.85E-07	4.95E-02	1.38E-06	9.24E-04	5.04E-02

	Max	2.35E-03	6.56E-08	6.57E-06	6.70E-01	1.86E-05	1.25E-02	6.83E-01
	Mean	9.93E-04	2.78E-08	2.78E-06	2.84E-01	7.88E-06	5.30E-03	2.89E-01
Cu	Min	2.00E-04	5.58824E-09	5.60E-07	5.00E-03	1.39E-07	4.67E-05	5.05E-03
	Max	6.41E-03	1.79196E-07	1.80E-05	1.60E-01	4.46E-06	1.50E-03	1.62E-01
	Mean	1.23E-03	3.43863E-08	3.45E-06	3.08E-02	8.55E-07	2.87E-04	3.11E-02
Ni	Min	4.27E-04	1.19E-08	1.19E-06	2.13E-02	5.79E-07	2.21E-04	2.16E-02
	Max	8.40E-04	2.35E-08	2.35E-06	4.20E-02	1.14E-06	4.36E-04	4.24E-02
	Mean	6.49E-04	1.81E-08	1.82E-06	3.25E-02	8.81E-07	3.37E-04	3.28E-02
Zn	Min	7.20E-04	2.01E-08	2.02E-06	2.40E-03	6.71E-08	3.36E-05	2.43E-03
	Max	4.69E-03	1.31E-07	1.31E-05	1.56E-02	4.37E-07	2.19E-04	1.59E-02
	Mean	2.55E-03	7.13E-08	7.15E-06	8.51E-03	2.38E-07	1.19E-04	8.63E-03
Adult								
As	Min	3.86E-06	5.67E-10	1.54E-08	1.29E-02	1.88E-06	1.25E-04	1.30E-02
	Max	6.29E-06	9.24E-10	2.51E-08	2.10E-02	3.07E-06	2.04E-04	2.12E-02
	Mean	4.94E-06	7.27E-10	1.97E-08	1.65E-02	2.41E-06	1.60E-04	1.66E-02
Cd	Min	4.71E-07	6.93E-11	1.88E-09	4.71E-04	6.93E-08	1.88E-04	6.60E-04
	Max	6.29E-07	9.24E-11	2.51E-09	6.29E-04	9.24E-08	2.51E-04	8.79E-04
	Mean	5.40E-07	7.94E-11	2.15E-09	5.40E-04	7.94E-08	2.15E-04	7.56E-04
Cr	Min	3.86E-05	5.67E-09	1.54E-07	1.29E-02	1.98E-04	2.57E-03	1.56E-02
	Max	8.14E-05	1.20E-08	3.25E-07	2.71E-02	4.19E-04	5.42E-03	3.30E-02
	Mean	6.20E-05	9.12E-09	2.47E-07	2.07E-02	3.19E-04	4.12E-03	2.51E-02
Pb	Min	1.86E-05	2.73E-09	7.41E-08	5.31E-03	7.76E-07	1.41E-04	5.45E-03
	Max	2.51E-04	3.70E-08	1.00E-06	7.18E-02	1.05E-05	1.91E-03	7.38E-02
	Mean	1.06E-04	1.57E-08	4.25E-07	3.04E-02	4.45E-06	8.09E-04	3.12E-02
Cu	Min	2.14E-05	3.15E-09	8.55E-08	5.36E-04	7.84E-08	7.13E-06	5.43E-04
	Max	6.87E-04	1.01E-07	2.74E-06	1.72E-02	2.51E-06	2.28E-04	1.74E-02
	Mean	1.32E-04	1.94E-08	5.26E-07	3.30E-03	4.82E-07	4.38E-05	3.34E-03
Ni	Min	4.57E-05	6.72E-09	1.82E-07	2.29E-03	3.26E-07	3.38E-05	2.32E-03
	Max	9.00E-05	1.32E-08	3.59E-07	4.50E-03	6.42E-07	6.65E-05	4.57E-03
	Mean	6.96E-05	1.02E-08	2.78E-07	3.48E-03	4.97E-07	5.14E-05	3.53E-03
Zn	Min	7.71E-05	1.13E-08	3.08E-07	2.57E-04	3.78E-08	5.13E-06	2.62E-04
	Max	5.03E-04	7.39E-08	2.01E-06	1.68E-03	2.46E-07	3.34E-05	1.71E-03
	Mean	2.74E-04	4.02E-08	1.09E-06	9.12E-04	1.34E-07	1.82E-05	9.30E-04

Supplementary Table 3. Applied reference dose (RfD_{ing}, RfD_{inh}, RfD_{derm}) and slope factor contents in this study

	Unite	As	Cd	Cr	Pb	Cu	Ni	Zn	Reference
RfD_{ing}	mg/kg/day	3×10^{-4}	1×10^{-3}	3×10^{-3}	3.5×10^{-3}	4×10^{-2}	2×10^{-2}	3×10^{-1}	Ferreira-Baptista and De Miguel (2005)
RfD_{inh}	mg/kg/day	3.01×10^{-4}	1×10^{-3}	2.86×10^{-5}	3.52×10^{-3}	4.02×10^{-2}	2.06×10^{-2}	3×10^{-1}	Ferreira-Baptista and De Miguel (2005)
RfD_{der}	mg/kg/day	1.23×10^{-4}	1×10^{-5}	6×10^{-5}	5.25×10^{-4}	1.2×10^{-2}	5.4×10^{-3}	6×10^{-2}	Ferreira-Baptista and De Miguel (2005)
Inh SF	mg/kg/day	15.1	6.3	42	___	___	0.84	___	USEPA (2002), Ferreira-Baptista and De Miguel (2005)

The results showed that the ingestion route was the dominant route of exposure for children and adults, accounting for more than 95% of the total hazard index (HI) for most metals.

This aligns with findings from other urban dust studies (Ferreira-Baptista & De Miguel, 2005; Wei et al., 2015; Qader et al., 2026) and underscores the critical importance of preventing hand-to-mouth transfer of dust, especially for children during outdoor activities. The higher HI values for children—approximately an order of magnitude greater than for adults—are primarily attributable to their higher dust ingestion rate per unit body weight and more frequent contact with ground surfaces. Although the calculated HI values were below the safety threshold (HI < 1), indicating no significant non-carcinogenic risk, the elevated contribution of Pb and Cr to the total HI warrants attention. Chronic exposure to even low levels of Pb is known to cause neurodevelopmental deficits in children, and Cr (VI) is a recognized carcinogen via inhalation (USEPA, 2002). The presence of these metals is likely linked to local anthropogenic activities such as vehicle emissions (Pb from historical leaded gasoline and wear from batteries), industrial processes, and possibly the nearby oil and gas drilling operations, which are known to emit various metallic particulates.

Similar to a study on the non-carcinogenic risk of HMs in Shiraz (Fars Province) by Keshavarzi et al. (2015), HQ_ing and HI values for children were higher than those for adults. The mean Inh CR levels decreased in the following order for children: Cd (7.60×10^{-11}) < Ni (1.30×10^{-9}) < As (1.66×10^{-9}) < Cr (5.82×10^{-8}), while for adults, it followed: Cd (1.71×10^{-10}) < Ni (2.94×10^{-9}) < As (3.76×10^{-9}) < Cr (1.31×10^{-7}) (Table 3).

An Inh CR value between 1×10^{-6} and 1×10^{-4} indicates an acceptable or tolerable risk, whereas a value greater than 1×10^{-4} suggests an unacceptable risk. An Inh CR value below 1×10^{-6} is considered negligible. Therefore, no unacceptable Inh CR values were observed in either age group (Table 3 and Supplementary Table 3).

There were no RfD baseline values for any of the studied elements in the inhalation route (RfDinh) except for Cr element. As a result, based on the hypothesis that absorption of heavy metals after inhalation has similar effects on health as when the particles are swallowed. The reference dose value in the ingestion route is also considered for inhalation.

Source Attribution and Comparative Context

The elevated concentrations of heavy metals observed in Sarvestan street dust are indicative of diverse anthropogenic sources, significantly contributing to the overall pollution burden. Specifically, lead (Pb) and cadmium (Cd) levels, identified as significantly enriched elements, are largely attributed to vehicular emissions (from tire and brake wear) and local industrial activities such as battery manufacturing and automobile repair shops, particularly evident near Station 10. Furthermore, the proximity of the Sarvestan oil field and the active drilling operations by the National Drilling Company of Iran represent a critical, yet under-explored, potential source. Activities related to oil and gas exploration, production, and transportation often release various metallic particulates and process-related contaminants into the environment, which can settle as street dust. These findings align with studies reporting contributions from traffic and local industrial point sources in other urban environments (Menkiti et al., 2017; Cui et al., 2020; Nazzal et al., 2025). Copper (Cu) is commonly associated with brake pad wear and industrial processes. Nickel (Ni) and chromium (Cr) can originate from metallic abrasion and exhaust emissions. Zinc (Zn) is predominantly linked to tire wear. While the general contributions from traffic and local industry are clear, the influence of the petroleum industry must be considered a primary factor driving elevated levels, especially for metals like Ni and Cr, which are common in oil processing streams (Karimian Torghabeh et al., 2019). Further detailed source apportionment studies utilizing advanced multivariate statistical techniques (e.g., PMF) would be essential to quantitatively separate the impact of traffic/industry from the petroleum sector.

A comparative analysis with other Iranian cities reveals both similarities and notable differences in heavy metals profiles (Table 2). While Sarvestan's mean Pb concentration (74.5 mg/kg) is lower than in Mashhad (133.12 mg/kg) (Behravesh et al., 2015) or Rasht (822.1 mg/kg) (Alinia-Ahandani et al., 2021), it remains significantly higher than the UCC background value (20 mg/kg) (Taylor, 1995). These variations underscore the influence of local factors, including traffic intensity, specific local industries, and the presence of energy-related operations. The elevated levels near Station 10, for example, correlate with battery/repair shops, but the overall metal enrichment in the region warrants investigation into emissions from the nearby oil and gas activities, aligning with findings from similar industrial-urban interfaces globally (Delgado-Iniesta et al., 2022). Understanding these regional disparities is crucial for developing targeted pollution control strategies. Furthermore, the observed enrichment of Cd, Pb, and As poses potential ecological concerns, as these elements can accumulate in soil and aquatic ecosystems, affecting microbial communities and the food chain (Hakanson, 1980).

Implications for Public Health and Risk Management

The findings of this study carry significant implications for public health management in Sarvestan and similar developing urban areas. While the cumulative non-carcinogenic risks are within acceptable limits, the moderate ecological risk and significant enrichment of toxic elements like Cd, Pb, and As highlight a potential for future health concerns if pollution sources are not managed. Proactive measures are recommended to mitigate exposure, particularly for the vulnerable child population. These measures include:

Regular street cleaning and washing to reduce dust resuspension.

Strict regulation of emissions from industrial sites, especially battery manufacturing and automobile repair shops identified near Station 10.

Public awareness campaigns to educate parents and caregivers about the importance of handwashing for children after outdoor play and reducing tracked-in dust inside homes.

Establishing a continuous environmental monitoring program for heavy metals in dust and air, especially in areas close to oil and gas exploration activities, to track trends and provide early warnings.

Future research should focus on biomonitoring studies (e.g., measuring blood Pb levels in children) to validate the exposure estimates presented here and to investigate the speciation of Cr to distinguish between the less toxic Cr (III) and the highly carcinogenic Cr (VI)

Conclusions

In this study, heavy metals pollution, ecological risk, and human health risk assessment of street dust were investigated in Sarvestan city.

In conclusion, this study revealed that street dust in Sarvestan is moderately polluted with Cd, Pb, and As, posing a moderate potential ecological risk.

The human health risk assessment indicated that children face a higher non-carcinogenic risk than adults, primarily through the ingestion of dust. Although the current hazard levels are acceptable and the inhalation carcinogenic risk is negligible, the continuous enrichment of toxic metals from anthropogenic sources such as traffic, industries, and oil-related activities demands vigilant monitoring and preemptive actions. Implementing public health measures such as regular street cleaning, controlling industrial emissions, and public awareness campaigns, especially for parents regarding children's hand hygiene, is crucial to safeguard the health of the local community as the city continues its industrial and urban development.

Based on geochemical analysis, the mean concentration of HMs followed the order: Zn > Cu > Pb > Ni > Cr > As > Cd.

According to I_geo and EF values, the street dust in Sarvestan was classified as moderately polluted with Cd and highly enriched in Cd, Pb, and As. The RI results indicated a moderate risk level based on the E_r values of HMs in Sarvestan street dust.

The HQ levels via ingestion were higher than those via inhalation and dermal absorption. The mean HI value indicated an acceptable non-carcinogenic risk for both children and adults exposed to Sarvestan street dust. Additionally, the inhalation carcinogenic risk (Inh CR) values for both children and adults were negligible. This study demonstrated that urban street dust, influenced by vehicles and probably activities related to oil and gas exploration, are source of HMs pollution, posing a tolerable health risk to the population of Sarvestan.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

Conflicts of interest

The authors declare that they have no known conflicts of interest or personal relationships that might influence the work of this research.

Author Contributions

Amineh Darrudi: Conceptualization, data collection, data analysis, and drafting of the manuscript.
Masumeh Taheri: Methodology, Interpretation of results, conceptualization.
Amir Karimian Torghabeh: Supervision, conceptualization, methodology, and final approval of the version to be published.
Mohamad Hosein Mahmudy Gharaie: Supervision, conceptualization, methodology, data interpretation, and critical revision of the manuscript for important intellectual content.
All authors contributed to the study conception and design, reviewed and approved the final manuscript, and agree to be accountable for all aspects of the work.

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