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Original Research

Health Risk Assessment of Soil Heavy Metals in the Urban-Rural Area of Lanzhou City, Gansu Province, China

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Abstract

To investigate the health risks of typical soil heavy metals to surrounding residents of industrial land in the urban-rural area of Liuquan Town, Xigu District, Lanzhou City, China. The contents of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn were analyzed using an X-ray fluorescence spectrometer. Non-carcinogenic and carcinogenic risks of the heavy metals to children and adults were evaluated. Results showed higher soil Hg, Pb, and Zn contents in the study area than the corresponding background values of Gansu Province. The Hg pollution was the most serious, showing higher contents than the background water at 56.41% of the soil sampling sites. As, Cr, Cu, Ni, and Pb showed normal distributions, while Cd, Hg, and Zn exhibited skewed distributions. Hg and Cd showed the highest coefficients of variation of 0.966 and 0.548, respectively. Health risk evaluation results showed higher total non-carcinogenic risk (HI) and total carcinogenic risk (TCR) for children than those for adults by 5.411 and 2.156, respectively, indicating children are more susceptible to non-carcinogenic and carcinogenic risks. In addition, As, Cr, and Pb were the main contributors to the non-carcinogenic risk, while As and Cr were the main contributors to the carcinogenic risk.

Keywords: Soil, heavy metals, health risk assessment, urban-rural combination

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Introduction

Soil resources play a vital role in human life and social production [1, 2]. However, soil pollution has become a serious worldwide issue, impacting the surrounding environment considerably [3]. Therefore, soil pollution management has become a hot spot in current research [4, 5]. Heavy metals (e.g., Cd, Cr, Cu, Zn, Pb, Ni, Hg, and As) are a common class of soil contaminants, generally influenced by numerous extraneous factors (e.g., industrial and agricultural activities) [6]. The severity of soil heavy metal pollution has gradually led to the co-existence of pollutants in many areas worldwide, overlapping a variety of heavy metals and, consequently, resulting in complex soil heavy metal pollution in different areas, thus making the prevention and control of soils in polluted areas challenging [7, 8]. Previous studies on soil heavy metal contamination have revealed extremely strong abilities for contamination, enrichment, and migration of soil heavy metals derived from industrial activities in several areas, with high biological toxicity, strong hiding ability, and strong resistance to degradation, making it difficult to restore contaminated soils [9]. Health risk assessment is an effective approach for quantifying the heavy metal risks posed to human health through different exposure pathways [10]. Undeniably, heavy metal pollution can cause immense harm to the human body through various routes, including ingestion, skin contact, and inhalation. Therefore, it is necessary to evaluate the health risk associated with soil heavy metal contamination in industrial areas to protect the health of local residents.

Many scholars in China and worldwide have carried out multifaceted and multi-level evaluation studies on soil heavy metal contamination and its associated health risks in different regions. Regarding the methods used to calculate the exposure parameters, Zahida et al. [10] and Wang et al. [11] calculated the chronic daily intake (CDI) in Karachi (Pakistan) and the Hexi Corridor (Gansu Province, China), respectively, to assess the corresponding non-carcinogenic risk (HI) and carcinogenic risk (CR). Adimalla et al. [12] and Mehr et al. [13] conducted comprehensive evaluation studies on heavy metal health risks by calculating the average daily intake (ADD) and lifetime average potential daily dose (LADD) of heavy metals based on different exposure pathways in an urban region of South India and urban areas of Isfahan Province (Iran), respectively. Other researchers have used the average daily intake (ADI) to assess health risks. Li et al. [14] conducted a review of the current status of soil heavy metal contamination derived from mining activities and its associated health risk in China mining soils, highlighting continuous high carcinogenic and non-carcinogenic public risks, especially to children and people living around the most contaminated areas.

Previous studies have conducted soil heavy metal health risk assessments in different scale research areas. Jiang et al. [15] analyzed the soil heavy metal sources and health risks in a township in Jiangsu Province and showed that the total soil cancer risk level in the study area was about 10 times the acceptable risk limit. Ihedioha et al. [16] assessed the levels of some heavy metals in soils near solid waste dumpsites in Uyo, Nigeria, and assessed their associated human health risks. Adimalla et al. [17] evaluated the distribution, contamination, and health risks of heavy metal contents in the topsoil of North Telangana, India. Xiao et al. [18] assessed soil heavy metal contamination and its associated human health risk in a Liaoning iron and steel industry city (Anshan). Khan et al. [19] evaluated heavy metal contents in agricultural soils and crops, as well as their associated health risks, in the Swat region of northern Pakistan. Wu et al. [20] assessed soil heavy metal contamination and its human health risk in areas around an electronics manufacturing plant in Xiangyang, Hubei Province, China. Meihua et al. [21] assessed the characteristics and potential health risks of soil and crop heavy metal contamination in the Northeastern River Basin in China. Xiao et al. [22] studied soil heavy metal contamination and health risks associated with artisanal gold mining in Tongguan, Shaanxi, China. Li et al. [23] assessed the heavy metal contamination and health risk of soil around a lead-zinc smelter in Huize County, Yunnan Province, China.

On the other hand, several researchers have assessed soil heavy metal contamination-associated health risks for different population groups and validated health risk model parameters. Wei et al. [24] assessed soil heavy metals associated with health risks to populations near municipal waste incineration plants in China and correlated HI with CR using ADD without grouping the studied population. In contrast, Gupta et al. [25] evaluated heavy metal contamination of agricultural soils and health risks in Jhansi, India, for two population groups, namely adults and children, which is the most common grouping method applicable to several study cases. Other scholars have assessed the risks of heavy metals on health for different population groups. For example, Chen et al. [26], Yang et al. [27], and Jiang et al. [28] classified populations into 3 groups, namely adult males, adult females, and children, to accurately estimate the health risks of soil heavy metals. These studies have, indeed, used the method developed by the USEPA to extrapolate oral toxicity values and dermal absorption slope for dermal risk assessment due to the lack of reference doses for dermal absorption evaluations.

China is at the forefront of economic development. However, soil pollution has been caused by the promotion of industrialization in the early stages of development and the neglect of environmental issues [29]. The provincial capital of Gansu Province (Lanzhou) in Northwest China is a typical industrial city that has experienced rapid industrialization in recent years, contributing significantly to the development of Northwest China. However, this industrialization has resulted in serious environmental pollution [29]. At present, the impact of heavy metals on the environment is very serious. The current research mostly uses chemical remediation and bioremediation, but the effect is not significant and also has a slow time frame, triggering the existence of other risks [29].

In this paper, the study area, Liuquan Town, is located in Xigu District, Lanzhou City, which is a typical industrial area in China. The study area has experienced rapid development in recent years, aggravating the negative impacts of industrial activities on the natural environment and surrounding residents near the industrial areas, thus posing potential health risks. Current related studies in the region have focused only on heavy metal pollution and the health risks to children associated with heavy metal pollution of drinking water and vegetables [30, 31]. However, to the best of our knowledge, there is a lack of assessment studies on the health risks associated with soil heavy metal pollution in the study area. Huang et al. [32] assessed soil heavy metal pollution and its potential sources in Lanzhou City. Local residents in the region may be threatened by the carcinogenic and non-carcinogenic risks of soil heavy metals.

In this paper, we conducted soil sampling in the urban-rural combination of Liuquan Town, Xigu District, Lanzhou City, Gansu Province, to evaluate the health risk associated with soil heavy metal contents. Heavy metal contents in the soil samples were determined using a portable X-ray fluorescence spectrometer (XRF). In addition, the carcinogenic and non-carcinogenic risks were evaluated separately for adults and children in the study area using health risk characterization models. The results of the study are intended to objectively and systematically reflect the potential health risks in the region, providing a scientific and accurate reference basis for ensuring effective management of heavy metal pollution and protection of residents' health in the study area.

Materials and Methods

Study Area

Lanzhou is a prefecture-level city and the capital of Gansu Province, China (Fig. 1a). It is one of the important central cities in the western region of China and an important node city of the Silk Road Economic Belt. Lanzhou City is one of the Chinese cities that initiated industrialization at an early stage. Lanzhou City has experienced rapid development in recent years. Indeed, a total of 237 industrial parks were established in Lanzhou City, which may lead to environmental pollution [32, 33]. Xigu District, in the western part of Lanzhou City (Fig. 1b), is the core industrial zone of Gansu Province and Lanzhou City. In addition, Lanzhou has carried out eight national key construction projects, seven of which are in Xigu District, involving the four major industries of petroleum, chemical, machinery, and smelting. After years of development, it has formed a complete industrial system of electric power,

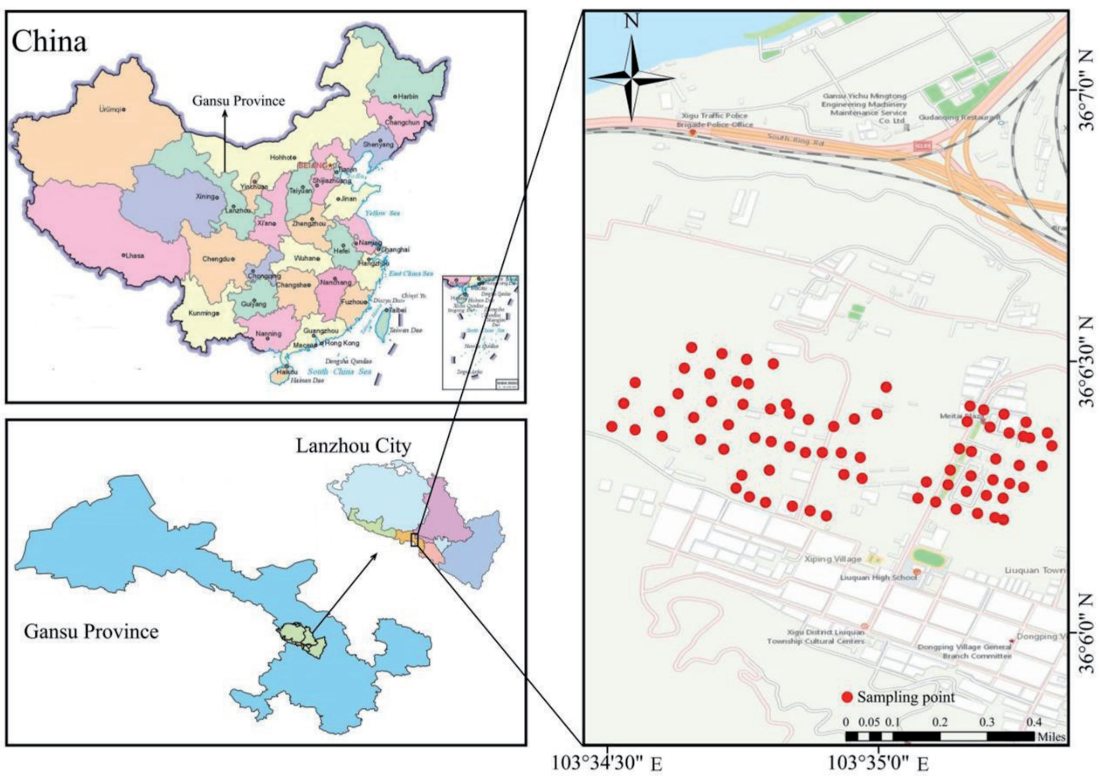

Fig. 1. Geographic locations of the study area and soil sampling sites.

chemistry, smelting, etc., which is a typical industrial area in the northwest of China, and the core industrial area of Gansu Province and Lanzhou City, and the largest petrochemical industry base in the west of China [30].

Despite its small area of only 17.87 km^2, Liuquan Town includes more than 50 industrial enterprises, which may result in potential environmental pollution and associated human health risks.

Sample Collection

A total of 78 surface soil samples were collected from farmland, orchards, and wasteland areas in the urban-rural combination of industrial areas using the grid distribution method, taking into account the distribution of functional areas (Fig. 1). Soil samples were collected from the 0-20 cm soil layer using a shovel, then placed in numbered, sealed bags. In addition, the GPS coordinates of each sampling site were recorded. The collected soil samples were first dried in a dry and light-free place in the laboratory, then large impurities, such as stones, plant residues, and animal residues, were removed. Afterward, 50g of soil samples were crushed with a wooden stick, ground, and sieved through a 100-mesh nylon sieve, then pressed into tablets under 10-t pressure in a manual tabletop press and placed in numbered bags.

Heavy Metal Analysis

The prepared soil samples were analyzed for the contents of eight heavy metals, namely As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn, using a portable XRF with a soil test mode. In addition, the composition of the standard solid reference material (GBW07424, GSS-10) was determined for every 10 soil samples under the same experimental conditions to ensure accurate determination of the soil heavy metal contents. The recovery rate and data calibration of selected heavy metals had been provided in a previously published paper [32].

Data Analysis

The determined experimental data were statistically analyzed using Excel 2006 and IBM SPSS Statistics 27. All graphs were generated using ArcGIS 10.8, Origin 2021, and CorelDRAW 2019.

Health Risk Evaluation

Soil Heavy Metal Exposure Model and Parameter Selection

As, Hg, Cd, and Pb pose non-carcinogenic health risks. In addition, As and Cd are also known to pose carcinogenic risks. In the calculation process, this paper calculates the non-carcinogenic health risk profile of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn and the health risk profile of As, Cd, Cr, and Hg [34]. These heavy metals can enter the human body through three exposure pathways, namely hand-to-mouth ingestion, dermal contact, and inhalation, thus posing health risks. In this study, the average daily exposures to carcinogenic (adults) and non-carcinogenic (adults and children) heavy metals through the three exposure pathways were calculated using the following formulas [35]:

$$ADD_{ing} = \frac{c \cdot IngR \cdot CF \cdot EF \cdot ED}{BW \cdot AT} \tag{1}$$

$$ADD_{inh} = \frac{c \cdot InhR \cdot EF \cdot ED}{PEF \cdot BW \cdot AT} \tag{2}$$

$$ADD_{derm} = \frac{c \cdot SA \cdot CF \cdot SL \cdot ABS \cdot EF \cdot ED}{BW \cdot AT} \tag{3}$$

The lifetime average daily exposures to different exposure routes of carcinogenic heavy metals in children were calculated using the following formulas [35]:

$$LADD_{ing} = \frac{c \cdot CF \cdot EF}{AT} \times (\frac{IngR_{child} \cdot ED_{child}}{BW_{child}} + \frac{IngR_{adult} \cdot ED_{adult}}{BW_{adult}}) \tag{4}$$

$$LADD_{inh} = \frac{c \cdot EF}{PEF \cdot AT} \times (\frac{InhR_{child} \cdot ED_{child}}{BW_{child}} + \frac{InhR_{adult} \cdot ED_{adult}}{BW_{adult}}) \tag{5}$$

$$LADD_{derm} = \frac{c \cdot CF \cdot EF \cdot SL \cdot ABS}{AT} \times (\frac{SA_{child} \cdot ED_{child}}{BW_{child}} + \frac{SA_{adult} \cdot ED_{adult}}{BW_{adult}}) \tag{6}$$

Where ADD_{ing}, ADD_{inh}, and ADD_{derm} denote the average daily exposures to heavy metals by ingestion, inhalation, and dermal contact, respectively [$mg \cdot (kg \cdot d)^{-1}$]; c denotes the soil heavy metal content ($mg \cdot kg^{-1}$); IngR denotes the ingestion rate of soil ($mg \cdot d^{-1}$); InhR denotes the respiration rate ($m^3 \cdot d^{-1}$); CF is a conversion factor ($kg \cdot mg^{-1}$); EF denotes the exposure frequency ($d \cdot a^{-1}$); ED denotes the years of exposure (a); BW denotes the mean body weight (kg); AT denotes the mean exposure time of heavy metals (d); PEF denotes the dust emission factor ($m^3 \cdot kg^{-1}$); SA denotes the exposed skin surface area (cm^2); SL denotes the skin adhesion [$mg \cdot (cm^2 \cdot d)^{-1}$]; and ABS denotes the skin absorption factor (dimensionless). $LADD_{ing}$, $LADD_{inh}$, and $LADD_{derm}$ are the lifetime average daily exposure to heavy metals through the human life-cycle exposure pathways of ingestion, inhalation, and dermal contact [$mg \cdot (kg \cdot d)^{-1}$]; $InhR_{child}$ and $InhR_{adult}$ denote the respiratory rates of children and adults, respectively ($m^3 \cdot d^{-1}$); ED_{child} and ED_{adult} denote the number of years of children and adult exposure (a); BW_{child} and BW_{adult} denote the average body weight of children and adults (kg), respectively.

The values of the above-mentioned parameters were determined based on China's site environmental evaluation guidelines (DB11/T656-2019) [36] and the results obtained in previous related studies in China and worldwide [37-39]. The AT values for carcinogenic and non-carcinogenic heavy metals were considered differently in the exposure calculation. Indeed, the average ED values were set to 24 and 6 a for adults and children, respectively, for non-carcinogenic heavy metal exposure [34]. Therefore, the AT values of adults and children were 8760 (24×365) and 2190 (6×365) d, respectively. On the other hand, the average ED value of adults was set at 24 a for calculating the exposure to carcinogenic heavy metals. The average ED values of children and adults were first weighted and averaged. The maximum average ED value was calculated at 30 a, including 6 and 24 a for children and adults, respectively, and then the exposure was equally distributed over the entire life span (70 a). The average AT of adults and children to carcinogenic heavy metals was estimated at 70×365 d. The values of each parameter considered in this study are reported in Table 1.

Health Risk Models

The health risk characterization models of non-carcinogenic and carcinogenic heavy metals in the soils were used in this study based on the amount and exposure pathways of heavy metals, according to the following formulas [35]:

$$HQ_i = \sum_{j=1}^{3} \frac{ADD_{ij}}{RfD_{ij}} \tag{7}$$

$$\mathrm{HI} = \sum_{i=1}^{4} \mathrm{HQ_i} \tag{8}$$

$$CR_i = \sum_{j=1}^{3} ADD_{ij} \cdot \mathrm{SF_{ij}} \tag{9}$$

$$\mathrm{TCR} = \sum_{i=1}^{2} \mathrm{CR_i} \tag{10}$$

Where HQ_i denotes the health risk index of a non-carcinogenic heavy metal (*i*); ADD_{ij} denotes the average daily exposure to a non-carcinogenic heavy metal (*i*) through the jth route [mg·(kg·d)$^{-1}$]; RfD_{ij} denotes the reference dose of the jth exposure route of a non-carcinogenic heavy metal (*i*) [mg·(kg·d)$^{-1}$]; HI denotes the total non-carcinogenic risk index of the eight heavy metals through the three exposure routes (ingestion, inhalation, and dermal contact); CR_i denotes the health risk index of a carcinogenic heavy metal (*i*); SF_{ij} denotes the slope coefficient of the jth exposure route of a carcinogenic heavy metal (*i*) [(kg·d)·mg^{-1}]; TCR denotes the total carcinogenic risk index of all carcinogenic heavy metals through the three exposure routes. HQ_i and HI values less than 1 suggest negligible non-carcinogenic health risks, while HQ_i and HI values above 1 suggest non-carcinogenic health risks. The USEPA considers that when the CR and TCR values are not greater than 10^{-6}, there is no or very low cancer risk; when they are between 10^{-6} and 10^{-4}, there is an acceptable level of cancer risk; and when they are greater than 10^{-4}, it is considered that there may be a potential cancer risk. The RfD and SF values of the exposure routes were determined in this study based on the environmental guidelines for site assessment in China (DB11/T656-2009) and the results of previous studies conducted in China and other regions of the world (Table 2).

Results and Discussion

Soil Heavy Metal Contents

The results of the soil heavy metal contents in the study area and their comparison with the corresponding background values and soil heavy metal contents in other cities are reported in Table 3. The average contents of Zn, Cr, Pb, Ni, Cu, As, Hg, and Cd in the collected soil samples were 80.41, 55.93, 23.08, 20.41, 14.60, 4.82,

Table 1. Basic parameters of heavy metal exposure [34, 38].

Parameters	Meaning	Values		Unit
		Adults	Children	
IngR	Ingestion rate	100	200	mg·d^{-1}
InhR	Inhalation rate	15	7.5	m^3·d^{-1}
CF	Conversion factor	1×10^{-6}	1×10^{-6}	kg·mg^{-1}
EF	Exposure frequency	365	365	d·a^{-1}
ED	Years of exposure	24	6	a
BW	Average weight	53.1	15	kg
AT	Average exposure time of heavy metals	70×365 (Carcinogenic)	70×365 (Carcinogenic)	d
		24×365 (non-carcinogenic)	6×365 (non-carcinogenic)	
PEF	Dust emission factor	1.6×10^9	1.6×10^9	m^3·kg^{-1}
SA	Exposed skin surface area	4350	1600	cm^2
SL	Skin adhesion	0.2	0.2	mg·(cm^2·d)$^{-1}$
ABS	Skin absorption factor	0.001	0.001	Dimensionless

Table 2. RfD and SF values of different exposure pathways of soil heavy metals [36, 37].

Exposure pathways		As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
RfD ($mg \cdot kg \cdot d^{-1}$)	Hand-to-mouth intake	3.00×10^{-4}	1.00×10^{-3}	3.00×10^{-3}	4.20×10^{-2}	3.00×10^{-4}	2.00×10^{-2}	3.50×10^{-3}	3.00×10^{-1}
	Skin contact	3.00×10^{-4}	1.00×10^{-5}	6.00×10^{-5}	1.20×10^{-2}	2.40×10^{-5}	5.40×10^{-3}	5.25×10^{-4}	6.00×10^{-2}
	Inhalation	1.23×10^{-4}	1.00×10^{-3}	2.86×10^{-5}	4.02×10^{-2}	3.00×10^{-4}	2.06×10^{-2}	3.52×10^{-3}	3.00×10^{-1}
SF ($kg \cdot d \cdot mg^{-1}$)	Hand-to-mouth intake	1.5	6.1	-	-	-	-	-	-
	Skin contact	1.5	6.1	-	-	-	-	-	-
	Inhalation	4.30×10^{-3}	1.80×10^{-3}	42	-	-	8.40×10^{-1}	-	-

Table 3. Descriptive statistical results of soil heavy metals in the study area and comparison with background values and other typical cities in China.

Research Area	Statistical parameters	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Study Area (n = 78)	Maximum ($mg \cdot kg^{-1}$)	6.819	0.125	68.241	23.593	0.129	29.709	26.522	132.689
	Minimum ($mg \cdot kg^{-1}$)	3.874	0.020	44.928	4.022	0.003	8.543	20.839	63.287
	Average ($mg \cdot kg^{-1}$)	4.82	0.03	55.93	14.60	0.04	20.41	23.08	80.41
	Standard deviation	0.70	0.02	5.14	3.68	0.04	5.14	1.24	9.21
	Variance	0.49	0.00	26.44	13.51	0.00	26.38	1.53	84.78
	Coefficient of variation	0.15	0.55	0.09	0.25	0.97	0.25	0.05	0.12
Gansu Province [40]		12.6	0.116	70.2	24.1	0.02	35.2	18.8	68.5

0.04, and 0.03 $mg \cdot kg^{-1}$, respectively. The average Hg, Pb, and Zn contents in the study area were higher than the corresponding background contents in the Gansu soils by 2.01, 1.23, and 1.18, respectively. In contrast, the average contents of the remaining heavy metals did not exceed the corresponding background values for Gansu. Indeed, one sampling site exhibited a higher soil Cd content than the Cd background content in Gansu, while 44 and 74 sampling sites showed higher soil Hg and Zn contents than the Hg and Zn background contents in Gansu, respectively. In addition, all the sampling sites showed higher soil Pb contents than the Pb background content in Gansu. It can be seen that the soil heavy metals in the study area were characterized by relatively high contents of Hg, Pb, and Zn.

The coefficient of variation was computed in this study to reflect the average variability of soil heavy metal elements in the study area. Indeed, the coefficient of variation has been commonly used to evaluate the magnitude of external influences on a certain element [32]. According to Table 3, the coefficients of variation of the observed soil heavy metal contents in this study followed the order of Hg>Cd>Cu>Ni>As>Zn>Cr>Pb. This finding indicates slight variations in the soil As, Zn, Cr, and Pb contents, moderate variations in the soil Cu and Ni contents, and high variations in the soil Hg and Cd contents.

The frequency distributions of the observed soil heavy metal contents in the study area are shown in Fig. 2. According to the obtained results, the skewness values of the observed soil As, Cr, and Hg contents were 0.58, 0.04, and 0.67, respectively. The corresponding kurtosis values were -0.23, -0.39, and -0.79, indicating that the distributions of the soil As, Cr, and Hg contents had positive skewness, with lower tails compared to a standard normal distribution. The skewness and kurtosis values of the observed soil Cu contents were -0.29 and 0.19, respectively, indicating a negative skewness distribution with higher tails compared to a standard normal distribution. The observed soil Ni contents showed skewness and kurtosis values of -0.19 and -0.79, indicating a negative skewness distribution and lower tails compared to a standard normal distribution, respectively. In contrast, the soil Pb skewness and kurtosis values were 0.53 and 0.05, indicating a positive skewness distribution and higher tails compared to a standard normal distribution, respectively. Notably, the skewness of Cd and Zn was 3.72 and 2.40, respectively; both greater than 1 and also higher than the other heavy metals. Moreover, the kurtosis of Cd and Zn was 15.69 and 12.53, respectively; both greater than 3 and also higher than the other heavy metals. These results indicated that Cd and Zn exhibited positive skewness, and their distribution peaks were steeper than the standard normal distribution.

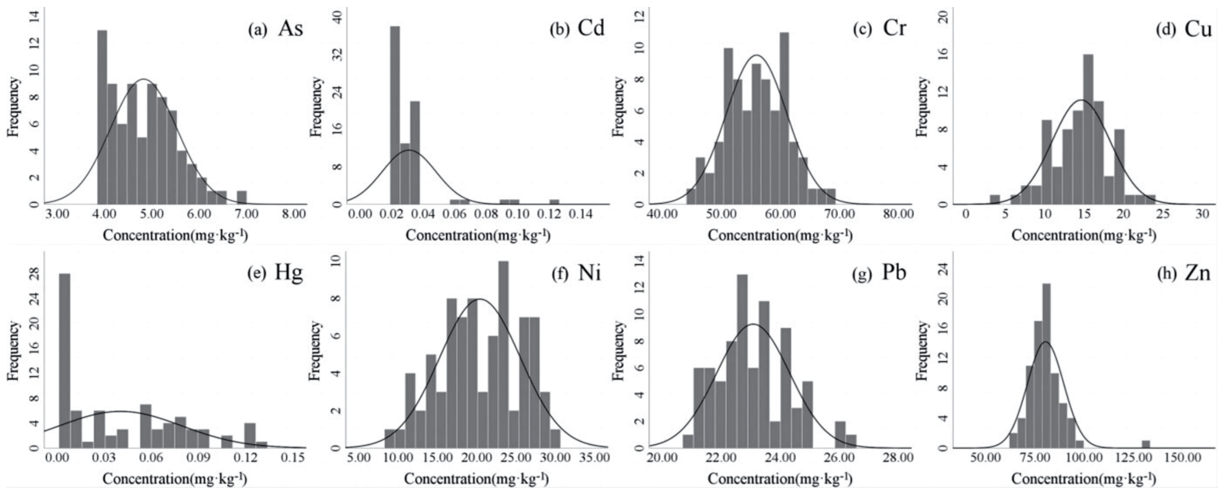

Fig. 2. Frequency distributions of the observed soil heavy metal contents in the study area (n = 78).

Thus, Cd and Zn had a greater difference compared to the standard normal distribution.

Health Risk Evaluation Results

Health Risk Assessment of Soil Heavy Metals for Adults

As reported in Table 4, the HQ and HI values of the eight heavy metals in the study area for adults were less than 1, suggesting the absence of non-carcinogenic health risks. In contrast, the CR and TCR values of soil As and Cr in the study area for adults exceeded the soil management standard recommended by the USEPA (10^{-6}) [37], reaching high levels. These findings are consistent with those reported by Li and Chen [41]. According to Fig. 3, the spatial distributions of the HI and TCR values associated with the soil heavy metals for adults in the study area were nearly the same.

In this study, HQ_{As}, HQ_{Cr}, and HQ_{Pb} contributed to the HI for adults by 27.08%, 58.95%, and 10.98%, respectively, accounting for more than 90.00% of the total contribution (Fig. 4a). Therefore, As, Cr, and Pb were the main contributors to the HI in the study area. On the other hand, CR_{As} and CR_{Cr} contributed to the TCR for adults by 56.05% and 41.33%, respectively,

Table 4. Non-carcinogenic and carcinogenic risk indices of soil heavy metals for adults.

Element	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
HQ	3.09E-02	5.94E-05	6.73E-02	6.61E-04	2.55E-04	1.94E-03	1.25E-02	5.09E-04
HI	1.14E-01							
CR	4.67E-06	1.22E-07	3.44E-06	-	-	9.63E-08	-	-
TCR	8.33E-06							

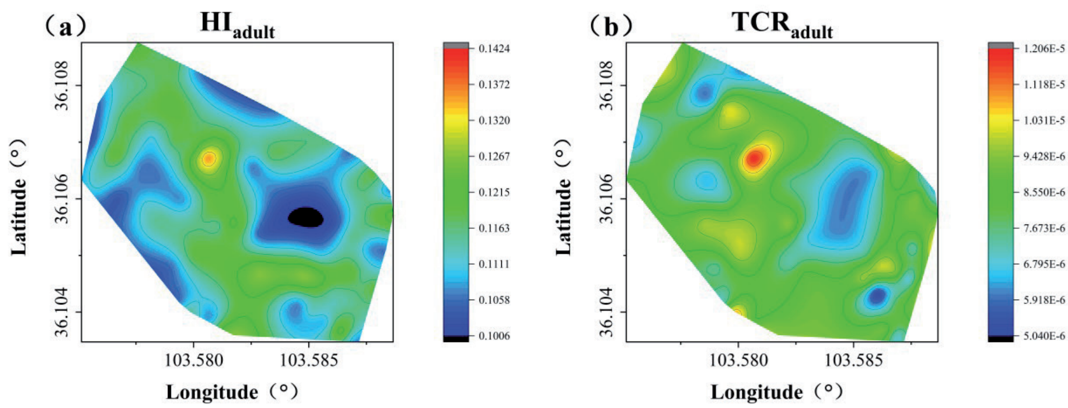

Fig. 3. Spatial distributions of the total non-carcinogenic a) and carcinogenic b) risks for adults in the study area.

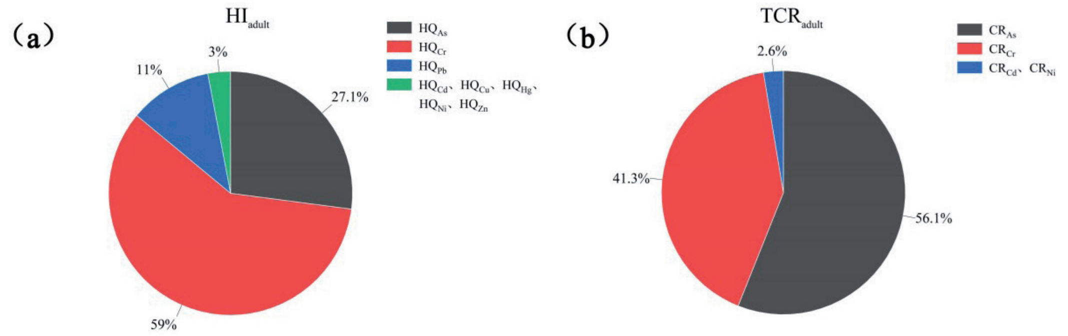

Fig. 4. Contributions of HQ and CR to the total non-carcinogenic a) and carcinogenic b) risks for adults, respectively.

accounting for more than 90.00% of the total contribution, thus demonstrating the key contributions of As and Cr to the TCR in the study area (Fig. 4b). Similarly for Zhang et al. [42], which found that the average carcinogenic risk of As, Cr, and Cd from a coal chemical plant in Ningxia, China, was higher than the acceptable carcinogenic risk limits, but their risk factors were within the acceptable limits, which is consistent with the results revealed in this study.

Health Risk Assessment of Soil Heavy Metals for Children

The HQ and HI values of the eight heavy metals for children in the study area were less than 1 (Table 5), indicating the absence of non-carcinogenic health risks for children. However, the CR and TCR of soil As and Cr for children exceeded the soil management standard recommended by the USEPA [37], showing high values. Children are more susceptible to non-carcinogenic and carcinogenic health risks compared to adults. Indeed, Yang et al. [43] indicated that children living around factories and mines (coal chemical plants in Northwest China) are more vulnerable to heavy metal pollution compared to adults. According to Fig. 5, the HI and TCR values of soil heavy metals for children in the study area showed consistent spatial distributions.

According to the obtained results, HQ_{As}, HQ_{Cr}, and HQ_{Pb} were the main contributors to the HI for children in the study area, showing contribution rates of 34.82%, 47.03%, and 14.25%, respectively, thus accounting for 96.10%. In contrast, CR_{As} and CR_{Cr} were the main

Table 5. Non-carcinogenic and carcinogenic risk indices of soil heavy metals for children in the study area.

Elements	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
HQ	2.15E-01	4.14E-04	2.91E-01	4.64E-03	1.79E-03	1.36E-02	8.81E-02	3.58E-03
HI	6.18E-01							
CR	1.29E-05	3.38E-07	4.56E-06	-	-	1.28E-07	-	-
TCR	1.80E-05							

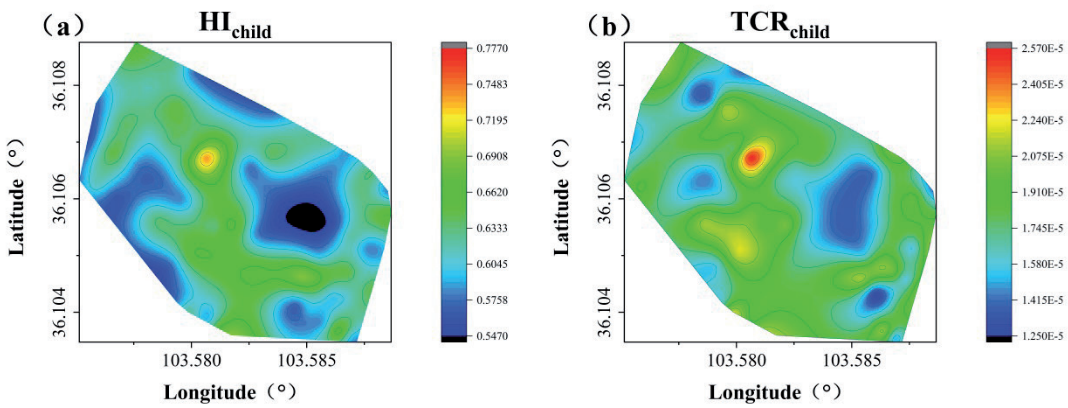

Fig. 5. Spatial distributions of total non-carcinogenic a) and carcinogenic b) risks for children in the study area.

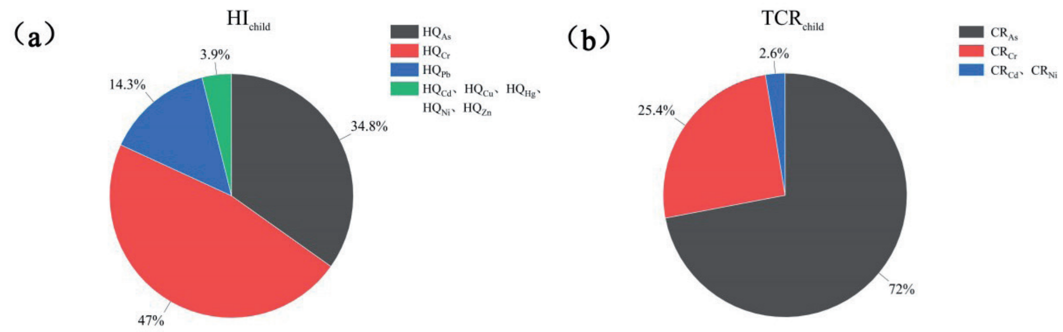

Fig. 6. Contributions of HQ and CR to the total non-carcinogenic a) and carcinogenic b) risks, respectively, for children in the study area.

contributors to the TCR for children in the study area, showing contributing rates of 72.00% and 25.41%, respectively, and accounting for more than 97.41% (Fig. 6). Thus, it can be seen that As and Cr are the main risk factors in the study area. For this research area, Chen et al. [30] had previously evaluated the health risk of heavy metals (Cd, Cr, Pb, and As) in drinking water for children and found that As and Cr exhibited relatively higher non-carcinogenic risk and cancer risk than Cd and Pb, and both the non-carcinogenic risk and the carcinogenic risk of the selected heavy metals were also within the acceptable level of health risk. These findings were consistent with the results obtained from the present study.

By comparing the relevant calculated data, it can be found that the HQ and HI values of children are greater than those of adults, and the HI value of children is 5.41 times that of adults. Meanwhile, the CR and TCR values of children are also greater than those of adults, and the TCR value of children is 2.16 times that of adults. Thus, it can be seen that children are more likely to be exposed to non-carcinogenic risk and carcinogenic risks than adults in this study area. Uwamungu et al. [31] had previously investigated the health risk of heavy metals (Cd, Cu, Cr, and Pb) in vegetables in this same study area and found that children are also exposed to a higher health risk of the selected heavy metals than adults, which was also in agreement with the present study.

In the present study, the health risks for adults and children both indicated that Cr and As contributed the most to non-carcinogenic and carcinogenic risks, respectively. From a health risk perspective, Cr and As were the dominant pollutants in the soil heavy metals of this study area. Cr and As are common heavy metals in soil [44, 45], especially in the vicinity of industrial and mining enterprises, which usually have high concentrations, ecological risks, and health risks [46-49]. Cr and As are strongly bioaccumulative and non-biodegradable, so they can directly affect human food safety and physical health through agricultural soil [46, 47]. Research has shown that As is related to human cancer, cardiovascular disease, neurological diseases, and diabetes [50], while Cd can cause health problems, including skin lesions, ulceration and perforation of the nasal septum, perforation of the eardrum, reduced spermatogenesis, and lung carcinoma [51, 52]. Thus, it is necessary to strengthen the control of As and Cr in this research area and pay special attention to the exposure of children to heavy metals.

Conclusions

In this paper, eight heavy metals were measured in Xigu District, Lanzhou City, Gansu Province, and the related non-carcinogenic and carcinogenic risks were calculated and compared with international standards to obtain the relevant conclusions as follows:

(1) The soil Hg, Pb, and Zn in the urban and rural areas of Xigu District, Lanzhou City, were 2.01, 1.23, and 1.18 higher than the background values of Gansu, respectively. The obtained results revealed relatively high soil Hg, Pb, and Zn contents in the study area, of which soil Hg and Cd exhibited the highest coefficients of variation, reaching 0.97 and 0.55, respectively.

(2) As, Cr, Hg, Pb, Cd, and Zn exhibited positive skewness, while Cu and Ni showed negative skewness. Meanwhile, the distributions of Cu, Pb, Cd, and Zn were steep compared to the normal distribution. In contrast, the distributions of As, Cr, Hg, and Ni were flat compared to a normal distribution, with a flat peak.

(3) The results of eight soil heavy metals in the study area showed that the non-carcinogenic risk to adults and children did not exceed the soil management standard recommended by the USEPA（HI<1）. However, HQ and HI values of soil heavy metals were higher in children in the study area compared to adults, and the HI values of children were 5.41 times higher than those of adults. Moreover, As, Cr, and Pb were the major contributors to the HI values in the area. However, at the same time, the soils in the area were carcinogenic. As, Cr, Cd, and Ni had higher CR and TCR values in children than adults. The TCR values in children were 2.16 times higher than those in adults. And As and Cr were the main contributors to TCR in the area. Therefore, the CR and TCR in the study area should be seriously considered to effectively control the health risks associated with soil heavy metals in the study area.

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Conflict of Interest

The authors declare no conflict of interest.

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