Research Article

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Identification of the spatial distributions, pollution levels, sources, and health risk of heavy metals in surface dusts from Korla, NW China

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Abstract: A total of 54 surface dust samples were gathered from Korla in NW China, and the concentrations of six heavy metal elements, such as Hg, Cd, As, Pb, Cr, and Cu, were determined by standard methods. The geostatistical analysis, multivariate statistical analysis, pollution load index (PLI), and the US EPA health risk assessment model were used to analyze the spatial distribution, pollution, and its potential health risk of heavy metals in surface dusts, and the main sources of heavy metals were also identified. The obtained results indicate that the average concentrations of As in surface dust of Korla is lower than the background values determined in Xinjiang soil, whereas the average concentrations of Hg, Cd, Pb, Cr, and Cu elements exceeded the corresponding background values by factors of 3.71, 1.87, 1.96, 1.14, and 1.29, respectively. The higher concentration of analyzed heavy metals is observed in the northeastern and northern parts in the study area. The pollution level of heavy metals decreased in the following order: Hg > Pb > Cd > Cu > Cr > As. Based on the identified concentrations, the collected dust samples are found to be heavily polluted by Hg and slightly polluted by As, and the remaining elements, Pb, Cd, Cu, and Cr, are found to be low polluted. Furthermore, the PLI values of heavy metals in surface dust vary between 0.74 and 2.74, with an average value of 1.40, at the low pollution level. In addition, As in surface dust in the study area is mainly natural source, while Hg, Cd, Cr, Cu, and Pb are mainly anthropogenic sources. Overall, the carcinogenic and noncarcinogenic health risks of the analyzed elements, instigated mainly by oral ingestion of surface dust, are found to be within the acceptable range for both children and adults. As and Cr are the main noncarcinogenic elements, whereas Cr is the major carcinogenic element among the investigated dust-bound heavy metals in Korla.

Keywords: surface dust, heavy metal, pollution, distribution, health risks, Korla city

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1 Introduction

Surface dust is the main source and potential banks of pollutants in the urban environment [1]. Surface dust is regarded as the carrier of various environmental pollutants, such as traffic emissions, industrial emissions, and other human activities [2,3]. Heavy metal elements are harmful environmental pollutants with characteristics of high toxicity, concealment, persistent existence, and bio-accumulation [4,5]. Pollution of urban surface dust with heavy metals is a serious environmental issue when it poses a threat to the human health and urban eco-environment [6,7]. Through the circulation and migration among various ecosystems, heavy metals accumulating in surface dust can be resuspended in the atmosphere or flushed into the surrounding water system and ultimately cause potential risks [8]. In light of this information, research concerning the pollution and potential health risk of heavy metals in urban surface dust has emerged as an important frontier in environmental research [9,10].

Numerous studies have been carried out on heavy metals in surface dusts in super cities or towns all over the word in recent decades, whose spatial distribution patterns [11], source identification [12], ecological risk assessment [13], and health risk assessment [5] were conducted. Some researches focused on the dusts on the urban roads [1] and national highways [6]. Some other researches reported the pollution risks of heavy metals in surface dust from urban living areas [14], shops [15], bus stations [16], urban parks [17], schools [3,18], different functional urban areas [19], driving schools [20], and gas stations [21]. Meanwhile, pollution risks of heavy metals in indoor dusts [22] and surface dusts from different urban functional zones [23] have also been reported. Many of these literature indicate that heavy metals in surface dust in different parts of cities make a significant contribution to pollution of urban environments, and the main anthropogenic sources of heavy metals in surface dust include industrial activities, traffic-related activities, urban construction, and the use of pesticides and fertilizers. The spatial distribution patterns of heavy metals in surface dust are primarily affected by anthropogenic activities [8,11]. The pollution level of most heavy metals in surface dust from industrial area and traffic area are relatively higher than those of residential area and commercial area [24]. It is worth mentioning that heavy metal concentrations of surface dusts from the parks and educational areas of some cities exceed their background values of the soils [8,25]. With the more and more intense human activities in urban areas, a large amount of heavy metals will be continuously discharged into the urban environment and threatened the whole eco-environment and human health. Therefore, the assessment of heavy metal pollution risks of urban surface dust is very important since it is a basic work for the sustainable development.

Korla, the largest city and the economic center of the southern Xinjiang, is an important industrial city in northwest arid zones of China. It is also an important city of the "silk road economic belt." In recent decades, due to rapid urban developments and increasing traffic density, Korla has been influenced by various types of urban human activities, and thus, the environmental pollution by particulate matters (PMs) and surface dust has become a serious environmental issue [10,26]. So far, however, there is no published literature found yet on the heavy metal pollution assessment of the surface dust of the Korla, and it is necessary to investigate the pollution levels, sources, and potential health risks of hazardous heavy metals in the surface dusts in this area. This research investigates, for the first time, the heavy metal pollution of surface dusts from the most industrialized city, the Korla, in Xinjiang, China. Surface dust samples were collected from 54 locations, and concentrations of six hazardous heavy metals (mercury [Hg], cadmium [Cd], arsenic [As], lead [Pb], chromium [Cr], and copper [Cu]) in the collected samples were determined by standard methods. The spatial distribution, pollution levels, possible sources, and potential health risks of heavy metals in surface dust were assessed using the geostatistical analysis, multivariate statistical analysis, the pollution load index (PLI), correlation analysis,

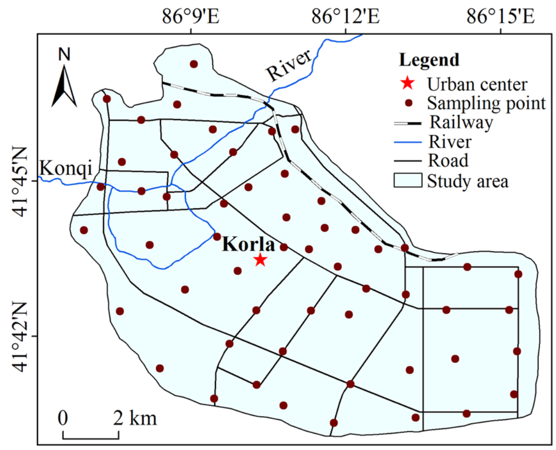

Figure 1: Location of Korla and sampling points.

cluster analysis, and the health risk assessment model introduced by the United States Environmental Protection Agency (US EPA).

2 Study area

The research area (85°06′–86°16′E and 41°37′–42°48′N) is located in the northeastern edge of Taklimakan Desert, the southern slope of Hora Mountains, and the alluvial fan plain of Konqi River, with a total area of 108.8 km^2 (Figure 1). The terrain is high in the north and low in the south and high in the west and low in the east, at altitudes ranging between 890 and 950 m. Korla has a continental desert climate, with an average annual temperature, precipitation, and evaporation capacity of 11.4°C, 50 mm, and 2,800 mm, respectively. Sandstorms are frequent, and the dominant wind direction is northeast [27]. The research area is rich in mineral resources, such as coal, iron, andalusite, manganese, oil, and other minerals, and the reserves of andalusite are the first in China. A new generation of pillar industries is dominated by manufacturing, production and supply of electricity, petroleum and petrochemical industry in recent years.

3 Materials and methods

3.1 Sample collection, analysis, and quality control

A total of 54 surface dust samples were collected, in the light of sampling methods introduced by MAPRC [28], from different locations in Korla (Figure 1). Samples were collected in September 2018 following the conclusion of a long dry period of about 1 month. The surface dust samples were mainly gathered by gently sweeping at all sampling sites, a comparable area of 1 m^2 from road surface, pavement edges, roofs of buildings, and windowsill in the study area. At each sampling location, five subsamples of surface dust were gathered. Subsequently, the subsamples were mixed in a polyethylene bag and transferred to the laboratory as one composite surface dust sample. In the laboratory, the sampled surface dust was air dried, then ground, and sieved through a 0.15 mm nylon mesh. After digestion, the concentrations of six heavy metals (Hg, Cd, As, Pb, Cr, and Cu) in the collected samples were determined by standard methods. All digested samples, laboratory blanks, and standard spiked samples (Chinese national standards samples, GSS–12) were analyzed for quality control and quality assurance. The recoveries of samples that were spiked with standards ranged from 94 to 106%. All of the surface dust samples were tested repeatedly, and the determined consistency of the repeated element measurements was higher than 95%. The concentrations of As and Hg were measured by using an atomic fluorescence photometer (BAF-2000), while the concentration of Cd was measured by using an atomic absorption spectrometer (SOLAAR-M6), the concentrations of Cr and Cu were measured by using an ICP optical emission spectrometer (ICP-5000), and the concentration of Pb was measured by using an atomic absorption spectrometry (ICE-3500). The detection limits for Hg, Cd, As, Pb, Cr, and Cu are 0.002, 0.01, 0.01, 0.10, 0.40, and 0.10 mg/kg, respectively.

3.2 Pollution assessment of heavy metals

Based on the background value of soil in Xinjiang [10], the pollution level of heavy metals in dust samples are assessed by the PLI [29]. It is calculated based on the following equation:

$$P_i = C_i/C_\mathrm{b}, \tag{1}$$

$$\mathrm{PLI} = \sqrt[n]{P_1 \times P_2 \times \cdots P_n}, \tag{2}$$

where P_i indicates the pollution index for element i, C_i is the concentration of element i, C_b is the background value of element i in the soils of Xinjiang, and PLI indicates the PLI. The five categories of P_i are used to describe the pollution level of a single element: unpolluted ($P_i \le 0.7$), slightly polluted ($0.7 < P_i \le 1$), low polluted ($1 < P_i \le 2$), moderately polluted ($2 < P_i \le 3$), and heavily polluted ($P_i \ge 3$). The four categories for the PLI are used: unpolluted ($\mathrm{PLI} \le 1$), low polluted ($1 < \mathrm{PLI} \le 2$), moderately polluted ($2 < \mathrm{PLI} \le 3$), and heavily polluted ($\mathrm{PLI} \ge 3$) [26,29].

3.3 Health risk assessment of heavy metals

3.3.1 Exposure analysis

The level of exposure to heavy metals in surface dust was estimated using the chronic daily intake (CDI; mg/kg/day). Three main exposure pathways of PM intake, such as incidental oral ingestion, inhalation, and dermal contact, were considered. The CDI in the three exposure pathways was calculated by the following equations [30–32]:

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

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

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

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

The CDI values of surface dust via the three exposure pathways were calculated using the parameters listed in Table 1.

3.3.2 Noncarcinogenic risk assessment

The noncarcinogenic potential health risk for an individual heavy metal was estimated as the hazard quotient (HQ) as in equation (7):

$$\mathrm{HQ} = \mathrm{CDI/RfD}, \tag{7}$$

where RfD indicates the reference dose (mg/kg/day), which is an estimation of a daily exposure to the human population. In consideration of the estimation of the overall noncarcinogenic health risk posed by all analyzed heavy metals in surface dusts, the calculated HQ values of heavy metals were summed and represented as a hazard index (HI).

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

According to the US EPA [32], If HI < 1, it is considered that “no significant health risk” of noncarcinogenic effects of surface dust exists. However, when HI > 1, then there is a probability of noncarcinogenic effects of surface dust occurring.

Table 1: The exposure parameters used to estimate CDI

Factor	Meaning and units	Values		Ref.
		Adults	Children	
IngR	Dust ingestion rate (mg/d)	100	200	[33]
InhR	Dust inhalation rate (m^3/d)	16.2	7.5	[17]
CF	Unit conversion factor (kg/mg)	1×10^{-6}	1×10^{-6}	[31]
EF	Exposure frequency (d/a)	350	350	[34]
ED	Exposure duration (year)	24	6	[33]
SA	Exposed skin area (cm^2)	16,000	7,600	[35,36]
AF	Skin adherence factor (mg/cm^2/d)	0.07	0.20	[33]
ABS	Dermal absorption factor (unitless)	0.001	0.001	[33]
PEF	Article emission factor (m^3/kg)	1.36×10^9	1.36×10^9	[33]
BW	Average body weight (kg)	62.4	20.08	[35,36]
AT_{nc}	Average exposure time for noncancer (d)	ED × 365	ED × 365	[37]
AT_{ca}	Average exposure time for cancer (d)	70 × 365	70 × 365	[37]

3.3.3 Carcinogenic risk assessment

The carcinogenic risks of Cd, Cr and As elements, which are considered as the carcinogenic heavy metals [38], from three exposure pathways were estimated using equations (9) and (10).

$$CR = CDI \times SF, \quad (9)$$

$$TCR = \sum CR = CR_{ingest} + CR_{inhale} + CR_{dermal}, \quad (10)$$

where CR is the carcinogenic risk for an individual heavy metal (unitless), TCR is the total carcinogenic risk posed by all analyzed heavy metals (unitless), and SF is the carcinogenic slope factor of heavy metals (mg/kg/day).

The acceptable or tolerable TCR value for regulatory purposes is from 1×10^{-6} to 1×10^{-4}, while the TCR value exceeding 1×10^{-4} is regarded as unacceptable. The TCR value below 1×10^{-6} is not considered to pose significant health effects [39]. The RfD and SF values of analyzed heavy metals are selected according to the relevant literature [10,16,17,40] (Table 2).

3.4 Statistical analysis

The original data of six heavy metals (Hg, Cd, As, Pb, Cr, and Cu) in the collected surface dust samples were summarized using ranges, median values, average values, standard deviations, and coefficients of variation (ratio of the standard deviation to the mean). The multivariate statistical analysis including Pearson's correlation coefficient analysis, and cluster analysis (CA), based on the Ward's method, were used to identify the possible sources of heavy metals in surface dust. The statistical analysis was performed by Origin software (Origin 2018, Origin Lab, USA).

3.5 Geostatistical analysis

The spatial distribution patterns of the six heavy metals in surface dust in the study area were illustrated based on the geostatistical analysis method. The geostatistical analysis method is an effective way to identify the spatial heterogeneity and spatial patterns of heavy metal concentrations in surface dust [10,41]. The main tool in the geostatistical analysis is the semivariogram function, $\gamma(h)$, which shows the spatial dependence between neighboring observations [41]. The semivariogram can be defined as the following equations:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (11)$$

where $\gamma(h)$ is the semivariogram, h is the distance between sampling sites, $Z(x)$ is the magnitude of variable, and $N(h)$ is the total number of pairs of attributes that are separated by h. The $\gamma(h)$ includes exponential model, Gaussian model, and spherical model [41]. To describe the spatial distribution patterns of the concentrations of heavy metals in surface dust, geochemical maps were applied by using ArcGIS 10.2 software (ArcGIS 10.2, ESRI Company, USA) and method of the Ordinary Kriging Interpolation.

Table 2: The RfD and SF values of noncarcinogenic and carcinogenic metals

Elements	RfD/mg/(kg d)			SF/(kg d)/mg		
	Oral ingestion	Inhalation	Dermal contact	Oral ingestion	Inhalation	Dermal contact
As	0.0003	0.000123	0.0003	1.50	0.0043	1.50
Cd	0.001	0.001	0.00001	—	6.30	—
Cr	0.003	0.0000286	0.00006	0.50	42.0	—
Cu	0.040	0.0402	0.012	—	—	—
Pb	0.0035	0.00352	0.000525	—	—	—
Hg	0.0003	0.0003	0.000024			

4 Results and discussions

4.1 The concentrations of heavy metals in surface dusts

The minimum, maximum, average, and background concentrations of the analyzed heavy metals in surface dust in Korla are presented in Table 3, along with the standard deviation and the coefficient of variation (CV). It should be noted that the background values refer to the heavy metal concentrations of soils in Xinjiang. As shown in Table 3, on average, the concentrations of Hg, Cd, As, Pb, Cr, and Cu in the collected surface dust samples are 0.063, 0.224, 10.65, 37.93, 56.44, and 34.33 mg/kg, respectively. Except for As, all heavy metals present average concentrations higher than the corresponding background values. For Hg, Cd, Pb, Cr, and Cu elements, the average concentrations exceed the background values in Xinjiang soils by factors of 3.71, 1.87, 1.96, 1.14, and 1.29, respectively. It appears that the concentrations of Hg, Cd, and Pb in surface dust were significantly higher than their corresponding background values. Based on these results, Hg, Cd, and Pb are particularly more abundant in surface dust in Korla.

Table 3: Statistics of heavy metal concentrations in surface dust in Korla (n = 54)

Items	Hg	Cd	As	Pb	Cr	Cu
Minimum/(mg/kg)	0.010	0.042	5.41	8.62	30.20	13.10
Maximum/(mg/kg)	0.539	4.200	19.50	142.0	164.0	155.0
Median/(mg/kg)	0.033	0.120	10.25	33.35	53.85	29.0
Average/(mg/kg)	0.063	0.224	10.65	37.93	56.44	34.33
St.D/(mg/kg)	0.09	0.56	2.31	21.91	17.29	21.06
CV	1.43	2.52	0.22	0.58	0.31	0.61
Background value/(mg/kg)	0.017	0.120	11.20	19.40	49.30	26.70

The standard deviations in heavy metal concentrations are relatively higher, as presented in Table 3. This explains that the concentrations of each heavy metal vary significantly from one sampling point to the other. CV shows the different dimensions of indicators. The CV listed in Table 3 indicates the spatial variation of the given metal data. The higher CV value indicates the bigger anthropogenic influence [26]. CV values lower than 0.2 reflect low variability, CV values between 0.2 and 0.5 reflect moderate variability, and CV values within 0.5–1.0 and those greater than 1.0 reflect high and extremely high variability, respectively [42]. Based on this criterion and the calculated CVs of the analyzed species, the CVs of Hg and Cd are 1.43 and 2.52, respectively, with extremely high variation. The CV values of Pb and Cu are 0.58 and 0.61, with high variation. It indicates that the spatial distribution of Hg, Cd, Pb, and Cu elements in surface dust is quite different, and these elements in surface dust are more likely to be affected by extrinsic factors, such as traffic and industry. However, CVs for As and Cr are 0.22 and 0.31, respectively, with moderate variation. It explains that As and Cr in surface dust in the study area may less affected by external factors.

4.2 The spatial distribution of heavy metals in surface dusts

Spatial distribution of heavy metals in surface dusts is typically analyzed using the geostatistical analysis method [12,43]. In this study, the spatial distribution patterns of the six heavy metals in surface dust in the study area were illustrated using the ordinary Kriging interpolation based on the geostatistical analyses method and GIS technology (Figure 2). Empirical analysis shows that the distribution of concentration data of six heavy metals in this study does not follow normal distribution but log-normal distribution. Therefore, the concentration data after logarithmic transformation is used during the geostatistical analysis.

The patterns depicted in Figure 2 are substantially heterogeneous, with each heavy metal showing a different distribution feature. The high concentrations of Hg were mainly observed in the northern areas, and along this direction, the high value areas of Hg were obviously expanded into the urban center. Areas such as old sections of the city have large population, frequent human activities, and frequent commercial activities. The low concentrations of Hg were detected primarily in the western and eastern areas investigated in this study. The concentration of As is lower than the background value of Xinjiang, whereas high concentration of As is located in eastern areas and low concentration in the southwestern in the study area. Cd, Pb, Cr, and Cu elements in the study area show similar spatial distribution patterns. The high values of these four elements were mainly distributed in

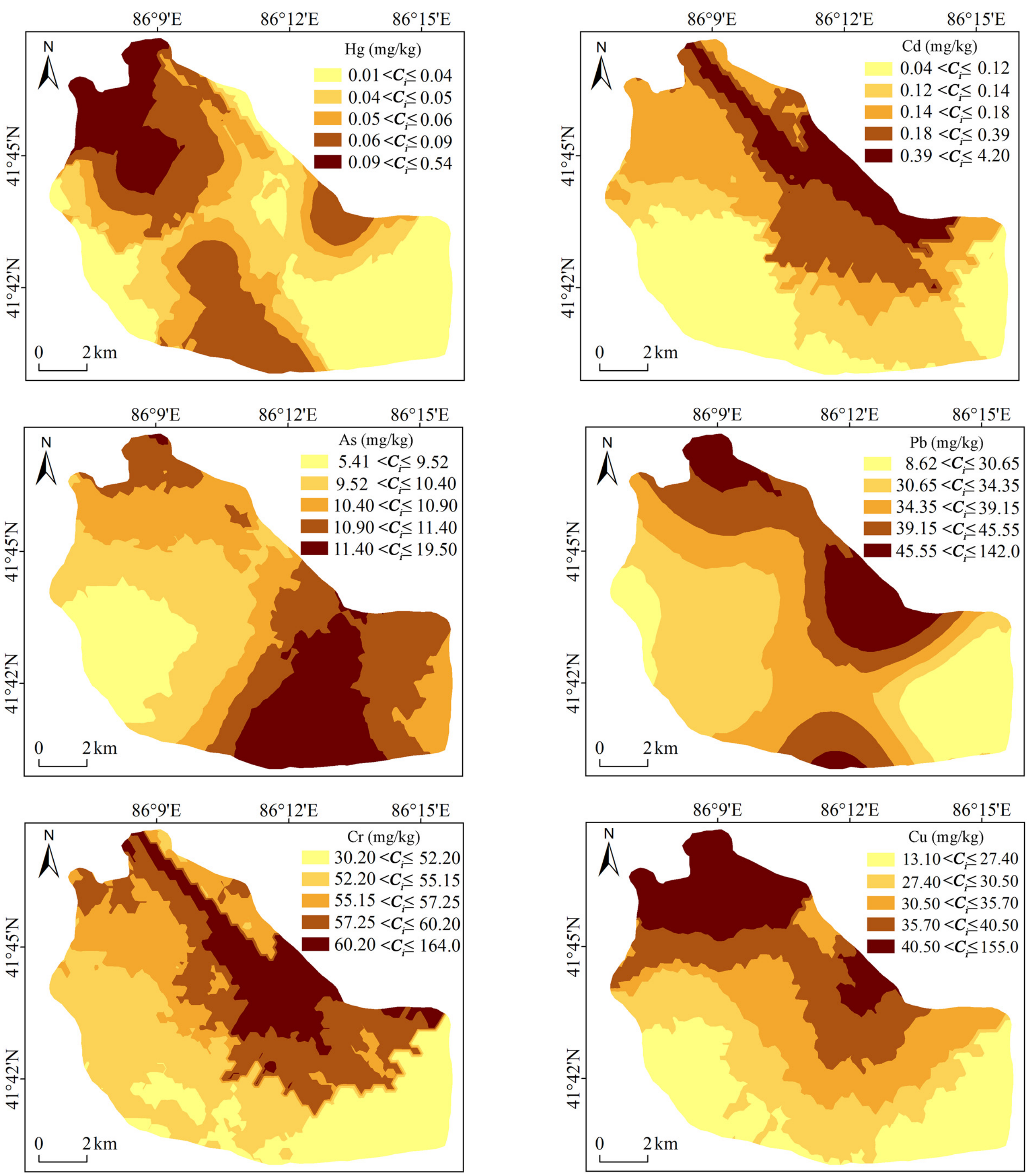

Figure 2: Spatial distributions of heavy metal concentrations in surface dust in Korla.

northeastern and northern parts of the study area, and the concentrations of these four elements decreased gradually from the northeast to the southwest of the study area. Industrial activities are relatively frequent, and traffic density is relatively higher in these areas. Overall, based on the field investigation in the study area, the concentrations of Hg, Cd, Pb, Cr, and Cu in surface dust near main roads, factories, and residential areas in the northern parts of the study area are relatively high. It indicates that pollution emissions from urban life, industrial production, and transportation are most likely the main sources of heavy metals in surface in the study area.

4.3 Pollution assessment of heavy metals in surface dusts

The heavy metals identified in the surface dusts in Korla were categorized based on the values of the single-factor pollution index (P_i) and PLI. The box and whisker plots shown in Figure 3 summarize the basic statistics for the P_i and PLI value of heavy metals investigated in the surface dust in the study area. As shown in Figure 3, the P_i values of heavy metals decrease in the order of Hg > Pb > Cd > Cu > Cr > As, with higher P_i values indicating greater levels of pollution. According to the classification standard of P_i, the analyzed heavy metals in surface dusts are heavily polluted by Hg ($P_i = 3.71$) and slightly polluted by As ($P_i = 0.95$). The remaining elements, Cd ($P_i = 1.86$), Pb ($P_i = 1.96$), Cr ($P_i = 1.14$), and Cu ($P_i = 1.29$), are found to be low polluted. The PLI of heavy metals in surface dust vary between 0.74 and 2.74, with an average value of 1.40, at the low pollution level.

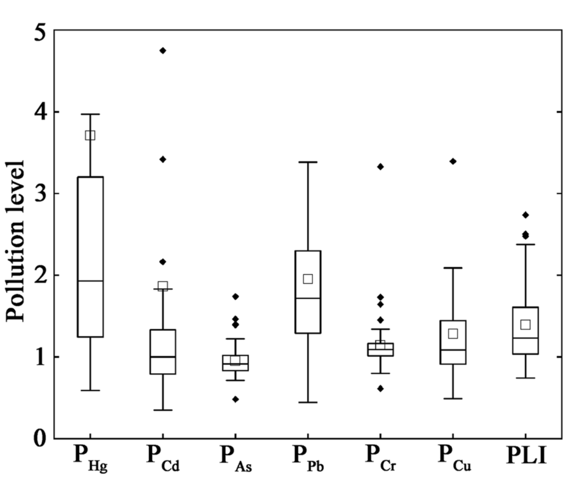

Figure 3: Boxplot of pollution levels of heavy metals in surface dust in the study area.

However, based on the maximum P_i and PLI values of heavy metals, the surface dusts are heavily polluted by Hg ($P_i = 31.71$), Cd ($P_i = 35.0$), Pb ($P_i = 7.32$), Cr ($P_i = 3.33$), and Cu ($P_i = 5.81$), and low polluted by As ($P_i = 1.74$). The maximum PLI value is 2.74 at the moderately pollution level. This implies that heavy metals, particularly Hg, Cd, Pb, Cr, and Cu, are significant pollutants in surface dusts in Korla and thus should be monitored closely. In addition to being primary pollutants, Hg, Cd, Pb, and Cu show relatively high CVs and standard deviations for P_i values, which means that the pollution levels of these elements vary significantly from one sampling point to the other. Therefore, it may be concluded that the degree of pollution is correlated with the anthropogenic activity.

4.4 Main sources of heavy metals

Heavy metals in surface dust are directly produced by industrial emissions, traffic emissions, domestic activities, and soil geochemistry [8,44]. Multivariate statistical analyses, including correlation analysis and CA, are widely used to identify the pollution hot spots and potential sources of heavy metals [45]. A significant correlation between heavy metals indicates that there may be similar origins of heavy metals. On the contrary, low correlation shows that heavy metals have weak dependence and different origins [12]. Table 4 lists Pearson's correlation coefficients of the investigated heavy metals in surface dust in the study area. As presented in Table 4, the correlations among Cd–Pb–Cr–Cu, Pb–Cr–Cu, and Cu–Cr were detected using the significance test at 0.01 levels, with significant positive correlations, as well as with the correlations between Hg–As–Pb–Cu detected using the significance test at 0.05 levels. This indicates that Hg, Cd, As, Pb, Cr, and Cu in the surface dust of Korla may share similar characteristics or common origins.

Table 4: Correlation matrix for heavy metals in the surface dust in Korla

Metals	Hg	Cd	As	Pb	Cr	Cu
Hg	1	0.078	0.288*	0.297*	0.026	0.307*
Cd		1	0.186	0.509**	0.464**	0.485**
As			1	0.151	−0.016	0.261
Pb				1	0.476**	0.628**
Cr					1	0.663**
Cu						1

Note: ** $P < 0.01$; * $P < 0.05$.

Hierarchical clustering is a way to investigate groupings in the data simultaneously over a variety of scales and distances. It does this by creating a cluster tree with various levels. The tree is a multilevel hierarchy where clusters at one level are joined as clusters at the next higher level. The algorithm that is used starts with each case or variable in a separate cluster and then combines clusters until only one is left. This allows the researcher to decide what level of clustering is most appropriate for his or her research. Due to the complex relationship among the elements, the CA, based on the Ward's method, was used to identify specific similar origins of heavy metals that are highly correlated and to distinguish the natural and anthropogenic inputs of these heavy metals. The CA of the heavy metals generates the dendrograms (Figure 4). The results of this hierarchal clustering analysis indicate three distinguished clusters of heavy metals (according to 10 height distances), As into Cluster 1; Hg into Cluster 2; and Cd, Pb, Cr, and Cu elements were grouped into Cluster 3, which indicate that they share the common origins. This corresponds to the results of correlation analysis.

Cluster 1 includes the As element that show lower average concentrations in surface dust compared to the corresponding background values in Xinjiang soils. This element is predominantly controlled by the geochemical composition of the soil's parent material and geogenic processes based on its identified concentration and pollution level [46,47]. Therefore, As in surface dust in the study area is mainly originated from the parent material of soil formation and geogenic processes, and it is mainly lithological (natural) origin.

Cluster 2 of element is Hg. Previous study reported that the main origins of Hg in surface dusts are commercial activities (mainly the wholesale markets and commodity exchange markets in the northwestern parts of the study area), family sources, and other human activities in urban areas [48]. Hg was the most polluted element in the surface dust in Korla, and the average concentration of Hg is 3.71 times of the corresponding background value, which is greatly affected by human pollution. Besides, the higher concentrations of Hg were mainly located in the northern areas and the urban center, which have higher population density, frequent human activities, and frequent commercial activities. Therefore, it can be concluded that the Hg element in surface dust in Korla is mainly human sources, which is affected by the urban commercial activities and domestic pollution sources.

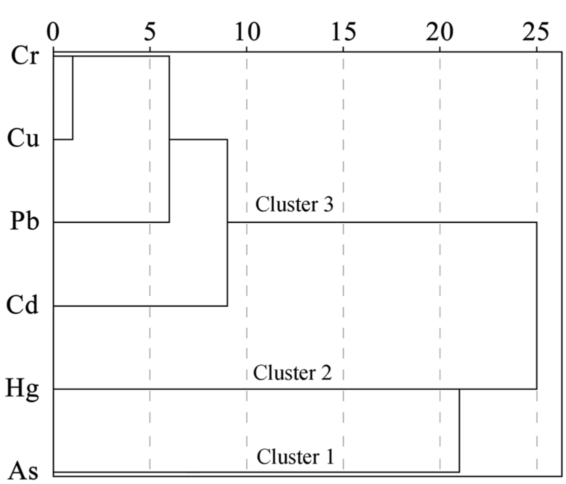

Figure 4: Hierarchical dendrogram of heavy metals in surface dust in Korla.

Cluster 3 is composed of the significantly correlated Cd, Pb, Cr, and Cu elements in surface dust. It indicates that these four elements share the common origins. Previously, it was reported that Pb and Cd elements in surface dust mainly originates from the emission sources of vehicle exhaust, lubricating oil, bearings, tire wear, oil products, and smelting [25,49]. Other related studies [25,45] reported that Cu in surface dust originates from the wear of brake lining, and the wear of automobile metal parts, and Cr in surface dust is associated with industrial emission. Besides, during the industrial production process, equipment containing Cr is easily oxidized to Cr^{6+}-based compounds under high temperature and high oxygen calcination partial pressure [49,50]. The average concentrations of Cd, Pb, Cr, and Cu in surface dust in Korla were 3.71, 1.87, 1.96, 1.14, and 1.29 times of the corresponding background values, respectively. The higher concentrations values of these four elements were mainly distributed in the northeastern and northern areas, such as areas along the railway and national highway (G30, G218), with frequent industrial activities and higher traffic density. Zhang and Li [51] reported that the total number of motor vehicles in Korla exceeded 20×10^4. Meanwhile, as a typical coal-fired city, Korla has high coal consumption, with an average annual coal consumption of about 343×10^4 t [51]. Based on the aforementioned analysis, it can be concluded that Cr, Cu, Pb, and Cd elements in surface dust in Korla are of anthropogenic origin, which are mainly affected by traffic emission and incomplete fossil fuel combustion.

4.5 Noncarcinogenic risk of heavy metals

The potential health risks of heavy metals in surface dust in Korla were estimated using the health risk assessment model introduced by the US EPA. Considering the physiological and behavioral differences between adults and children, both were used to estimate effects of heavy metals on human health. The CDI of each heavy metal via the incidental oral ingestion, inhalation, and dermal contact exposure pathways was calculated for adults and children, and the HQs and hazard indexes (HI) were calculated based on the results of CDI estimation. Table 5 presents that the average HQ values for adults and children, which were ranked as follows: $HQ_{As} > HQ_{Cr} > HQ_{Pb} > HQ_{Cu} > HQ_{Cd} > HQ_{Hg}$. The HQ values of As and Cr elements were much higher than those of other four elements, and they account for 46.0 and 37.92% of the total HI for adults compared to 48.17 and 34.93% of the HI for children, respectively. Therefore, As and Cr elements are identified as major contributors to the noncarcinogenic human health risks of heavy metals in surface dust in Korla. When ranked based on exposure pathways, the HI for different exposure pathways decreases in the following order: $HQ_{ingest} > HQ_{dermal} > HQ_{inhale}$. It explains that incidental oral ingestion is the main pathway of exposure to noncarcinogenic health risks of heavy metals in surface dust in the study area. The HI value of heavy metals for children (0.71) is 5.92 times higher than that for adults (0.12). This is basically due to the fact that children are more sensitive to a given dose of toxin and more likely to inadvertently ingest the surface dust [52,53]. These results indicate that heavy metal pollution of surface dusts is more harmful to health of children than to adults. Overall, the total HQ and HI values lower than 1, for both children and adults, indicates that heavy metals in surface dust in the study area do not pose any long-term noncarcinogenic health impacts [33].

4.6 Carcinogenic risk of heavy metals

The potential carcinogenic health risks of three carcinogenic heavy metals, such as Cd, As, and Cr, were estimated based on the carcinogenic slope factors (SF) of these elements. The estimated carcinogenic risk indexes (CR) for an individual heavy metal and the total carcinogenic risk indexes (TCR) posed by all analyzed heavy metals via the incidental oral ingestion, inhalation, and dermal contact exposure pathways are listed in Table 6.

As shown in Table 6, Cr in surface dust shows the highest average CR value, whereas Cd in surface dust shows the lowest average CR value for adults, as well as for children. The CR values of Cr accounts for 63.83 and 63.91% of the TCR values for adults and children, respectively. Therefore, among the analyzed heavy metals, Cr poses the highest potential carcinogenic health risk to human. Table 6 presents that incidental oral ingestion is the main pathway of exposure. Similar to potential noncarcinogenic health risks, the TCR value of heavy metals for children (3.63×10^{-5}) is 1.54 times higher than that of adults (2.35×10^{-5}). It is clear that the TCR values of both groups are low, which indicates that heavy metals in surface dust in the study area do not pose any noncarcinogenic health risks.

Overall, it can be concluded that As and Cr elements are selected as priority control heavy metals in surface dusts in Korla due to the higher potential human health risks of these elements. Therefore, it is necessary to control their production so as to reduce any potential health impacts to human.

The spatial distribution patterns of HI and TCR value of heavy metals in surface dust were analyzed based on the geostatistical analysis and GIS technology (Figure 5). The patterns illustrated in Figure 5 were substantially analogous and showed obvious regional differentiation characteristics. In general, the high values of HI and TCR of adults and children are mainly distributed in the northeastern areas, and the risk index decreased upon moving away from the northeastern areas of the study area. This corresponds to the results of spatial distribution of concentrations of heavy metals in surface dust. Based on the main sources analysis, these high health risk areas are mainly affected by urban commercial activities, industrial activities, traffic, fuel combustion, and domestic pollution sources.

Table 5: The noncarcinogenic risk indexes of heavy metals in surface dust in Korla

Elements	HQ_{ingest}		HQ_{inhale}		HQ_{dermal}		HQ_{total}		HI	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children	Adults	Children
Hg	3.23×10^{-4}	2.01×10^{-3}	3.85×10^{-8}	5.53×10^{-8}	4.52×10^{-5}	1.91×10^{-4}	3.68×10^{-4}	2.20×10^{-3}	**0.12**	**0.71**
Cd	3.44×10^{-4}	2.14×10^{-3}	4.09×10^{-8}	5.89×10^{-8}	3.85×10^{-4}	1.62×10^{-3}	7.29×10^{-4}	3.76×10^{-3}		
As	5.45×10^{-2}	3.39×10^{-1}	1.58×10^{-5}	2.28×10^{-5}	6.11×10^{-4}	2.58×10^{-3}	5.52×10^{-2}	3.42×10^{-1}		
Pb	1.67×10^{-2}	1.04×10^{-1}	1.97×10^{-6}	2.84×10^{-6}	1.24×10^{-3}	5.24×10^{-3}	1.79×10^{-2}	1.09×10^{-1}		
Cr	2.89×10^{-2}	1.80×10^{-1}	3.61×10^{-4}	5.20×10^{-4}	1.62×10^{-2}	6.83×10^{-2}	4.55×10^{-2}	2.48×10^{-1}		
Cu	1.32×10^{-3}	8.20×10^{-3}	1.56×10^{-7}	2.25×10^{-7}	4.92×10^{-5}	2.08×10^{-4}	1.37×10^{-3}	8.40×10^{-3}		

Table 6: The carcinogenic risk indexes of heavy metals in surface dust in Korla

Elements	CR_{ingest}		CR_{inhale}		CR_{dermal}		CR_{total}		TCR	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children	Adults	Children
Cd	—	—	8.84×10^{-11}	3.18×10^{-11}	—	—	8.84×10^{-11}	3.18×10^{-11}	$\mathbf{2.35 \times 10^{-5}}$	$\mathbf{3.63 \times 10^{-5}}$
As	8.41×10^{-6}	1.31×10^{-5}	2.87×10^{-12}	1.03×10^{-12}	9.42×10^{-8}	9.94×10^{-8}	8.51×10^{-6}	1.32×10^{-5}		
Cr	1.49×10^{-5}	2.31×10^{-5}	1.49×10^{-7}	5.35×10^{-8}	—	—	1.50×10^{-5}	2.32×10^{-5}		

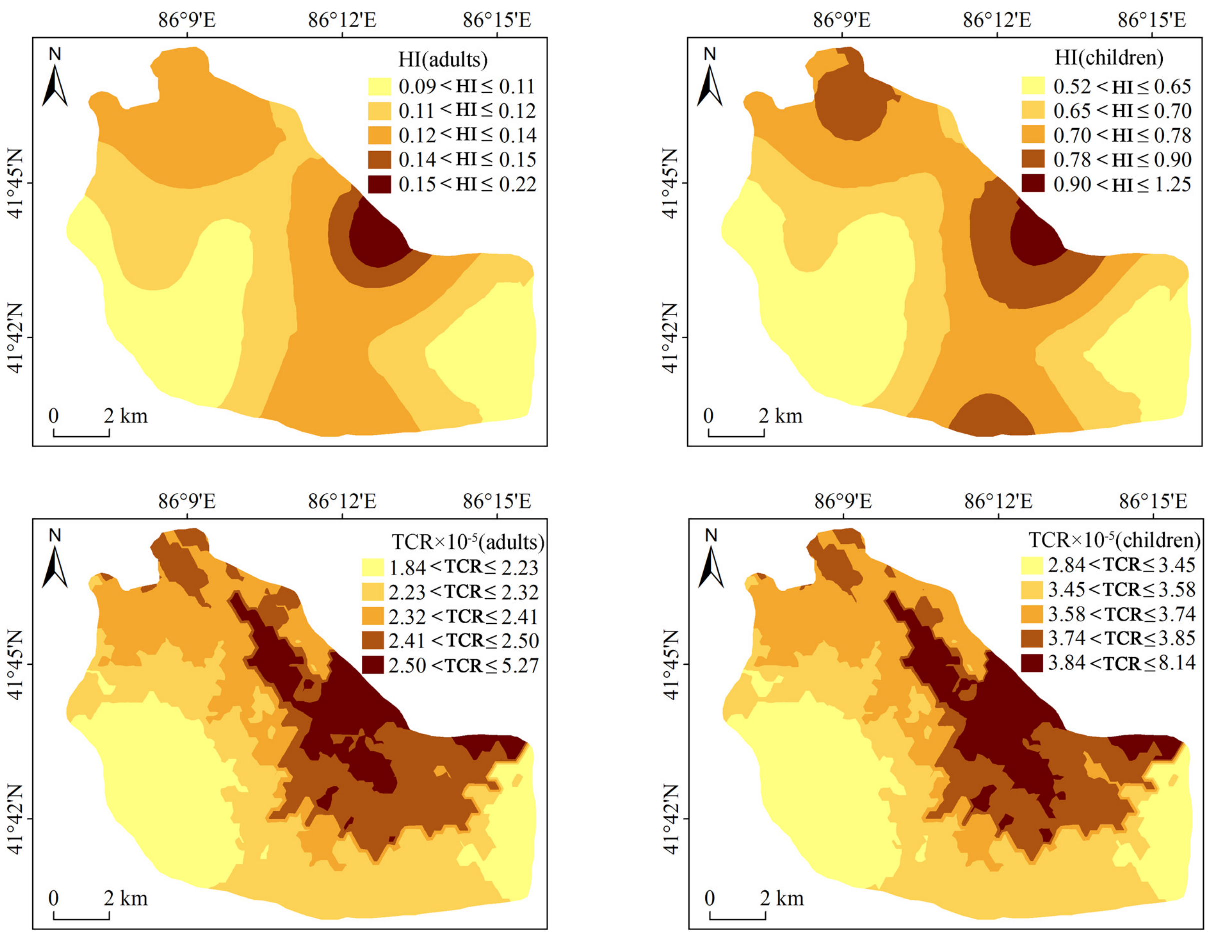

Figure 5: Spatial distribution pattern of HI and TCR.

5 Conclusions

In this research, a total of 54 surface dust samples were collected in Korla, NW China, and the concentrations of six heavy metals (Hg, Cd, As, Pb, Cr, and Cu) were determined by standard methods. The spatial distribution patterns, pollution levels, main sources, and potential human health risks of these heavy metals were estimated. Obtained results show that the average concentrations of Hg, Cd, Pb, Cr, and Cu exceed the corresponding background values in Xinjiang soils. Results of pollution assessment indicate that surface dusts in Korla are heavily polluted by Hg, slightly polluted by As, and low polluted by Cd, Pb, Cr, and Cu. Higher pollution of surface dusts are distributed in the northeastern and northern areas of the study area, based on the spatial distribution patterns of the analyzed heavy metals. Moreover, the correlation and cluster analyses demonstrate that Hg, Cd, Pb, Cr, and Cu were mainly originated from anthropogenic sources; specifically, Hg was originated from commercial activities and domestic pollution sources, and Cd, Cr, Cu, and Pb were mainly originated from transportation and incomplete fossil fuel combustion in the study area. However, As originates mainly from natural sources, which is mainly controlled by soil parent material. Results of health risk assessments indicate that oral ingestion is the main pathway of exposure to potential carcinogenic and noncarcinogenic health risks of heavy metals in surface dusts in the study area. The potential carcinogenic and noncarcinogenic risk levels are tolerable, and As and Cr are the main noncarcinogenic elements, while Cr is the main carcinogenic element. It is suggested that specific measures should be adopted to eliminate reduce health risks and to ensure the protection of human health.

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