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Pollution and Health Risk Assessment of Hazardous Elements in Surface Dust along an Urbanization Gradient

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Abstract: Pollution of urban surface dust with hazardous elements (HEs) is a serious environmental issue due to its toxicity and potential hazardous effects. Surface dust samples were collected from core urban, urban, and suburban gradients in the Urumqi city of the arid NW China, and the concentrations of six HEs, such as arsenic (As), cadmium (Cd), nickel (Ni), lead (Pb), mercury (Hg), and chromium (Cr), were determined. The pollution load index (*PLI*) and the US EPA health risk assessment model were applied to analyze and compare the pollution levels and potential health risk of HEs in surface dusts in different urbanization gradients. The obtained results indicate that the average concentrations of Hg, Cd, and Ni in surface dust decrease in the order of core urban > urban > suburban, whereas the average concentrations of As, Cr, and Pb decrease in the order of urban > core urban > suburban. The *PLI* of HEs in surface dust decreased in the order of core urban > urban > suburban. The concentrations of HEs in the core urban and urban gradients are relatively higher than in the suburban gradient. Furthermore, the total non-carcinogenic and carcinogenic risk index of investigated HEs in surface dust decrease in order of urban > core urban > suburban, for both adults and children. In addition, the pollution of surface dust with HEs in all urbanization gradients is more harmful to the children's health than to the adults. Overall, the potential non-carcinogenic and carcinogenic health risks of the investigated HEs, instigated primarily by oral ingestion of surface dust, are found to be within the acceptable range. However, urbanization can effects the accumulation of HEs in surface dust, and Cr is the main non-carcinogenic risk factor, whereas Cd is the main carcinogenic risk factor among the analyzed HEs in surface dust in all urbanization gradients.

Keywords: urbanization gradient; surface dust; hazardous elements; pollution; health risk

1. Introduction

Surface dust is the "source" and "sink" of hazardous elements (HEs) in urban environments, which is closely related to urban ecosystem and human health [1,2]. The concentration of HEs in surface dust in many cities is increasing at an alarming rate, which has become one of the crucial eco-environmental problems in urban [3,4]. Increasing demand for metals in industries and urbanization process have strongly disturbed the natural geochemical cycling of the urban ecosystem [5,6], and urbanization processes can result in the accumulation of HEs in surface dust in urban ecosystems [7,8]. Traffic exhaust, incinerators, industrial waste, and the atmospheric deposition of dust and aerosols have continuously added HEs to the urban environment [9], and HEs accumulate in the human body can cause irreversible damage to human health [10,11]. Therefore, HEs in surface dust can serve as a comprehensive indicator of the quality of the urban environment [12].

Pollution of urban surface dust by HEs, whether through natural or anthropogenic sources, is an increasing environmental problem due to its potential toxicity and hazardous effects on the urban eco-environment and human health [2,13,14]. Hazardous elements in surface dust can transmit from grand surface to soil and water, and can easily enter the human body through direct contact, dust

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inhalation, and hand-to-mouth intake [15,16]. Exposure to HEs has been known to cause serious systemic health issues such as kidney and liver damage, breast and gastrointestinal cancer, respiratory diseases, neurological disorders, anemia, skin lesion, renal diseases, and congenital malformation [17,18]. In light of this information, the pollution and potential health risk assessment of HEs in urban surface dust has emerged as a new forefront topic in environmental research.

Recently, many studies have studied pollution risk of HEs in soil along an urbanization gradient. For example, conducted an extensive survey of HEs in soil in the highly urbanized and commercialized Hong Kong Island area of Hong Kong, and found a distinctly different associations among HEs in the urban, suburban, and country park soils. Their results explored that the Pb isotopic composition of the urban, suburban, and country park soils in the Hong Kong Island area showed that vehicular emissions were the major anthropogenic sources for Pb [19]. observed the accumulation of HEs in soils along an urban-rural gradient in the rapidly growing Hangzhou City of Eastern China, and found a significant relationship between the concentrations of HEs in soil and distance from the urban center, soils in the urban areas are enriched with Cd, Cu, Pb, and Zn [20]. Explored the influence of urbanization on the concentration of HEs in soil in a typical industrial town in the Yangtze River delta, the fastest urbanization area in China, and suggested that the urbanization process affects not only the concentrations but also the spatial distribution patterns of HEs in soil [21]. Analyzed HEs in topsoil from holm oak woodlands located along an urbanization gradients (urban, peri urban and extraurban sites) in two Italian regions, and pointed out that some elements varied according to the supposed urbanization gradient (urban > peri urban > extraurban sites) [22]. Analyzed the metal enrichment differences in environment among super city, town, and rural area, and indicated that Cd, Cu, Hg, Pb, Sb, and Zn concentrations in urban surface dust were 1.48, 1.57, 2.73, 1.58, 6.20, and 1.98 times higher than rural surface soils on average, respectively [23]. Investigated the richness, coverage and concentration of HEs in vascular epiphytes in isolated trees along an urbanization gradient in the southern Brazil, and found a decreasing gradient of epiphyte richness and coverage as urbanization increased [24]. Observed HEs in soil in urban and rural locations near Charles City, Iowa, USA, and suggested that the degree of urbanization and industrial development within the Charles City urban cluster was sufficiently intense to differentiate the urban soils from the surrounding agricultural landscape [25]. Assessed the pollution levels and potential health risk of HEs in topsoil along a typical urbanization gradient in the Urumqi city of northwest China, and found that the contamination levels of HEs in soil decreased in the order of urban > rural > suburban gradients, and urbanization has had obvious effects on the accumulation of HEs in soil in arid land oasis city [26].

The above-mentioned research works mainly focus on the HEs pollution of soil along an urbanization gradient, but there are very few studies related to the heavy metal pollution of urban surface dust along an urbanization gradient. Compared the risk of HEs in road sediments across an urban-rural gradient, and indicated that average concentrations of analyzed HEs can be ranked as: central urban > central suburban county > central suburban county > rural town > rural village. Evaluated risk associated with HEs in road-deposited sediment along an urban-rural gradient in the Beijing, China, and suggested that the pollution risk associated with HEs in road-deposited sediment in urban areas was generally higher than that in rural areas [27]. One recent study reported that urbanization has had a significant effects on the trace elements pollution of surface soil along an urbanization gradient in the Urumqi [26]. So far, however, there has been no pursuant discussion about the pollution of surface dust by HEs along an urbanization gradient, and the pollution risk of surface dust by HEs along an urbanization gradient still need further evaluation.

In view of the shortage of current research, surface dust samples from a typical urbanization gradient in the Urumqi city of NW China were collected, and concentrations of six HEs were measured. The main objectives of this study are to identify the pollution levels of HEs in surface dust along an urbanization gradient, and to compare potential health risks of HEs on adults and children via oral ingestion, inhalation, and dermal contact of these surface dust. Results of this study are expected to provide theoretical and technical support for the protection of human health and eco-environmental safety of urban areas in arid zone oasis.

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2. Materials and Methods

2.1. Study Area

The city of Urumqi is one of the most important cities in the "Silk Road Economic Belt", and the provincial capital of Xinjiang, NW China. This city is located in the southern parts of the Junghar Basin, the northern parts of the Tarim Basin, and lies within the geographical coordinates of 87°28′–87°45′ E and 43°42′–43°54′ N, with a total urban area of about 500 km^2. The climate of this city is a typical continental desert climate with average annual temperature, precipitation, and evaporation of about 6.7 °C, 280 mm, and 2730 mm, respectively [26,28]. A typical and continuous "core urban-urban-suburban" gradient, illustrated in Figure 1, was selected in the Urumqi city to study the effects of urbanization on the concentrations of HEs in surface dust. Each urbanization gradient extended over a distance of about 8 km.

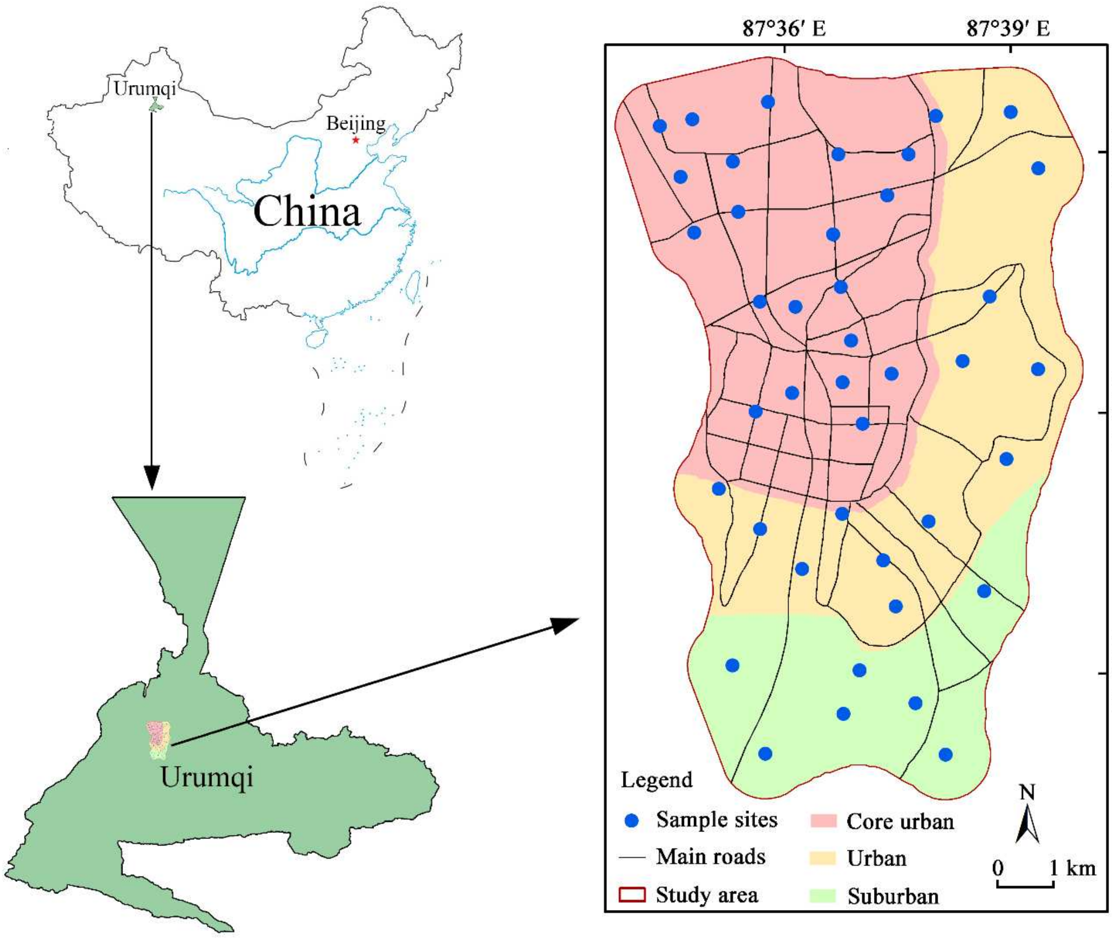

Figure 1. Locations of the study area and sample sites.

2.2. Sample Collection, Preparation, and Analysis

A total of 41 surface dust samples were collected from the core urban, urban, and suburban gradients, which were divided according to previous studies [26]. The sample sites are illustrated on the map in Figure 1. Considering the heterogeneity of HEs in surface dust, a total of 21 samples were collected from the core urban gradient, while 13 samples were collected from the urban, and 7 samples were collected from the suburban gradient. At each sample site, about 10 subsamples of surface dust were collected from road, pavement, and gutter surface using a clean polyethylene brush, and the subsamples were mixed as one composite surface dust sample in a polyethylene bag and sent to the laboratory.

All samples were air dried then ground and sieved through a 0.15 mm nylon mesh, and digested by an $HCl–HNO_3–HF–HClO_4$ method, as described in "HJ/T 166–2004" [29]. Then, the concentration of As was measured using an atomic fluorescence spectrometry (PERSEE, PF–7, China), whereas the concentrations of Cd, Ni, Pb, Hg, and Cr were analyzed using a Flame atomic absorption spectrophotometer–flameless (Agilent 200AA, USA). The laboratory quality control methods, including reagent blanks, and duplicates were used to assess the analytical data quality. For the precision of the analytical procedures, a standard solution of elements was used to compare samples to national standards (Chinese national standards samples, GSS-12). The recoveries of surface dust samples that were spiked with standards ranged from 93.67 to 105.86%.

2.3. Pollution Assessment of Hazardous Elements

The overall pollution level of HEs in surface dust is evaluated using the pollution load index (*PLI*) introduced by Tomlinson [30]. The calculation formula of *PLI* is as follows:

$$CF_i = C_i/C_b \tag{1}$$

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \cdots CF_n} \tag{2}$$

where, CF_i is the single pollution index for element *i*, and C_i and C_b represent the measured concentration and the background concentration of element *i*, respectively. The following criteria were used to classify the pollution grades of the *CF* and *PLI*: no pollution ($CF \le 0.7$), slight pollution ($0.7 < CF \le 1$), low pollution ($1 < CF \le 2$), moderate pollution ($2 < CF \le 3$), and heavy pollution ($CF \ge 3$); No pollution ($PLI \le 1$), low pollution ($1 < PLI \le 2$), moderate pollution ($2 < PLI \le 3$) and heavy pollution ($PLI \ge 3$).

2.4. Health Risk Assessment of Hazardous Elements

2.4.1. Exposure Analysis

The exposure level of HEs in surface dust is evaluated on the basis of the chronic daily intake (*CDI*, mg/kg/day). The *CDI* in three exposure routes, such as oral ingestion, inhalation, and dermal contact, is calculated by the following equations [31–33]:

$$CDI_{\text{ingest}} = [(C_i \times IngR \times CF \times EF \times ED)/(BW \times AT) \tag{3}$$

$$CDI_{\text{inhale}} = [(C_i \times InhR \times EF \times ED)/(PEF \times BW \times AT) \tag{4}$$

$$CDI_{\text{dermal}} = [(C_i \times SA \times AF \times ABS \times EF \times ED)/(BW \times AT) \tag{5}$$

$$CDI_{total} = CDI_{ingest} + CDI_{inhale} + CDI_{\text{dermal}} \tag{6}$$

The exposure parameters for *CDI* estimation and their meanings are given in Table 1.

Table 1. The exposure parameters for *CDI* estimation.

Parameters	Meaning and Units	Children	Adult
IngR	Consumption rate of dusts (mg/d)	200	100
InhR	Dust inhalation rate (m^3/d)	7.5	16.2
CF	Unit conversion factor (kg/mg)	1×10^{-6}	1×10^{-6}
EF	Exposure frequency (d/a)	350	350
ED	Exposure duration (year)	6	30
SA	Exposed skin area (cm^2)	899	1600
AF	Skin adherence factor (mg/(cm^2/d))	0.20	0.07
PEF	Particulate emission factor (m^3/kg)	1.36×10^9	1.36×10^9
BW	Average body weight (kg)	21.2	62.4
AT_{nc}	Average exposure time for non-cancer (d)	365×ED	365×ED
AT_{ca}	Average exposure time for cancer (d)	365×70	365×70
ABS	Dermal absorption factor (unitless)	Hg=Cr=Ni=Pb=0.01; As=0.03; Cd=0.005	

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2.4.2. Non-Carcinogenic Risk Assessment

In general, a person is exposed to HEs in surface dust via three main routes: ingestion, inhalation, and dermal contact. The hazard index (*HI*), which is based on the Hazard Quotient (*HQ*) of a single HE, was applied to quantify the non-carcinogenic health risk of HEs. The calculation formula for *HQ* and *HI* is as follows:

$$HQ = \frac{CDI}{RfD} \tag{7}$$

$$HI = \sum HQ = HQ_{\text{ingest}} + HQ_{\text{inhale}} + HQ_{\text{dermal}} \tag{8}$$

where *RfD* indicates the reference dose (mg/kg/day). An *HQ* or *HI* < 1 means the non-carcinogenic health risk of HEs to humans is negligible, and an *HQ* or *HI* ≥ 1 means HEs in surface dust may pose potential non-carcinogenic risk [34].

2.4.3. Carcinogenic Risk Assessment

The total carcinogenic risk index (*TCR*), which is based on the carcinogenic risks (*CR*) of a single HE, was applied to quantify the carcinogenic health risk of HEs in surface dust. The calculation formula is as follows:

$$CR = CDI \times SF \tag{9}$$

$$TCR = \sum CR = CR_{\text{ingest}} + CR_{\text{inhale}} + CR_{\text{dermal}} \tag{10}$$

where *SF* indicates the carcinogenic slope factor (mg/kg/day). An *CR* or *TCR* < 10^{-6} means the carcinogenic health risk of HEs to humans is negligible, an *CR* or *TCR* ≥ 10^{-4} means HEs in surface dust have caused potential carcinogenic risks to humans, and if $10^{-6} \leq CR$ or $TCR \leq 10^{-4}$, it means potential carcinogenic risks pose by HEs in surface dust is acceptable or tolerated [35]. The *RfD* and *SF* values of HEs in surface dust were determined based on the relevant research results [36,37], as given in Table 2.

Table 2. The *RfD* for non-carcinogenic elements and *SF* for carcinogenic elements.

Elements	*RfD*/(mg/(kg·d)			*SF*/(mg/kg·d)$^{-1}$		
	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal
Pb	0.0035	0.00352	0.000525	/	/	/
Ni	0.020	0.0206	0.0054	/	0.84	/
As	0.0003	0.000123	0.0003	1.50	0.0043	1.50
Cd	0.001	0.001	0.00001	/	6.30	/
Hg	0.0003	0.0003	0.000024	/	/	/
Cu	0.04	0.0402	0.012	/	/	/

3. Results and Discussion

3.1. Concentration of HEs in Surface Dust along the Urbanization Gradient

As shown in Table 3, on average, the concentrations of As, Hg, Cd, Cr, Ni, and Pb in the collected surface dusts in the core urban gradient were 9.14 mg/kg, 0.18 mg/kg, 0.24 mg/kg, 63.83 mg/kg, 36.95 mg/kg, and 36.61 mg/kg, respectively.

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Table 3. Hazardous elements concentrations in surface dust along the urbanization gradient.

Gradient	Statistics	As	Hg	Cd	Cr	Ni	Pb
Core urban (*n*=21)	Minimum/(mg/kg)	5.30	0.07	0.09	50.07	21.61	16.00
	Maximum/(mg/kg)	14.20	0.55	0.50	81.08	74.94	56.30
	Average/(mg/kg)	9.14	0.18	0.24	63.83	36.95	36.61
	St.D/(mg/kg)	2.42	0.11	0.12	7.91	13.22	11.09
	CV	0.26	0.61	0.50	0.12	0.36	0.30
Urban (*n*=13)	Minimum/(mg/kg)	5.00	0.07	0.12	45.01	27.34	18.80
	Maximum/(mg/kg)	15.90	0.29	0.36	94.38	47.43	146.00
	Average/(mg/kg)	9.96	0.14	0.21	65.52	32.99	40.28
	St.D/(mg/kg)	3.05	0.07	0.06	12.66	6.58	31.23
	CV	0.31	0.50	0.29	0.19	0.20	0.78
Suburban (*n*=7)	Minimum/(mg/kg)	8.00	0.07	0.09	48.01	18.20	19.20
	Maximum/(mg/kg)	9.60	0.25	0.35	74.97	39.04	44.00
	Average/(mg/kg)	8.61	0.13	0.19	61.13	31.39	27.11
	St.D/(mg/kg)	0.48	0.06	0.09	9.10	6.73	7.59
	CV	0.06	0.46	0.47	0.15	0.21	0.28
Background value*		9.99	0.076	0.23	53.20	29.90	14.10

Note: * Background values refer to the heavy metal concentrations of soils in Urumqi.

The average concentrations of these six HEs in surface dusts in the urban gradient were 9.96 mg/kg, 0.14 mg/kg, 0.21 mg/kg, 65.52 mg/kg, 32.99 mg/kg, and 40.28 mg/kg, respectively. And, the average concentrations of these six HEs in the suburban gradient were 8.61 mg/kg, 0.13 mg/kg, 0.19 mg/kg, 61.13 mg/kg, 31.39 mg/kg, and 27.11 mg/kg, respectively. It should be noted that the average concentrations of Hg, Cr, Ni, and Pb elements in surface dust in all urbanization gradients and Cd in surface dust in core urban exceed the corresponding background values, with the highest enrichment of Hg element in surface dust in all urbanization gradients in the study area.

Obviously, the average concentrations of Hg, Cd and Ni in surface dust decreased in the order of core urban > urban > suburban, whereas the average concentrations of As, Cr, and Pb in surface dust decrease in the order of urban > core urban > suburban. This suggests that the concentrations of analyzed HEs in surface dust differ among the investigated urbanization gradients, and the suburban surface dust was less enriched with HEs in comparison with the core urban and the urban surface dust. As is mainly originated by fuel combustion and is emitted into the atmosphere with exhaust gases [38]. In cities, industrial production and heating are associated with fuel combustion. Cd is found in brakes, tires, lubricating oil, and roads, So Cd in surface dust comes mainly from traffic sources [39]. HEs such as Cr and Ni enter the atmosphere with the exhaust gases from industrial activities. The source of Pb was fuel combustion and traffic exhaust. Industrial activities such as small-scale gold mining and non-ferrous metal production may be the main sources of Hg [38–40]. The HEs released into the atmosphere from the soil can re-enter the surface dust through sedimentation and then re-suspend as particulate matter.

According to the grading criteria of the coefficient of variations (CV) and the calculated CVs of the analyzed HEs in surface dust in each urbanization gradient, Hg in all urbanization gradients, Cd in the core urban and suburban gradients, and Pb in the urban gradient were highly variable (CV > 36%), indicating that these HEs in corresponding urbanization gradients varies significantly across the sample sites, and their possible origins may be mainly influenced by anthropogenic activities. Meanwhile, As in the core urban and urban gradients, Cd and Cr in the urban gradient, Ni in all gradients, and Pb in the core urban and suburban gradients were moderately variable (16% < CV ≤ 36%), indicating that these elements are most likely influenced by both natural and anthropogenic factors. However, As in the suburban gradient and Cr in the core urban and suburban gradients exhibited a low variability (CV < 16%), suggesting that these two elements in corresponding urbanization gradients are dominated by natural sources.

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3.2. Spatial Distribution of Concentration of HEs in Surface Dust

A GIS-based ordinary Kriging interpolation method was applied in order to map the spatial distribution of the concentrations of investigated HEs in surface dust in the study area (Figure 2). The spatial distribution of As and Pb illustrated in Figure 2 are similar to one another, with high concentrations are seen primarily in the core urban and urban gradients, and low concentrations are seen mainly in the suburban gradients. This finding is in agreement with the conclusion of study [41].

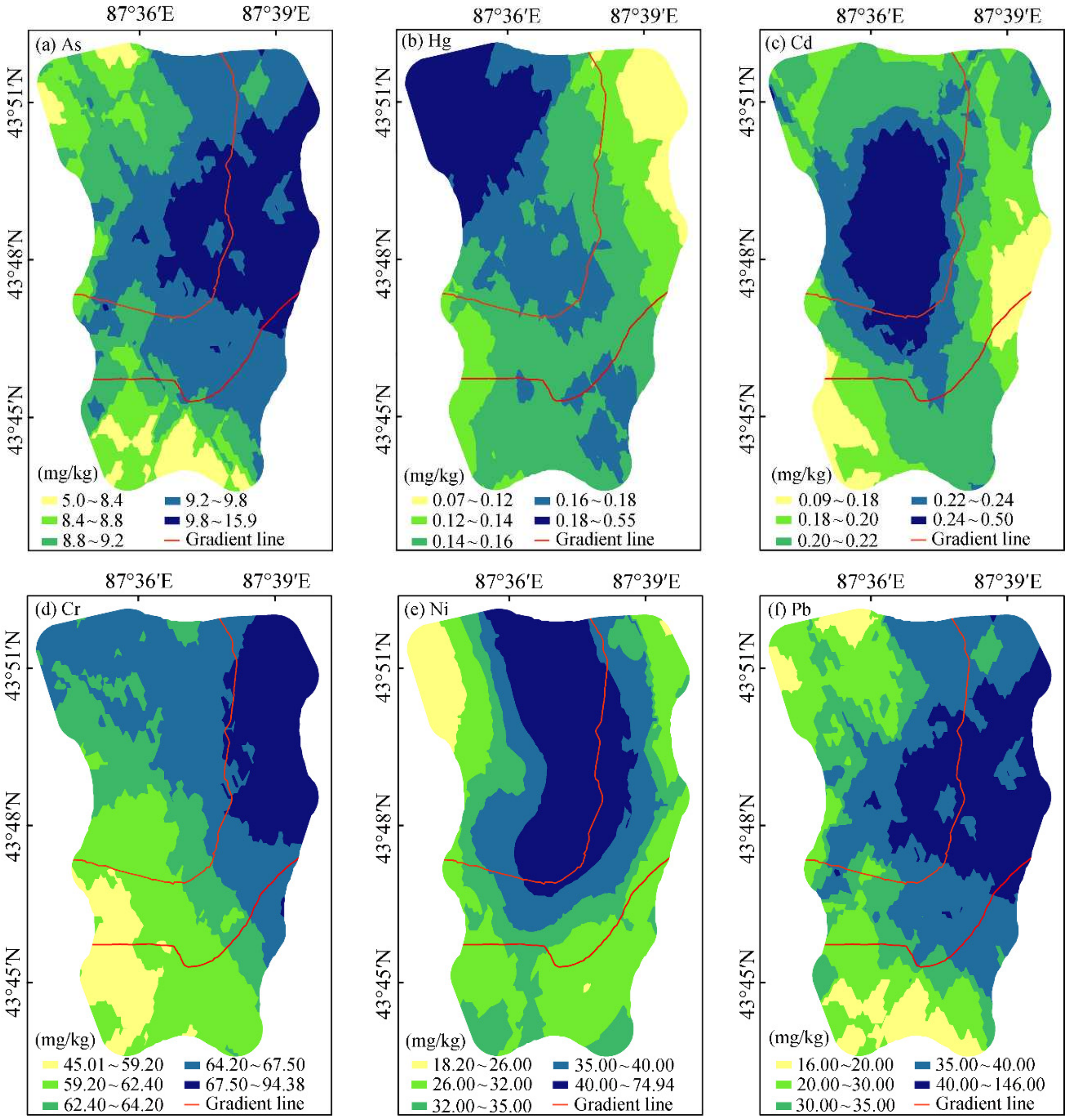

Figure 2. Spatial distribution of the concentrations of hazardous elements in surface dust.

A zonal spatial distribution pattern of Hg, Cd, and Ni elements are found in this study, with the most accumulation are observed in the core urban gradient and least accumulation are observed in the suburban gradient. The concentrations of these three HEs decreased from the core urban gradient to the suburban gradient in the study area. In the case of Cr, also a zonal spatial distribution pattern was observed in this study, with the most accumulation in the urban gradient and least accumulation in the suburban gradient. The concentrations of Cr decreased from the northeastern parts to the southwestern parts in the study area. However, low concentrations of all HEs in this study are seen in the suburban gradient, with a low road density, traffic flow, population density, and industrial production. Overall, the concentrations of HEs in surface dust in the core urban and the urban

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gradients are relatively higher than suburban gradient, which seems to be a clear indication that urbanization can influence the accumulation of HEs in surface dust in the study area.

3.3. Pollution Assessment of HEs in Surface Dust along the Urbanization Gradient

As shown in Table 4, the decreasing order of pollution levels of HEs in surface dust in different urbanization gradients are distinctive. On average, the *CF* values of the analyzed HEs in surface dust in the core urban gradient can be ranked as: Pb(2.60) > Hg(2.34) > Ni(1.24) > Cr(1.20) > Cd(1.02) > As(0.91), while the *CF* values of HEs in the urban surface dust can be ranked as: Pb(2.86) > Hg(1.89) > Cr(1.23) > Ni(1.10) > As(1.00) > Cd(0.90), and the *CF* values of HEs in the suburban surface dust can be ranked as: Pb(1.92) > Hg(1.73) > Cr(1.15) > Ni(1.05) > As(0.86) > Cd(0.80).

Table 4. Pollution levels of hazardous elements in surface dust along the urbanization gradient.

Gradient	Statistics	*CF*						*PLI*
		As	**Hg**	**Cd**	**Cr**	**Ni**	**Pb**	
Core urban (*n*=21)	Minimum	0.53	0.95	0.41	0.94	0.72	1.13	0.94
	Maximum	1.42	7.24	2.17	1.52	2.51	3.99	1.97
	Average	0.91	2.34	1.02	1.20	1.24	2.60	1.35
Urban (*n*=13)	Minimum	0.50	0.93	0.52	0.85	0.91	1.33	1.04
	Maximum	1.59	3.82	1.57	1.77	1.59	10.35	1.61
	Average	1.00	1.89	0.90	1.23	1.10	2.86	1.29
Suburban (*n*=7)	Minimum	0.80	0.97	0.37	0.90	0.61	1.36	0.87
	Maximum	0.96	3.29	1.52	1.41	1.31	3.12	1.56
	Average	0.86	1.73	0.80	1.15	1.05	1.92	1.15

According to the grading criteria and the calculated values of *CF*, the surface dust is low polluted by Cr and Ni, and slightly polluted by As in all urbanization gradients; A moderate pollution of Hg is observed in the core urban gradient, while a moderate pollution of Pb is observed in the core urban and the urban gradients; Besides, the urban and the suburban surface dusts are low polluted by Hg and slightly polluted by Cd. However, Cd in the core urban and Pb in the suburban gradient showed a low pollution level.

However, the average *CF* values of Hg, Cd, and Ni in surface dust decrease in the order of core urban > urban > suburban, while the average *CF* values of As, Cr and Pb in surface dust decrease in the order of urban > core urban > suburban. It indicates that surface dust in the suburban gradient, where the population density and traffic flow are relatively lower, is relatively clean in comparison with surface dust in the core urban and the urban gradients. Overall, hazardous elements, particularly Hg and Pb, are likely to be the significant pollutant of surface dust in all urbanization gradients in the Urumqi city and thus, should be monitored closely.

The average *PLI* values of HEs in surface dust in the core urban, urban, and suburban gradients in the study area are 1.35, 1.29, and 1.15, respectively, at the low pollution level. The *PLI* of HEs decreased in the order of: core urban > urban > suburban. The average *PLI* values of HEs in surface dust in the core urban gradient surpass the average *PLI* values in the urban and the suburban gradient by 4.65% and 17.39%, respectively. Overall, Hg contributed the most to the *PLI* of HEs in surface dust in all gradient zones, which account for 57.69%, 68.25%, and 66.47% of the *PLI* of HEs in surface dust in core urban, urban, and suburban gradients, respectively, indicating that Hg is the most dominant pollution factor in surface dust in all urbanization gradients in the study area.

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3.4. Non-Carcinogenic Risk of HEs in Surface Dust along the Urbanization Gradient

The hazard quotients (*HQ*) of each HEs in surface dust in all urbanization gradients via the ingestion, inhalation, and dermal contact exposure routes was estimated for adults and children and then the cumulative effect of the *HQ* of analazyed HEs was estimated using the hazard indexes (*HI*). Potential health risks of HEs in different urbanization gradients were compared and discussed.

As shown in Table 5, the average *HQ* values of investigated HEs in surface dust in the core urban, urban, and suburban gradients decrease in the order of: $HQ_{Cr} > HQ_{As} > HQ_{Pb} > HQ_{Ni} > HQ_{Cd} > HQ_{Hg}$, for both adults and children. For children, the *HQ* values of Cr were higher than those of other HEs, and they accounted for 52.53%, 51.26%, and 54.59% of the corresponding *HI* values of surface dust in the core urban, urban, and suburban gradients, respectively, compared to 55.77%, 54.46%, and 57.74% of *HI* for adults, respectively. These results imply that Cr contributed the most to the total *HI* values of analyzed HEs in surface dust in all urbanization gradients, indicating that Cr is the main non-carcinogenic risk factor in surface dust, and has the highest potential non-carcinogenic health risk.

Table 5. Non-carcinogenic risk index of hazardous elements in surface dust.

Gradient	Metals	HQ_{ingest}		HQ_{inhale}		HQ_{dermal}		*HQ*		*HI*	
		Children	**Adults**	**Children**	**Adults**	**Children**	**Adults**	**Children**	**Adults**	**Children**	**Adults**
Core urban	As	2.91×10^{-1}	4.68×10^{-2}	1.96×10^{-5}	1.36×10^{-5}	2.62×10^{-3}	5.24×10^{-4}	2.94×10^{-1}	4.73×10^{-2}	0.910	0.158
	Hg	5.66×10^{-3}	9.10×10^{-4}	1.56×10^{-7}	1.08×10^{-7}	6.36×10^{-4}	1.27×10^{-4}	6.29×10^{-3}	1.04×10^{-3}		
	Cd	2.25×10^{-3}	3.62×10^{-4}	6.20×10^{-8}	4.31×10^{-8}	6.06×10^{-3}	1.22×10^{-3}	8.31×10^{-3}	1.58×10^{-3}		
	Cr	2.03×10^{-1}	3.27×10^{-2}	5.88×10^{-4}	4.09×10^{-4}	2.74×10^{-1}	5.49×10^{-2}	4.78×10^{-1}	8.80×10^{-2}		
	Ni	1.76×10^{-2}	2.84×10^{-3}	4.72×10^{-7}	3.28×10^{-7}	5.88×10^{-4}	1.18×10^{-4}	1.82×10^{-2}	2.96×10^{-3}		
	Pb	9.99×10^{-2}	1.61×10^{-2}	2.74×10^{-6}	1.90×10^{-6}	5.99×10^{-3}	1.20×10^{-3}	1.06×10^{-1}	1.73×10^{-2}		
Urban	As	3.17×10^{-1}	5.10×10^{-2}	2.13×10^{-5}	1.48×10^{-5}	2.85×10^{-3}	5.71×10^{-4}	3.20×10^{-1}	5.16×10^{-2}	0.956	0.166
	Hg	4.58×10^{-3}	7.37×10^{-4}	1.26×10^{-7}	8.78×10^{-8}	5.15×10^{-4}	1.03×10^{-4}	5.09×10^{-3}	8.40×10^{-4}		
	Cd	1.98×10^{-3}	3.19×10^{-4}	5.47×10^{-8}	3.80×10^{-8}	5.35×10^{-3}	1.07×10^{-3}	7.33×10^{-3}	1.39×10^{-3}		
	Cr	2.09×10^{-1}	3.36×10^{-2}	6.03×10^{-4}	4.19×10^{-4}	2.81×10^{-1}	5.64×10^{-2}	4.90×10^{-1}	9.04×10^{-2}		
	Ni	1.58×10^{-2}	2.53×10^{-3}	4.22×10^{-7}	2.93×10^{-7}	5.25×10^{-4}	1.05×10^{-4}	1.63×10^{-2}	2.64×10^{-3}		
	Pb	1.10×10^{-1}	1.77×10^{-2}	3.01×10^{-6}	2.09×10^{-6}	6.59×10^{-3}	1.32×10^{-3}	1.17×10^{-1}	1.90×10^{-2}		
Suburban	As	2.74×10^{-1}	4.41×10^{-2}	1.84×10^{-5}	1.28×10^{-5}	2.47×10^{-3}	4.94×10^{-4}	2.77×10^{-1}	4.46×10^{-2}	0.839	0.146
	Hg	4.18×10^{-3}	6.72×10^{-4}	1.15×10^{-8}	8.00×10^{-8}	4.69×10^{-4}	9.40×10^{-5}	4.64×10^{-3}	7.66×10^{-4}		
	Cd	1.77×10^{-3}	2.84×10^{-4}	4.87×10^{-8}	3.39×10^{-8}	4.77×10^{-3}	9.55×10^{-4}	6.53×10^{-3}	1.24×10^{-3}		
	Cr	1.95×10^{-1}	3.13×10^{-2}	5.63×10^{-4}	3.91×10^{-4}	2.62×10^{-1}	5.26×10^{-2}	4.58×10^{-1}	8.43×10^{-2}		
	Ni	1.50×10^{-2}	2.41×10^{-3}	4.01×10^{-7}	2.79×10^{-7}	4.99×10^{-4}	1.00×10^{-4}	1.55×10^{-2}	2.51×10^{-3}		
	Pb	7.40×10^{-2}	1.19×10^{-2}	2.03×10^{-6}	1.41×10^{-6}	4.43×10^{-3}	8.89×10^{-4}	7.84×10^{-2}	1.28×10^{-2}		

In terms of the exposure routes, the average values of the *HQ* of investigated HEs in surface dust in all urbanization gradients followed the order $HQ_{ingest} > HQ_{dermal} > HQ_{inhale}$. This implys that unconscious ingestion was the main route of exposure to potential non-carcinogenic health risks of HEs in surface dust in the study area.

The *HI* values of HEs in surface dust in the core urban, urban, and suburban gradients were 0.910, 0.956, and 0.839 for children, respectively, compared to 0.158, 0.166, and 0.146 for adults, respectively. The calculated *HI* values of HEs in surface dust for children are much higher than that for adults. It imply that HEs in surface dust pose much higher potential non-carcinogenic health risks to children than to adults. This can be explained by the fact that children's hemoglobin is more sensitive to HEs in surface dust and they absorb them at a much faster rate than adults [6,42].

On the whole, according to the classification criteria for non-carcinogenic health risk, the *HQ* and *HI* values of the investigated HEs in surface dust in all urban gradients were lower than 1, for both children and adults, which suggest that the non-carcinogenic health risk of HEs to humans is negligible. Moreover, the obtained *HI* values of HEs for adults and children can be ranked as: $HI_{urban} > HI_{core\ urban} > HI_{suburban}$, indicating that HEs in surface dust in suburban gradient have less potential health risk than that of other urban gradients.

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3.5. Carcinogenic risk of HEs in Surface Dust along the Urbanization Gradient

According to the classification list introduced by the International Agency for Research on Cancer [43], As, Cd, Cr, and Ni are considered as carcinogenic HEs in this study. The carcinogenic risk (*CR*) of these four HEs in surface dust in all urbanization gradients via the ingestion, inhalation, and dermal contact exposure routes was estimated for adults and children, and then the cumulative effect of the *CR* of analyzed HEs was estimated using the total carcinogenic risk (*TCR*).

As shown in Table 6, the average *CR* values of four carcinogenic HEs in surface dust in the core urban, urban, and suburban gradients decrease in the order of: $CR_{Cd} > CR_{As} > CR_{Ni} > CR_{Cr}$, for both adults and children. It indicates that Cd is the main carcinogenic risk factor in surface dust, and has the highest potential carcinogenic health risk. Meanwhile, the average values of the *CR* of four carcinogenic HEs in surface dust followed the order $CR_{ingest} > CR_{dermal} > CR_{inhale}$. It indicates that ingestion is the main route of exposure to potential carcinogenic health risks of HEs in surface dust in the study area.

Table 6 shows that the *TCR* values of carcinogenic HEs in surface dust in the core urban, urban, and suburban gradients were 3.77×10^{-5}, 3.94×10^{-5}, and 3.59×10^{-5} for children, respectively, compared to 3.10×10^{-5}, 3.24×10^{-5}, and 2.95×10^{-5} for adults, respectively. The calculated *TCR* values of four carcinogenic HEs in surface dust for children are relatvely higher than that for adults. It indicates that As, Cd, Cr, and Ni elements in surface dust pose much higher potential carcinogenic health risks to children than to adults.

However, according to the classification criteria for carcinogenic health risk, the *CR* and *TCR* values of the *CR* or *TCR* in surface dust in all urban gradients were lower than the acceptable risk threshold value (10^{-4}), for both children and adults, which suggest that the potential carcinogenic risks pose by hazardous elements in surface dust is acceptable, and they cannot pose a carcinogenic health risk for either adults or children. Moreover, the obtained *TCR* values of HEs for adults and children can be ranked as: $TCR_{urban} > TCR_{core\ urban} > TCR_{suburban}$, indicating that carcinogenic elements in surface dust in suburban gradient have less potential health risk than that of other urban gradients.

Table 6. Carcinogenic risk index of hazardous elements in surface dust.

Gradient	Metals	CR_{ingest}		CR_{inhale}		CR_{dermal}		*CR*		*TCR*	
		Children	Adults	Children	Adults	Children	Adults	Children	Adults	Children	Adults
Core urban	As	1.12×10^{-5}	9.03×10^{-6}	8.87×10^{-13}	3.08×10^{-12}	3.03×10^{-7}	7.08×10^{-7}	1.15×10^{-5}	9.74×10^{-6}	3.77×10^{-5}	3.10×10^{-5}
	Cd	/	/	3.35×10^{-11}	1.16×10^{-10}	/	/	2.62×10^{-5}	2.12×10^{-5}		
	Cr	2.61×10^{-5}	2.10×10^{-5}	6.05×10^{-8}	2.10×10^{-7}	/	/	3.35×10^{-11}	1.16×10^{-10}		
	Ni	/	/	7.01×10^{-10}	2.43×10^{-9}	/	/	7.01×10^{-10}	2.43×10^{-9}		
Urban	As	1.22×10^{-5}	9.84×10^{-6}	9.67×10^{-13}	3.36×10^{-12}	3.30×10^{-7}	7.72×10^{-7}	1.26×10^{-5}	1.06×10^{-5}	3.94×10^{-5}	3.24×10^{-5}
	Cd	/	/	2.95×10^{-11}	1.03×10^{-10}	/	/	2.69×10^{-5}	2.18×10^{-5}		
	Cr	2.68×10^{-5}	2.16×10^{-5}	6.21×10^{-8}	2.16×10^{-7}	/	/	2.95×10^{-11}	1.03×10^{-10}		
	Ni	/	/	6.26×10^{-10}	2.17×10^{-9}	/	/	6.26×10^{-10}	2.17×10^{-9}		
Suburban	As	1.06×10^{-5}	8.51×10^{-6}	8.36×10^{-13}	2.91×10^{-12}	2.85×10^{-7}	6.67×10^{-7}	1.09×10^{-5}	9.18×10^{-6}	3.59×10^{-5}	2.95×10^{-5}
	Cd	/	/	2.63×10^{-11}	9.14×10^{-11}	/	/	2.51×10^{-5}	2.03×10^{-5}		
	Cr	2.50×10^{-5}	2.01×10^{-5}	5.80×10^{-8}	2.01×10^{-7}	/	/	2.63×10^{-11}	9.14×10^{-11}		
	Ni	/	/	5.95×10^{-10}	2.07×10^{-9}	/	/	5.95×10^{-10}	2.07×10^{-9}		

Based on the results discussed above, Cr and Cd were identified as priority control HEs in all urbanization gradients in the study area due to high toxicity and potential health risks of these two HEs. On the whole, pollution risk assessment of HEs in surface dust from different urbanization gradients is a useful way to study the effects of urbanization on urban environment.

The results of the present research can provide some implications for urban environmental management efforts. Differences in the concentrations, pollution levels, and potential health risk of HEs exist among different urbanization gradients in the Urumqi city. Accumulation of HEs in urban surface dust is a dynamic process [44]. A monitoring network for urban surface dust should be established to ensure long-term monitoring on the dynamic change process of HEs in urban surface dust, which could provide more affective and updated information of HEs in urban surface dust for decision-makers. However, the exposure parameters for *CDI* estimation used in the present research were obtained from the US EPA Exposure Handbook or other related studies, which might not be very appropriate for potential health risk assessment of HEs in surface dust in the Urumqi city. Further research works should focus on the more accurate *CDI* estimation parameters to obtain a more accurate estimation of the potential human health risks of HEs in surface dust in arid land oasis cities.

4. Conclusion

In this research, a total of 41 surface dust samples were collected from the core urban, urban, and suburban gradients of the Urumqi city, NW China, and the concentrations of As, Hg, Cd, Cr, Ni, and Pb were determined. In brief, the concentrations, spatial distribution, pollution levels, and potential health hazards of these HEs were investigated and compared. Results indicated that:

1. The the average concentrations of Hg, Cr, Ni, and Pb elements in surface dust in all urbanization gradients and Cd in surface dust in core urban exceed the corresponding background values, with the highest enrichment of Hg element in surface dust in all urbanization gradients in the study area. The spatial distribution of As and Pb are similar to one another, with high concentrations were seen in the core urban and urban gradients. The high concentrations of Hg, Cd, and Ni accumulation were observed in the core urban gradient, while high concentrations of Cr were observed in the urban gradient.
2. The average *CF* values of Hg, Cd, and Ni in surface dust decrease in the order of core urban > urban > suburban, while the average *CF* values of As, Cr and Pb in surface dust decrease in the order of urban > core urban > suburban. The average *PLI* values of HEs in surface dust in the core urban, urban, and suburban gradients in the study area are 1.35, 1.29, and 1.15, respectively, at the low pollution level. The *PLI* of HEs decreased in the order of: core urban > urban > suburban. Hg is the main pollution factor in surface dust in all urbanization gradients in the study area.
3. The *HI* values of HEs in surface dust in the core urban, urban, and suburban gradients were 0.910, 0.956, and 0.839 for children, respectively, compared to 0.158, 0.166, and 0.146 for adults, respectively. Meanwhile, the *TCR* values of carcinogenic HEs in surface dust in the core urban, urban, and suburban gradients were 3.77×10^{-5}, 3.94×10^{-5}, and 3.59×10^{-5} for children, respectively, compared to 3.10×10^{-5}, 3.24×10^{-5}, and 2.95×10^{-5} for adults, respectively. The *HI* and *TCR* values of HEs for adults and children can be ranked as: urban > core urban > suburban. The potential non-carcinogenic and carcinogenic health risks of the investigated HEs, instigated primarily by oral ingestion of surface dust, are found to be within the acceptable range, and Cr is the main non-carcinogenic risk factor, whereas Cd is the main carcinogenic risk factor among the analyzed HEs in surface dust in all urbanization gradients.

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