Environ Monit Assess (2024) 196:788
https://doi.org/10.1007/s10661-024-12936-0

RESEARCH

Risk assessment and source analysis of trace elements in soils around county landfills in Tibet

**Dean Meng · Jiamin Ma · Wenwu Zhou ·
Peng Zhou · Jiaqi Wang · Dan Zeng**

Received: 18 February 2024 / Accepted: 24 July 2024 / Published online: 6 August 2024

Abstract The ecology of the Qinghai−Tibet Plateau is fragile, and the ecosystems in the region are difficult to remediate once damaged. Currently, landfilling is the mainstay of domestic waste disposal in China, and numerous, widely distributed county landfills exist. trace elements (TEs) in waste are gradually released with waste degradation and cannot be degraded in nature, affecting environmental quality and human health. To reduce the chance bias that exists in studies of individual landfills, we selected 11 representative county landfills in Tibet, total of 76 soil samples were collected, eight TEs (arsenic (As), mercury (Hg), chromium (Cr), copper (Cu), lead (Pb), cadmium (Cd), nickel (Ni), and zinc (Zn)) were determined, and analysed for the current status of pollution, risk to human health, and sources of TEs to explore the impact of the landfills. The results showed that only a few landfills had individual TEs exceeding the risk screening value of the *Soil Environmental Quality Risk Control Standard for Soil Contamination* (GB 15618–2018) (pH > 7.5). Most of the soils around the landfills had moderate levels of pollution, but some individual landfills had higher levels, mainly due to Cd and Hg concentrations. Source analysis showed that Hg originated mainly from atmospheric transport; the other TEs came mainly from the weathering of soil parent material and bedrock. The potential risk from TEs to human health was low, and the risk to children was greater than the risk to adults. Among the three exposure routes, oral ingestion resulted in the highest carcinogenic risk and noncarcinogenic risk, with a contribution rate of more than 95%. Among the TEs, Ni had the highest carcinogenic risk, followed by Cr and As, and As had the highest noncarcinogenic risk.

Keywords Qinghai−Tibet Plateau · Landfill · Trace elements · Risk assessment · Environmental pollution

Introduction

The Qinghai−Tibet Plateau is considered the third pole of the world and has an important sheltering function for China's ecological security (Wen et al., 2019). It is also known as the "water tower of Asia",

D. Meng · J. Ma · W. Zhou · P. Zhou · J. Wang ·
D. Zeng (✉)
School of Ecology and Environment, Tibet University,
Lhasa 850000, China
e-mail: yongzhong2008@163.com

D. Meng
e-mail: 2392736037@qq.com

J. Ma
e-mail: 1164304936@qq.com

W. Zhou
e-mail: wu798564213@163.com

P. Zhou
e-mail: 944623291@qq.com

J. Wang
e-mail: 1450644619@qq.com

providing drinking water for more than one billion inhabitants in Asia (Sun et al., 2019). However, Tibet's environment is very fragile, and once damaged, it is difficult to repair. As a result, ecological protection is an important aspect of sustainable development and societal stability in the Tibet Autonomous Region. With the rapid development of the economy and improvements to people's standard of living, the amount of domestic waste produced is expected to increase. Among waste matter, plastic, electronic products and other difficult-to-handle and high-pollution components are generated (Liu & Wu, 2011; Niu et al., 2023). Therefore, treatment of domestic waste has become an important part of ecological protection in the Qinghai–Tibet Plateau. Landfills are simple and cost-saving treatment methods.

Prior to 2017, China's domestic waste was mainly treated via landfilling, which accounted for more than 50% of the country's total waste disposal (National Bureau of statistics of the People's Republic of China (NBSPRC), 2021). Due to the shortcomings of landfilling, such as long processing times, large footprint and adverse impacts on surrounding environments, incineration has emerged as a form of waste treatment in recent years. However, in 2020, there were still 644 landfills in use in China, and 77.715 million tons of domestic waste was treated by these landfills annually, accounting for 33.14% of the total treatment capacity (NBSPRC, 2021). The land area of the Tibet Autonomous Region is large, and it has a sparse population with scattered population distribution. Domestic waste is characterized by small production volumes, widespread distribution, and high collection and transportation costs, making its disposal by incineration difficult. At present, landfills are the main form of waste treatment, and there are more than 140 landfills in the region, most of which are county landfills. In Tibet, village and township domestic waste is collected by the villages, transferred by townships, treated by the counties, and disposed of in county landfills.

Trace elements (TEs) present in waste products are gradually released with waste degradation, which may cause TEs pollution of soil and water, affecting environmental quality and human health (de Souza et al., 2023; Wang et al., 2022; Xiao et al., 2005). Trace elements cannot be degraded in nature and have a retention time of approximately 150 years in landfills, and the leaching rate is 400 mm/yr (Adelopo et al., 2018). High concentrations of TEs reduce the biomass of soil microorganisms and affect plant growth (Alves et al., 2016; Zhang et al., 2016). Trace elements in soil can also negatively affect human health through soil-crop-human and soil-crop-livestock-human exposure pathways or via direct ingestion (Obiri-Nyarko et al., 2021; Wang et al., 2023). They can remain in the body for more than a decade, exerting toxic effects (Karunanidhi et al., 2022). Prolonged exposure to low doses of TEs can lead to their accumulation in human bones, kidneys, nerves, digestion, blood, haematopoietic and cardiovascular systems and the formation of stable metal complexes with proteins, nucleic acids, vitamins and hormones, inducing pathological changes that may cause skin, blood and neurological disorders in humans (Jaishankar et al., 2014).

Therefore, landfill monitoring is particularly important for the ecological security of the Tibetan Plateau and the health of its inhabitants. Previously, researchers have focused mainly on the impact of landfills on surrounding environments in various prefectures in Tibet (Dan et al., 2021; Zhou et al., 2022, 2023). The results showed that landfills were potential ecological hazards, with individual TEs concentrations higher than the background values of TEs in Tibetan soils. Wang et al. (2020b) analysed the TEs content of soils around six landfills and in geothermal water in Tibet, and their results showed that the concentration of mercury (Hg) was six times greater than the background values. However, there has been no relevant research on the county landfills in the plateau region. To reduce the chance bias that might occur in studies of individual landfills, in this study, we selected 10 representative county landfills in Tibet based on the results of previous studies. The concentration of TEs was analysed by sampling the soil around the landfill site. The sources of TEs in landfill soils were determined using statistical methods, specifically, correlation coefficient method and principal component analysis (PCA). Single factor pollution index (PI), Nemerow comprehensive pollution index (NPI), potential ecological risk assessment (RI) and human health risk assessment were used to evaluate the impact of landfills on the environment and humans. This study provides a reference for the daily operation and management of landfills in the Tibetan Plateau region.

Materials and methods

Study area

This study focuses on the Tibet Autonomous Region, which contains four cities, Lhasa, Shigatse, Nyingchi, and Shannan. This region is a densely populated area and a major tourist area. The landfills in Damxung, Maizhokunggar, Lhunzhub, Gyantse County in Lhasa, Bainang, and Dinggyê; Yadong County in Shigatse; and Bomê, Mainling, Gongbo’gyamda County in Nyingchi, and Nagarzê County in Shannan were

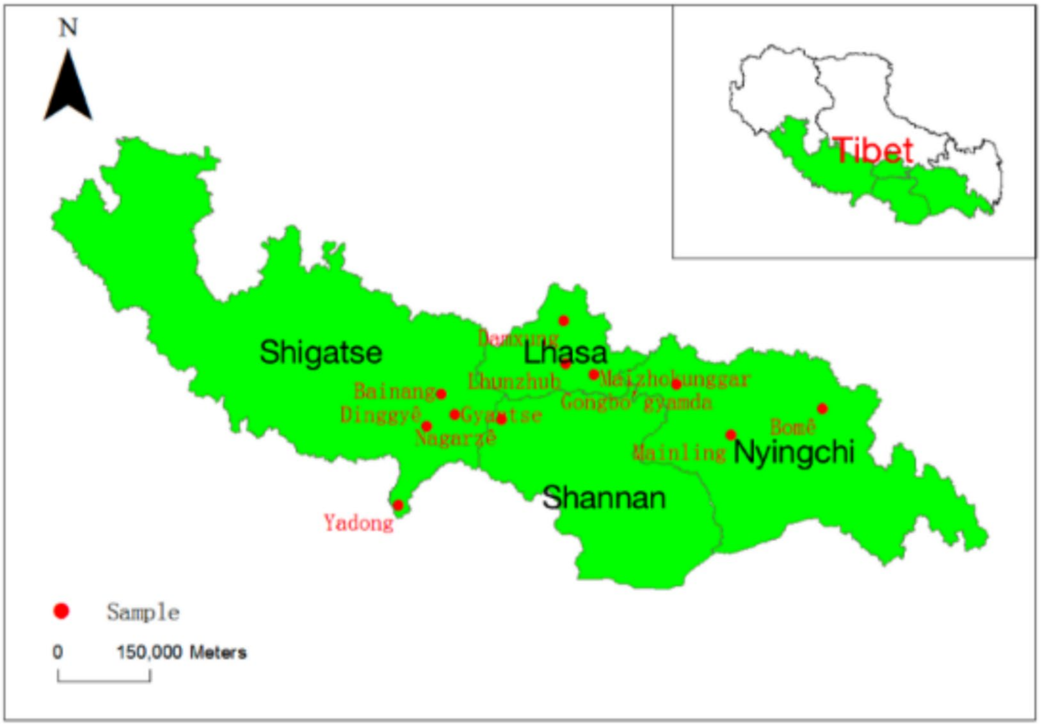


Fig. 1 Schematic of the study area

Table 1 Basic information on the study area

Study area	Altitude	Annual rainfall/mm	Local population (10,000)	Soil utilisation around the landfill site
Damxung	4300	481	4.79	grass
Lhunzhub	3700	491	5.06	grassland, farmland
Maizhokunggar	3836	515	4.95	grassland, farmland
Gyantse	4050	288	6.87	grassland
Bomê	2700	900	3.49	grassland
Mainling	3700	641	2.07	grassland
Gongbo’gyamda	3600	646	3.29	grassland, farmland, road
Bainang	4200	361	4.46	grassland
Yadong	3500	410	1.55	grassland
Dinggyê	4500	236	2.04	grassland
Nagarzê	4500	376	3.91	grassland

selected as the study areas. The geographical locations of these landfills are shown in Fig. 1.

As shown in Table 1, the altitude at the selected county landfills is between 2500 and 4700 m, and most of the counties in Tibet are within this range. Except in Bomi and Yadong, the annual rainfall was less than 500 mm. The geological structure of the Qinghai-Tibet Plateau is very complex, including folded mountain series, metamorphic rock series, intrusive rock series, and volcanic rock series. In this study, the soil around 11 landfill sites was mainly brown soil and Baga soil. Brown soil is mainly located at an altitude of 2400–3500 m, and its parent material is composed of slope and alluvial deposits of rocks such as granite and gneiss. Baga soil is mainly distributed at an altitude of 4100–4700 m, and its parent material is composed of residual and aeolian deposits of rocks such as sand shale, slate, and limestone.

During field research, it was found that most of the landfills in the Tibetan counties were dry, had low leachate generation, and could be treated by backwashing. The soil around each landfill site is mainly utilized through naturally formed grasslands and farmland. Farmland mainly grows crops such as barley and wheat, while the surrounding yaks and various wild animals feed on grass.

Soil collection and analytical methods

Due to the vast area and complex geological structure of Tibet, TEs levels vary greatly in each region (Cheng & Tian, 1993). To evaluate more accurately the impact of landfills, background samples were collected 200 m upwind of the landfills at a depth of 30 cm. Because it was difficult to collect background samples from Bainang, Gyantse, Dinggyê, Yadong and Nagarzê counties, the background values of TEs in the soil in Tibet were used as the background values for these five counties. Sampling points were established 50 m, 100 m and 150 m downstream of the landfill in three directions, and surface (0 cm), 10 cm and 30 cm samples were collected at the sampling points directly downstream. The sampling points could be adjusted according to the actual conditions. The collected samples were placed in sampling bags, dried naturally in a ventilated sample room, ground with a grinding apparatus and sieved through a 200-mesh sieve.

This paper focused on eight TEs, arsenic (As), mercury (Hg), chromium (Cr), copper (Cu), lead (Pb), cadmium (Cd), nickel (Ni), and zinc (Zn), which were also prioritised as TEs pollutants by the *U.S. Environmental Protection Agency* (US EPA, 2012). The detection steps are as follows: Weigh 0.1 g of soil sample and place it in a closed digestion tank made of polytetrafluoroethylene. Then add 5 mL of HNO_3, 3 mL of HF, and 2 mL of H_2O_2. Mix well and place it in a microwave digestion device for digestion. After digestion, cool to room temperature. Open the digestion tank and drive the acid at 90 ℃. Filter the extraction solution using slow quantitative filter paper and collect it in a 50 mL volumetric flask to volume, then use an instrument to measure the concentration. Copper, Cr, Pb, Zn, Ni and Cd were determined using an atomic absorption spectrophotometer (TAS-990), Hg was determined using an atomic fluorescence photometer (AFS-2202E), and As was determined using a UV−visible spectrophotometer. During the testing process, strict quality control is carried out, with blank samples and three parallel samples set, and the average value is taken. The recovery rate for spiking was between 85% -105%.

Environmental impact assessment methods

Single factor pollution index (PI)

The PI method is simple to apply and easy to compare and is the basis for other environmental evaluation methods (Xu et al., 2008). The PI is calculated as follows.

$$\mathrm{P_i} = C_i / \mathrm{S_i} \tag{1}$$

where $\mathrm{P_i}$ is the PI of a pollutant i in the soil, dimensionless. C_i is the measured concentration of pollutant i in the soil, mg/kg. $\mathrm{S_i}$ is the standard or background value of pollutant i, mg/kg.

Nemerow comprehensive pollution index (NPI)

The NPI is calculated on the basis of the PI and can highlight the impact of high concentrations of pollutants on the quality of soil (Nemerow, 1974), and the formula is as follows.

$$\mathrm{P} = \sqrt{\frac{\overline{\mathrm{P_i}}^2 + \mathrm{P}^2_{\max}}{2}} \tag{2}$$

Table 2 Grading criteria for PI and NPI evaluation

Rank	P_i	P	pollution level
1	≤ 1	≤ 0.7	Safe level
2	1 ~ 2	0.7 ~ 1.0	Alert level
3	2 ~ 3	1.0 ~ 2.0	Light pollution
4	3 ~ 5	2.0 ~ 3.0	Moderate pollution
5	> 5	> 3.0	Heavy pollution

Table 3 Grading standard for potential ecological risk

E_r^i	RI	Level
< 40	< 150	Minor ecological hazard
40 ~ 80	150 ~ 300	Moderate ecological hazard
80 ~ 160	300 ~ 600	Strong ecological hazard
160 ~ 320	≥ 600	Severe ecological hazard
≥ 320		Extreme ecological hazard

where $\overline{P_i}$ is the average value of the PI. P_{max} is the highest PI. The grading criteria for the evaluation of the PI and **N**PI are shown in Table 2.

Potential ecological risk assessment (RI)

In potential ecological risk assessment, the principle of sedimentology is applied to quantitatively classify the magnitude of potential hazards from TEs (Hakanson, 1980). The formula is as follows.

$$RI = \sum E_r^i \tag{3}$$

$$E_r^i = T_r^i \times P_i \tag{4}$$

where RI is the potential ecological risk. E_r^i is the potential ecological risk of heavy metal i. T_r^i is the toxicity response coefficient of heavy metal i, and the values for Cd, Hg, As, Cu, Pb, Cr, Zn and Ni are 30, 40, 10, 5, 5, 2, 1 and 5, respectively. The grading standards are shown in Table 3.

Analysis methods for TEs sources

Many sources of TEs exist in soils, which include geology, human activities, and atmospheric transport, which all have an impact on the content of TEs in the soil (Qiao et al., 2023; Zhang et al., 2023b). To better determine the impact of landfills on soil TEs in Tibet, we utilised SPSS 22.0 software to perform Pearson's correlation coefficient analysis and principal component analysis (PCA) on the sources of soil TEs in landfills. Pearson's correlation coefficient analysis can be used to determine the strength of the correlation between TEs (Huang et al., 2018). A significant correlation indicates that TEs in soils may originate from similar places or have similar geochemical origins (Zhang et al., 2018). Principal component analysis can reduce many complex metrics into a smaller number of composite metrics and is a commonly used method for analysing sources of TEs (Fang et al., 2019).

Assessment methods for health risk

According to the US EPA, the hazards of TEs exposure to human health are mainly categorized into carcinogenic (CRs) and non-carcinogenic risks (NCRs). According to behavioural and physiological differences, local residents were divided into two groups: children and adults. According to the exposure pathways for soil health risk evaluation mentioned in the *Technical Guidelines for Risk Assessment of Soil Contamination of Land for Construction* (HJ 25.3–2019), risk was mainly categorized as oral, dermal or respiratory. The long-term daily average exposure model formulas for these pathways are as follows.

$$\text{Oralingestion}: AAD_{ing} = \frac{C \times IngR \times EF \times ED \times CF}{BW \times AT} \tag{5}$$

$$\text{Particulateinhalation}: ADD_{inh} = \frac{C \times InhR \times EF \times ED}{BW \times AT \times PEF} \tag{6}$$

$$\text{Dermalcontact}: ADD_{der} = \frac{C \times SA \times SL \times ABS \times EF \times ED \times CF}{BW \times AT} \tag{7}$$

All relevant parameters used are listed according to the *Technical Guidelines for Risk Assessment of Contaminated Sites in the People's Republic of China* and related literature (Zhou et al., 2023; He et al., 2016;Li et al., 2014; Zhou et al., 2020), and the specific relevant parameters are listed in Table 4.

Table 4 Parameter names, units, symbols and reference values

Parameter name and unit			Notation	Reference values
Soil TE content			C_s	measured value
Oral route intake rate/(mg-d^{-1})	Lifetime		IngR	100
	Acute			200
Soil inhalation rate/(m^3-d^{-1})	Lifetime		InhR	12.8
	Acute			7.63
Exposure frequency/(d-a^{-1})	Lifetime		EF	350
	Acute			320
Exposure duration/a	Lifetime		ED	24
	Acute			6
Weight/kg	Lifetime		BW	62
	Acute			15.9
Average exposure time/d	Cancer risk		AT	68.2*365 = 24893
	Noncancer risk	Chronic		8760
		Acute		2190
Body surface area/cm^2	Lifetime		SA	2145
	Acute			1150
Skin adhesion coefficient/(mg.(cm^2.d)$^{-1}$)	Lifetime		SL	0.07
	Acute			0.2
skin absorption factor	Arsenic (As)		ABS	0.03
	Other elements			0.001
Particulate emission factor (m^3 kg^{-1})			PEF	1.36*10^9
conversion factor			*CF*	1×10^{-6}

The NCR index is the NCR arising from the various exposure pathways of a pollutant and is usually calculated using the ratio of exposure to a pollutant and a reference dose. The formula is as follows.

$$\mathrm{HQ} = \mathrm{ADD}/\mathrm{RfD} \tag{8}$$

The total NCR formula is as follows.

$$\mathrm{HI} = \sum\nolimits_{i=1}^{m} \sum\nolimits_{j=1}^{n} \mathrm{HQ}_{ij} = \sum\nolimits_{i=1}^{m} \sum\nolimits_{j=1}^{n} (\mathrm{ADD}/\mathrm{RfD})_{ij} \tag{9}$$

where ADD is the average daily human exposure dose, mg-(kg-d)$^{-1}$; RfD is the noncarcinogenic reference dose, mg-(kg-d)$^{-1}$; m is the type of pollutant; and n is the number of exposure routes. If the NCR indices HQ and HI are greater than 1, it indicates that there is a high NCR at the site, and if they are less than 1, then the site has a low NCR (Guo & Song, 2010). When the CR is $\leq 10^{-6}$, it is generally accepted that there is no CR; when $10^{-6} < \mathrm{CR} < 10^{-4}$, the CR is considered acceptable; and when the CR is $\geq 10^{-4}$, a potential CR is considered to exist.

The CR was calculated from the lifetime average daily exposure and the carcinogenicity slope factor. The formula is as follows.

$$\mathrm{CR} = \mathrm{ADD} \times \mathrm{SF} \tag{10}$$

The total CR formula is as follows:

$$\mathrm{TCR} = \sum\nolimits_{i=1}^{m} \sum\nolimits_{j=1}^{n} \mathrm{R}_{ij} = \sum\nolimits_{i=1}^{m} \sum\nolimits_{j=1}^{n} (\mathrm{ADD} \cdot \mathrm{SF})_{ij} \tag{11}$$

According to the classification system of the International Agency for Research on Cancer (IARC), the World Health Organization (WHO) and relevant literature, the reference dose (RfD) and carcinogenicity slope factor (SF) are shown in Table 5 (Zhou et al., 2020; Chang et al., 2009; Wang et al., 2020a; Zhang et al., 2020; Xu et al., 2023; US EPA, 1992; US EPA, 2000; US EPA, 2002; US EPA, 2011).

Table 5 Reference doses and carcinogenicity slope factors

TEs	RfD/mg-(kg-d)$^{-1}$			SF/[mg-(kg-d)]$^{-1-1}$		
	RfD$_{ing}$	RfD$_{inh}$	RfD$_{dermal}$	SF$_{ing}$	SF$_{inh}$	SFdermal
Cu	4×10^{-2}	4.02×10^{-2}	1.2×10^{-2}	–	–	–
Pb	3.5×10^{-3}	3.52×10^{-3}	5.25×10^{-4}	8.5×10^{-3}	–	–
Zn	3×10^{-1}	3×10^{-1}	6×10^{-2}	–	–	–
Hg	3×10^{-4}	8.57×10^{-5}	3×10^{-5}	–	–	–
Ni	2×10^{-2}	2.06×10^{-2}	5.4×10^{-3}	–	0.84	–
Cd	1×10^{-3}	1×10^{-3}	1×10^{-5}	0.38	6.1	6.1
Cr	3×10^{-3}	2.86×10^{-5}	6×10^{-5}	0.501	42	20
As	3×10^{-4}	3×10^{-4}	3×10^{-4}	1.5	3.66	1.5

Results and discussion

TE concentrations

Due to the large number of county landfills and sampling points used in the study, TEs mean (Mean) and median (Med) concentrations and coefficient of variation (CV) were calculated and are shown in Table 6. The soil pH around the landfills was > 7.5, and the risk screening value (pH > 7.5) in the *Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land* (GB 15618–2018) was used as the standard values. The Pb and Zn concentrations in Maizhokunggar County were high, reaching values of 194 mg/kg and 336 mg/kg, respectively, and exceeded their respective standard values (Table 6). The reason for this difference was that the background values of Pb and Zn in the soils of Maizhokunggar County were high, 193 mg/kg and 261 mg/kg, respectively. The concentrations of Cr and Ni in Bainang County were high, 195 and 234 mg/kg, respectively, with the latter exceeding the standard limit of 190 mg/kg. The TEs contents of the soils around the other landfills were much lower than the standard values.

The average concentration of As in Nagarzê County reached 77.9 mg/kg, which was significantly greater than that in the other counties, which might be attributed to the large amount of water in Nagarzê County. The elevated levels of As in the water bodies in Tibet were attributed to geological factors, notably in the Yarlung Zangbo and Sengge Zangbo watersheds (Fu et al., 2005; Wang et al., 2012). Arsenic was adsorbed in the sediments present in the water and contributed to the heightened levels of As in the sediments (Che et al., 2020). Meanwhile, as shown in Table 6, the CV values of Hg and several other TEs (As, Cd, Cu, Pb and Zn) in Maizhokunggar and Gyantse are relatively high, indicating that these landfills are highly influenced by human activities.

Spatial distribution of TEs

A spatial distribution map of heavy metal concentrations in the soil of Tibet's landfills was constructed by using the inverse distance weight interpolation method in ArcGIS 10.7. There were marked variations in TE concentrations across the region. As shown in Fig. 2, the Ni and Hg concentrations increased from east to west. The reason is that the Hg content in Dinggyê County and Ni content in Bainang County are high, while the concentrations of these two elements in other county landfills are relatively low. On the contrary, the other TEs exhibited high concentrations in the middle region and low concentrations on the sides. Due to the large population in Lhasa and surrounding counties, human activities have increased the TEs content in the soil. In addition to the impact of landfills, automobile exhaust, industrial emissions, and the use of pesticides all have an impact on the TEs content in the soil (Aytop, 2023).

Environmental impact assessment

PI and NPI

The results of the PI and NPI assessment are shown in Table 7. The results showed that most of the TEs found within landfills were classified at safe or alert levels. However, the PIs of Cd in Gyantse and Yadong Counties and of Ni in Bainang County corresponded to heavy pollution levels, and the PIs of Cd and Hg in Dinggyê County, Hg in Yadong County and As in Nagarzê

Table 6 TEs concentrations in soils around landfills in Tibetan counties (mg/kg)

	sampling number		Cu	Pb	Zn	Cr	Ni	Cd	As	Hg
Damxung	12	Mean	18.0	36.6	78.5	56.3	26.0	0.1	23.7	0.04
		Med	17.6	36.6	75.5	57.3	26.4	0.1	23.8	0.04
		CV(%)	11.3	10.8	14.6	13.2	12.4	21.5	22.50	29.2
Lhunzhub	14	Mean	24.8	29.2	79.8	56.2	27.2	0.1	8.6	0.03
		Med	24.8	27.7	74.9	54.5	27.6	0.1	8.7	0.03
		CV(%)	11.7	20.2	18.4	14.8	16.6	21.6	19.7	36.0
Maizhokunggar	8	Mean	54.8	193.6	336.0	49.0	23.2	2.2	38.4	0.06
		Med	34.5	64.6	99.1	49.9	21.2	0.4	18.5	0.04
		CV(%)	116	165	185	11.0	25.4	222	149	80.7
Bomê	4	Mean	13.9	36.1	96.5	40.1	23.1	0.3	10.3	0.06
		Med	14.3	37.1	93.9	42.6	23.5	0.3	11.0	0.07
		CV(%)	15.5	20.6	17.2	21.1	27.6	25.9	17.6	31.2
Mainling	11	Mean	28.9	24.4	84.9	66.8	34.0	0.1	7.6	0.02
		Med	28.5	23.4	81.8	68.6	34.1	0.1	7.7	0.02
		CV(%)	12.4	12.1	18.8	11.7	11.6	16.7	12.2	50.8
Gyantse	4	Mean	38.9	94.5	145.9	45.4	34.0	0.6	18.4	0.07
		Med	35.7	19.3	65.7	43.1	36.0	0.1	16.9	0.05
		CV(%)	27.8	166.3	120.4	16.7	27.8	170.1	24.1	60.4
Bainang	3	Mean	31.6	26.9	81.5	194.7	233.6	0.1	15.4	0.02
		Med	29.7	25.9	84.6	158.0	149.0	0.1	12.4	0.02
		CV(%)	16.5	19.4	12.4	47.6	84.4	16.7	40.7	48.7
Gongbo'gyamda	12	Mean	19.0	34.6	89.9	51.7	23.5	0.1	18.0	0.08
		Med	18.2	34.5	92.4	51.6	23.2	0.1	18.2	0.07
		CV(%)	15.4	9.2	12.3	14.4	14.9	13.9	21.7	48.0
Dinggyê	2	Mean	11.5	28.0	28.0	2.0	33.0	0.3	6.7	0.12
		Med	11.5	28.0	28.0	–	33.0	0.3	6.7	0.12
		CV(%)	6.2	0.00	60.6	–	38.6	13.7	2.54	1.2
Yadong	2	Mean	20.0	25.5	91.5	2.0	47.0	0.4	3.3	0.13
		Med	20.0	25.5	91.5	–	47.0	0.4	3.3	0.13
		CV(%)	42.4	41.6	45.6	–	57.2	5.0	1.7	7.95
Nagarzê	4	Mean	34.8	32.4	107	88.7	41.5	0.1	77.9	0.08
		Med	36.0	31.8	104	83.4	40.6	0.1	58.5	0.06
		CV(%)	19.1	15.2	19.0	17.2	7.1	15.6	78.8	77.7
Standard concentrations			100	170	300	250	190	0.6	25.0	3.4
Background values			21.9	28.9	73.7	77.4	32.1	0.1	18.7	0.03

County had moderate pollution levels. As a result, Gyantse, Bainang, Dinggyê, Yadong and Nagarzê had heavy pollution levels based on the NPI values.

Potential ecological risk assessment

The results of the potential ecological risk assessment are shown in Table 8. According to our grading system, Cd in Gyantse County and Hg in Dinggyê and Yadong Counties posed severe ecological hazards. Mercury in Gyantse and Nagarzê counties and Cd in Dinggyê County showed strong ecological hazards. Cadmium and Hg were the primary pollutants in these regions. The background values of Hg and Cd on the Tibetan Plateau were 0.03 mg/kg and 0.1 mg/kg, respectively, which were

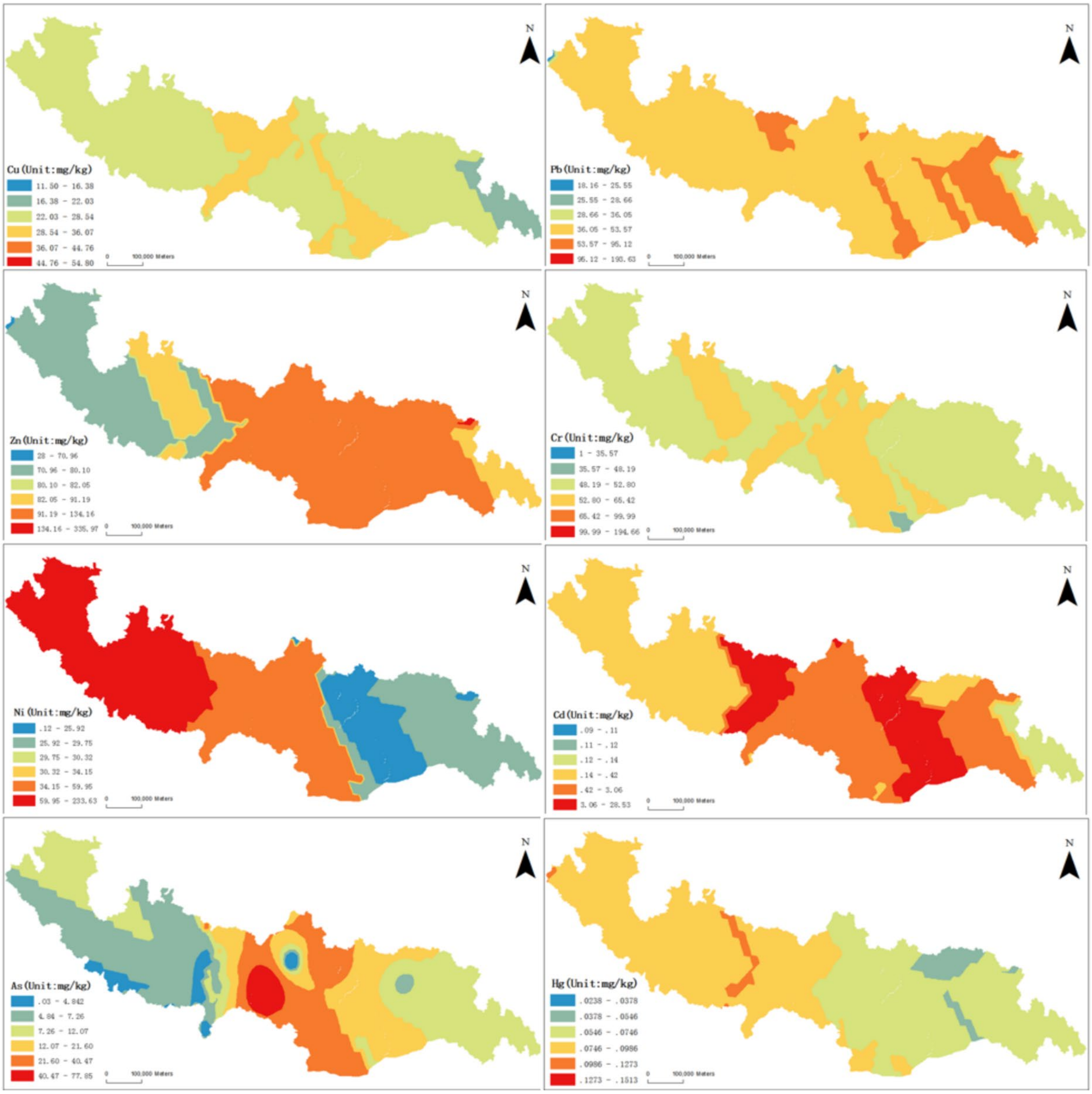


Fig. 2 Spatial distribution of soil TEs

much lower than the national averages (Cheng et al., 2014). For these elements, the RIs of Gyantse and Yadong counties showed strong ecological hazards, and Dinggyê and Nagarzê counties had moderate ecological hazards.

The RIs of the more strongly polluted counties of Gyantse, Dinggyê, Yadong and Nagarzê were calculated using the background value of Tibetan soil as the reference value, while the pollution level of Damxung County and other counties, for which the soil TEs content around the landfill was used as the reference value, was lower. Therefore, it was speculated that the landfills had a low level of influence on the TEs in the surrounding soil and that other factors might have caused the soil around the landfill to have elevated levels of TEs. Cadmium and Hg pollution was found in the Lhasa, Shannan, and Shigatse landfills (Dan et al., 2019; Zhou, 2020b; Zhou, 2020a;). In addition to the landfill areas,

Table 7 PI and NPI assessment results

Study area	PI								NPI
	Cu	Pb	Zn	Cr	Ni	Cd	As	Hg	
Damxung	0.84	1.06	0.91	0.83	0.89	0.71	0.93	1.29	1.12
Lhunzhub	1.35	0.97	1.08	0.94	1.05	1.48	0.98	0.91	1.30
Maizhokunggar	0.59	1.00	1.29	1.07	0.98	1.50	1.89	0.70	1.56
Bomê	0.98	0.96	1.11	0.87	0.93	1.14	0.83	1.10	1.07
Mainling	1.03	1.13	1.14	1.30	1.16	1.04	0.76	0.96	1.19
Gyantse	1.78	3.27	1.98	0.59	1.06	7.85	0.98	2.18	5.82
Bainang	1.44	0.93	1.11	2.52	7.28	1.26	0.82	0.80	5.34
Gongbo'gyamda	0.95	0.93	1.01	0.95	0.88	1.25	0.89	0.88	1.12
Dinggyê	0.53	0.97	0.38	0.01	1.03	3.88	0.36	4.10	3.06
Yadong	0.91	0.88	1.24	0.01	1.46	5.31	0.18	4.45	3.97
Nagarzê	1.59	1.12	1.45	1.15	1.29	1.66	4.16	2.53	3.23

Table 8 Results of potential ecological risk assessment

Study area	E_r^i								RI
	Cu	Pb	Zn	Cr	Ni	Cd	As	Hg	
Damxung	4.22	5.30	0.91	1.67	4.43	21.28	9.25	51.51	98.57
Lhunzhub	6.74	4.83	1.08	1.89	5.26	44.54	9.81	36.21	110.35
Maizhokunggar	2.95	5.02	1.29	2.13	4.90	45.05	18.92	28.19	108.43
Bomê	4.92	4.78	1.11	1.73	4.67	34.09	8.25	43.99	103.54
Mainling	5.17	5.64	1.14	2.61	5.78	31.07	7.62	38.52	97.54
Gyantse	8.88	16.35	1.98	1.17	5.30	235.50	9.84	87.13	366.15
Bainang	7.21	4.65	1.11	5.03	36.39	37.88	8.24	31.96	132.46
Gongbo'gyamda	4.74	4.65	1.01	1.89	4.39	37.50	8.95	35.02	98.15
Dinggyê	2.63	4.84	0.38	0.03	5.14	116.25	3.58	164.00	296.84
Yadong	4.57	4.41	1.24	0.03	7.32	159.38	1.76	178.00	356.71
Nagarzê	7.94	5.61	1.45	2.29	6.46	49.69	41.63	101.33	216.40

Cd and Hg pollution has been found to varying degrees in the soils of the Lhalu and Maidika wetlands, farmlands, grasslands, and urban areas (Li et al., 2023; Li et al., 2022; Liu et al., 2022; Zhong et al., 2021; Li, 2022; Wu et al., 2018). The sources of TEs pollution in soils around landfills need to be further analysed.

Analysis of TEs sources

Pearson's correlation coefficient analysis

Figure 3 showed that the Pearson's correlation coefficient of Cu-Pb–Zn-Cd, Cr-Ni and Cu-As in the soils around landfills in Tibet exceeded 0.4. These findings revealed a common source and origin for these TEs (Obiri-Nyarko et al., 2021). The correlation between Hg and the other TEs was weaker than that among the other TEs, suggesting that different sources existed for Hg and the other TEs. In addition to Hg, Cr and Ni showed low correlations with other TEs. This is commonly observed in other studies that Cr and Ni are strongly correlated, while they show low correlation with other TEs. Therefore, principal component analysis was subsequently used to further analyze the sources of heavy metals.

Principal component analysis

Principal component analysis is an important tool for identifying the sources of soil TEs (Martín et al., 2013). The data were subjected to Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity tests using SPSS Statistics software. The KMO value

Fig. 3 Correlation analysis of soil TEs

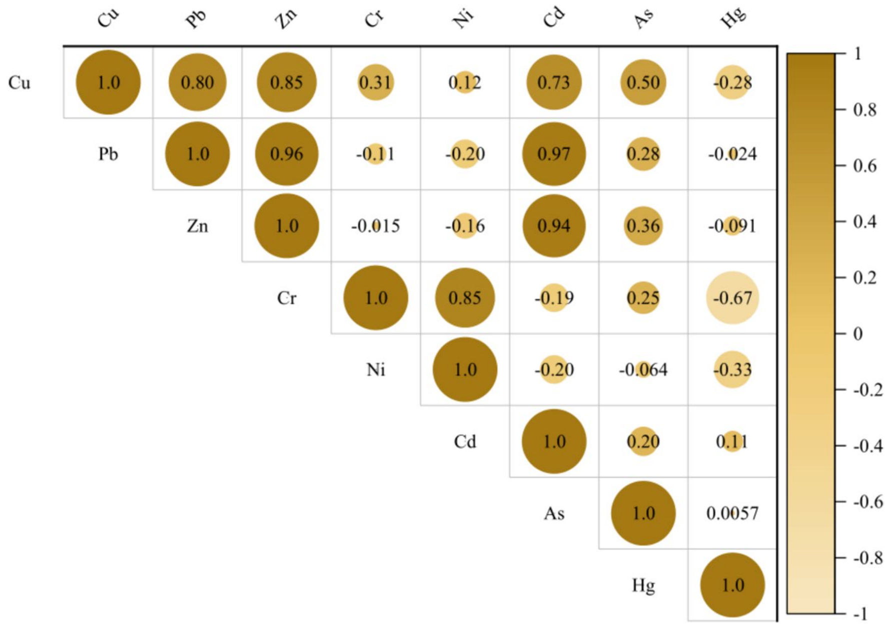


Table 9 Principal component analysis of soil TEs

	Rotated principal component		
	PC1	PC2	PC3
Cu	0.954	0.136	-0.123
Pb	0.970	0.012	-o.113
Zn	0.986	0.036	-0.83
Cr	-0.64	0.971	0.040
Ni	-0.82	0.928	0.262
Cd	0.984	0.16	-0.069
As	0.762	0.088	0.085
Hg	0.390	-0.311	0.861
Eigenvalue	4.536	1.930	0.858
Contribution rate	56.7%	24.1%	10.7%
Cumulative contribution rate	56.7%	80.8%	91.5%

was 0.63, and the significance level of Bartlett's sphericity test was 0.00, which indicated that the data were suitable for PCA. The Kaiser normalized maximum variance method was used for orthogonal rotation of the extracted component matrices, and the results are shown in Table 9. The eigenvalues of the first three principal components were greater than 0.8, and the cumulative variance contribution rate was 91.5%; therefore, these three components could represent the information contained in the original data well.

The variance contribution of principal component 1 (PC1) was 56.7%, in which Cu, Pb, Zn, Cd, and As had high loadings of 0.954, 0.970,0.986, 0.984, and 0.762, respectively. The accumulation of TEs in soils is mainly affected by the joint influence of traffic pollution and soil weathering, which impact Cd and Zn levels (Wang, 2018). In remote areas far from anthropogenic sources of pollution or in areas with high geological backgrounds, the natural weathering of soil-forming parent material and bedrock primarily controls TEs accumulation (Xie et al., 2008). In nature, As, Cd, Pb, and Zn are included among the chalcophile element and are typically found in the form of sulfides in different types of deposits (An et al., 2022; Zhang, 2005). The geological weathering of sulfide ores is thought to be an important source of As, Cd, Pb, and Zn. The landfills in the Tibetan counties had small amounts of waste, low rainfall, and low population density; thus, PC1 was considered to represent sources related to the soil-forming parent material.

The variance contribution of principal component 2 (PC2) was 24.1%, in which the loadings of Cr and Ni were greater than 0.971 and 0.928, respectively. Analysis of the raw TEs data revealed that only the soils around the landfills in Bainang County had high concentrations of Cr and Ni. It was speculated that Cr and Ni may be closely related to soil weathering processes. Mg-Fe-upermagnesian soils are characterized by high

Cr and Ni contents (Ent & Reeves, 2015; Zhang et al., 2023a). Mg-Fe-supermagnesian soils are widely distributed in the Tibetan Plateau region (An et al., 2022; Zhang et al., 2015). Therefore, it is believed that the sources of Cr and Ni in the soils were related to weathering of the soil parent material and the bedrock.

The variance contribution of principal component 3 (PC3) was 10.7%, and only Hg had a high loading of 0.861. Moreover, the low correlation between Hg and the other TEs indicated that the source of Hg was different from the sources of the other TEs. According to previous studies, TEs are emitted into the atmosphere from anthropogenic activities in Southeast Asia as well as in regions of China, such as Yunnan, Guizhou, and Sichuan, and deposit in the hinterland of the Tibetan Plateau due to cross-border atmospheric transport (Bing et al., 2021; Kang et al., 2009; Xiao et al., 2002). As a consequence, TEs accumulate in the soil. Mercury in the soils of the Tibetan Plateau mainly originates from atmospheric transport through direct wet and dry deposition of atmospheric Hg^0 or from apoplastic inputs from vegetation uptake of atmospheric Hg^0 (Wang et al., 2017). Accordingly, PC3 corresponded to a source related to atmospheric transport.

Health risk assessment

CR

The CR was calculated as shown in Table 10. The CRs for children ranged from 6.50E-05 to 5.03E-04 for oral ingestion, from 2.62E-09 to 2.29E-07 for particulate inhalation, from 6.50E-05 to 5.03E-04 for dermal contact, and from 6.69E-05 to 5.03E-04 for TCR. For adults, the CRs for oral ingestion ranged from 3.65E-05 ~ 2.82E-04, the CRs for particulate inhalation ranged from 4.92E-09 ~ 4.32E-07, the CRs for dermal contact ranged from 1.77E-06 ~ 1.19E-05, and the TCRs ranged from 3.79E-05 ~ 2.94E-04. Based on 10^{-4} as the evaluation standard, the soils of the county landfills in Tibet posed a relatively high potential risk of cancer, with both adults and children showing risks higher than 10^{-4}.

As shown in Fig. 4, the contributions of TEs and exposure routes for cancer risk were similar in both adults and children. Among the three different exposure routes, oral ingestion had the highest contribution (more than 95%), followed by dermal contact and particulate inhalation. Among the five TEs, Ni had the highest CR, with a contribution of 57%; Cr and As also contributed more than 20%; and Pb and Cd contributed less than 1%.

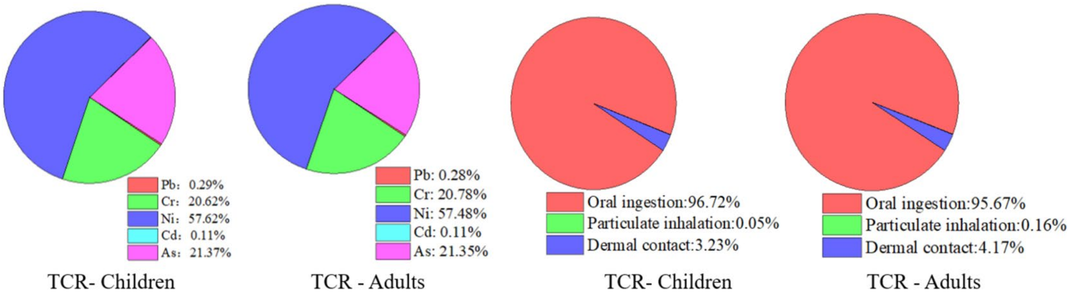
NCR

The NCRs of soils around the county landfills in Tibet are shown in Table 11, with the NCRs for children ranging from 2.50E-01 to 3.33E+00 for oral ingestion, 1.80E-05 to 1.04E-03 for particulate inhalation, 5.76E-03 to 1.19E-01 for dermal contact, and 2.55E-01 to 3.45E+00 for HI. For adults, the NCRs from oral ingestion ranged from 3.50E-02 to 4.67E-01,

Table 10 CR indices for different exposure routes

	Children				Adults			
	Oral ingestion	Particulate inhalation	Dermal contact	TCR	Oral ingestion	Particulate inhalation	Dermal contact	TCR
Damxung	1.05E-04	6.74E-08	1.05E-04	1.09E-04	5.89E-05	1.27E-07	2.69E-06	6.17E-05
Lhunzhub	8.49E-05	6.57E-08	8.49E-05	8.79E-05	4.76E-05	1.24E-07	2.18E-06	4.99E-05
Maizhokunggar	1.20E-04	6.07E-08	1.20E-04	1.25E-04	6.75E-05	1.14E-07	3.03E-06	7.07E-05
Bomê	7.29E-05	4.74E-08	7.30E-05	7.55E-05	4.09E-05	8.92E-08	1.84E-06	4.28E-05
Mainling	9.98E-05	7.78E-08	9.99E-05	1.03E-04	5.60E-05	1.47E-07	2.55E-06	5.87E-05
Gyantse	1.06E-04	5.46E-08	1.06E-04	1.10E-04	5.95E-05	1.03E-07	2.60E-06	6.22E-05
Bainang	5.03E-04	2.29E-07	5.03E-04	5.19E-04	2.82E-04	4.32E-07	1.19E-05	2.94E-04
Gongbo'gyamda	9.04E-05	6.15E-08	9.05E-05	9.37E-05	5.07E-05	1.16E-07	2.32E-06	5.32E-05
Dinggyê	6.50E-05	2.62E-09	6.50E-05	6.69E-05	3.65E-05	4.92E-09	1.41E-06	3.79E-05
Yadong	8.32E-05	2.62E-09	8.32E-05	8.56E-05	4.67E-05	4.93E-09	1.77E-06	4.84E-05
Nagarzê	2.25E-04	1.10E-07	2.25E-04	2.33E-04	1.26E-04	2.07E-07	5.76E-06	1.32E-04

those from particulate inhalation ranged from 8.48E-06 to 1.00E-03, those from dermal contact ranged from 1.05E-03 to 2.17E-02, and the HI ranged from 3.61E-02 to 4.89E-01. There was no significant NCR for adults, and the six county landfills had some NCRs for children, but the risk was low. Except in Nagarzê County, which had an HI of 3.45, the HIs of the county landfills were less than 2.

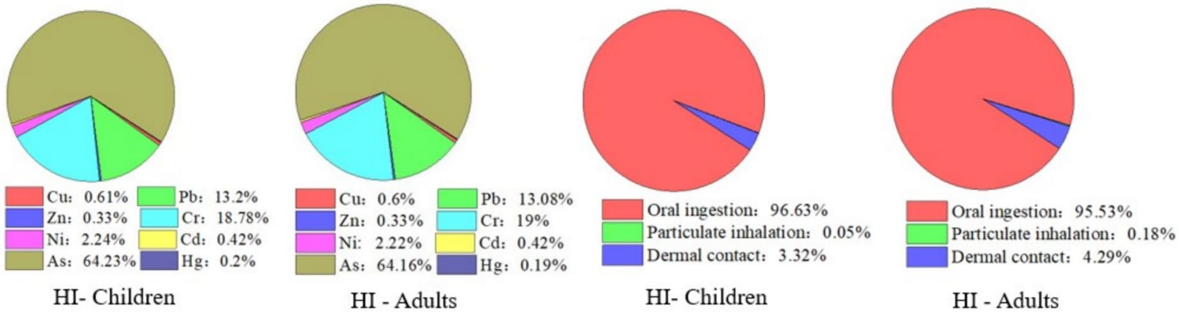


TCR- Children TCR - Adults TCR- Children TCR - Adults

Fig. 4 Contribution of different TEs and exposure routes to CR

Table 11 NCRs from different exposure routes

	Children				Adults			
	Oral ingestion	Particulate inhalation	Dermal contact	HI	Oral ingestion	Particulate inhalation	Dermal contact	HI
Damxung	1.22E+00	6.38E-04	4.31E-02	1.26E+00	1.71E-01	3.00E-04	7.89E-03	1.79E-01
Lhunzhub	6.41E-01	6.38E-04	2.37E-02	6.65E-01	8.99E-02	2.92E-04	4.35E-03	9.45E-02
Maizhokunggar	2.27E+00	5.89E-04	6.68E-02	2.34E+00	3.18E-01	2.77E-04	1.22E-02	3.31E-01
Bomê	6.65E-01	4.48E-04	2.28E-02	6.88E-01	9.33E-02	2.11E-04	4.18E-03	9.77E-02
Mainling	6.33E-01	7.33E-04	2.46E-02	6.59E-01	8.88E-02	3.45E-04	4.51E-03	9.37E-02
Gyantse	1.19E+00	5.20E-04	3.62E-02	1.22E+00	1.66E-01	2.45E-04	6.63E-03	1.73E-01
Bainang	1.51E+00	2.13E-03	6.21E-02	1.57E+00	2.12E-01	1.00E-03	1.14E-02	2.24E-01
Gongbo'gyamda	9.86E-01	5.82E-04	3.49E-02	1.02E+00	1.38E-01	2.74E-04	6.38E-03	1.45E-01
Dinggyê	3.68E-01	2.13E-05	9.91E-03	3.78E-01	5.16E-02	1.00E-05	1.82E-03	5.35E-02
Yadong	2.50E-01	1.80E-05	5.76E-03	2.55E-01	3.50E-02	8.48E-06	1.05E-03	3.61E-02
Nagarzê	3.33E+00	1.04E-03	1.19E-01	3.45E+00	4.67E-01	4.91E-04	2.17E-02	4.89E-01



HI- Children HI - Adults HI- Children HI - Adults

Fig. 5 Contribution of different TEs and exposure pathways to NCR

As shown in Fig. 5, the contributions of TEs and exposure routes to NCR were similar in both adults and children, and among the three different exposure routes, oral ingestion had the highest NCR, with a contribution of more than 95%, followed by dermal contact and then particulate inhalation, which had the lowest NCR, with a contribution of less than 1%. Among the eight TEs, As had the highest NCR contribution of more than 60%, Pb and Cr had contributions of more than 10%, and the other TEs had contributions less than 3%.

Uncertainty in health risk evaluation

In this study, we evaluated the total amount of soil TEs around landfills for health reasons, but the TEs were not fully absorbed into the human body, so the calculated health risk value was high. The parameters for health risk and exposure pathways were designed based on previous studies, but the actual exposure was lower than the calculated exposure. The Tibet Autonomous Region is sparsely populated, and there is no local population around the county landfills. In addition, we did not consider the antagonistic or synergistic effects of TEs on the human body or on exposure to TEs through the food chain or other pathways. The health risks in this article are calculated based on the total amount of TEs, without exploring the health risks under different forms of TEs. For example, Cr (VI) has a carcinogenic risk, while Cr (III) has no carcinogenic risk. Therefore, it is possible that the actual health risks would be different from those determined in the health risk evaluation in this study.

Conclusions

In this paper, we conducted field research, soil sampling, and TEs analysis in landfills in the counties of Tibet and evaluated the impact of landfills on the environment and human health based on TEs content, pollution risk assessments, human health risks and sources of TEs. The conclusions reached are as follows:

(1) The TEs concentrations in the soil around landfills in the Tibetan counties are low, and only a few landfills have individual TEs concentrations that exceed the risk screening value in the *Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land* (GB 15618–2018) (PH > 7.5).
(2) Most of the landfills are at a moderate level in terms of soil TEs pollution, but some landfills have a heavier pollution level. Pollution from Cd and Hg is severe.
(3) Landfilling has a small impact on TEs in the surrounding soil; the TEs originate mainly from the weathering of the soil matrix and bedrock, but Hg originates mainly from atmospheric transport.
(4) The landfill soils in the counties in Tibet may impact human health. The NCR and CR contributions of TEs and exposure routes were similar for adults and children. Among the three different exposure routes, oral ingestion had the highest CR and NCR, with a contribution of more than 95%. Among the TEs, Ni had the highest CR, with a contribution of 57%, and Cr and As contributed more than 20%. The highest NCR contribution was more than 60%.

The present study revealed that the TEs in soil mainly originated from the soil parent material and atmospheric transport. The landfill sites had a low impact on TEs in surrounding soil. This may be because the amount of waste and rainfall in plateau areas is small, and the landfill year is relatively short. Therefore, the migration of TEs in waste is limited. Therefore, in the future research, it is necessary to strengthen the research on small-scale waste treatment and resource utilization technology in the plateau area, as well as the research on the impact of soil quality and atmospheric transport on soil TEs in Tibet. The selection of different background samples (soil or parent material) can also have a significant impact on the calculation results (Aytop et al., 2023). Moreover, the impact of TEs speciation and bioeffective utilisation rate on human health risks should be studied.

Acknowledgements Thank the members of the research group for their contribution to the experiment. This work was supported by the key research and development plan project of the Department of science and technology of the Tibet Autonomous Region (No. XZ202301ZY0029G), National Natural Science Foundation of China Project (No. 52160026), The Tibetan Financial Forecast refers to the [2022] 1 Central Government Special Fund to support the reform and development of local universities.

Author Contributions All authors contributed to the study conception and design. Dan Zeng provided the research idea Material preparation, data collection and analysis were performed by Jiamin Ma, Wenwu Zhou and Dean Meng. The first draft of the manuscript was written by Dean Meng. Jiaqi Wang, Peng Zhou and Dean Meng completed the field survey and sampling work together and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the key research and development plan project of the Department of science and technology of the Tibet Autonomous Region (No. XZ202301ZY0029G), National Natural Science Foundation of China Project (No. 52160026), The Tibetan Financial Forecast refers to the [2022] 1 Central Government Special Fund to support the reform and development of local universities.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval This paper is a study on the risk assessment and source analysis of trace elements in soil around county landfills, not involving human and animal research.

Consent to participate All authors were participated in this work.

Consent to publish All authors agree to publish.

Competing interests The authors declare no competing interests.

References

Adelopo, A., Haris, P., Alo, B., Huddersman, K., & Jenkins, R. (2018). Multivariate analysis of the effects of age, particle size and landfill depth on heavy metals pollution content of closed and active landfill precursors. *Waste Management, 78*, 227–237. https://doi.org/10.1016/j.wasman.2018.05.040

Alves, L. R., Reis, A. R., & Gratão, P. L. (2016). Heavy metals in agricultural soils: from plants to our daily life (a review). *Científica, 44*, 346–361. https://doi.org/10.15361/1984-5529.2016v44n3p346-361

An, S., Liu, N., Li, X., Zeng, S., Wang, X., & Wang, D. (2022). Understanding heavy metal accumulation in roadside soils along major roads in the Tibet Plateau. *Science of the Total Environment, 802*, 149865. https://doi.org/10.1016/j.scitotenv.2021.149865

Aytop, H. (2023). Evaluation of environmental and ecological risks caused by metals in agricultural areas: an example in the Amik Plain of South Turkey. *International Journal of Environmental Health Research*, 1–12. https://doi.org/10.1080/09603123.2022.2097203

Aytop, H., Koca, Y. K., & Şenol, S. (2023). The importance of using soil series-based geochemical background values when calculating the enrichment factor in agricultural areas. *Environmental Geochemistry and Health*, 1–16. https://doi.org/10.1007/s10653-023-01640-6

Bing, H., Qiu, S., Tian, X., Li, J., Zhu, H., Wu, Y., & Zhang, G. (2021). Trace metal contamination in soils from mountain regions across China: Spatial distribution, sources, and potential drivers. *Soil Ecology Letters, 3*, 189–206. https://doi.org/10.1007/s42832-021-0080-8

Chang, J., Liu, M., Li, X. H., Lin, X., Wang, L. L., & Gao, L. (2009). Primary research on health risk assessment of heavy metals in road dust of Shanghai. *China Environmental Science, 29*, 548–554.

Che, F., Chen, J., Zhang, B., Jiang, X., & Wang, S. (2020). Distribution, risk and bioavailability of metals in sediments of Lake Yamdrok Basin on the Tibetan Plateau, China. *Journal of Environmental Sciences, 97*, 169–179. https://doi.org/10.1016/j.jes.2020.04.036

Cheng, Y. A., & Tian, J. L. (1993). *Background values and distribution characteristics of soil elements in Tibet*. Science Press.

Cheng, H. X., Li, K., Li, M., Yang, K., Liu, F., & Cheng, X. M. (2014). Geochemical background and baseline value of chemical in urban soil in China. *Earth Science Frontiers, 21*, 265–306.

Dan, Z., Zhou, P., Wang, J., Qiong, D. Z. M., Zhou, W. W., Li, Y., & Chen, G. Y. (2019). Investigation and research about soil heavy metals in the vicinity of the domestic waste sanitary landfill-lhasa. *Environmental Engineering, 37*, 194–199+154. https://doi.org/10.13205/j.hjgc.201911032

Dan, Z., Chen, G. Y., Zhou, P., et al. (2021). Factors influencing groundwater contamination near municipal solid waste landfills in the Qinghai-Tibetan plateau. *Ecotoxicology and Environmental Safety, 211*, 111913. https://doi.org/10.1016/j.ecoenv.2021.111913

de Souza, V. B., Hollas, C. E., Bortoli, M., Manosso, F. C., & de Souza, D. Z. (2023). Heavy metal contamination in soils of a decommissioned landfill southern Brazil: Ecological and health risk assessment. *Chemosphere, 339*, 139689. https://doi.org/10.1016/j.chemosphere.2023.139689

Fang, X., Peng, B., Wang, X., et al. (2019). Distribution, contamination and source identification of heavy metals in bed sediments from the lower reaches of the Xiangjiang River in Hunan province, China. *Science of the Total Environment, 689*, 557–570. https://doi.org/10.1016/j.scitotenv.2019.06.330

Fu, W., Zhou, Y. Z., Yang, Z. J., Bie, F. J., Li, W., He, J. G., Li, Z. Q., & Hu, P. (2005). Geological and geochemical characteristics of the silicified rocks in Jiangzi basin and their implications for mineralization. *Geoscience, 19*, 267–273.

Guo, G. H., & Song, B. (2010). Preliminary health risk assessment of the exposure of children to heavy in urban soils. *Resources and Environment in the Yangtze Basin, 19*, 946–952.

Hakanson, L. (1980). An ecological risk index for aquatic pollution control. a sedimentological approach. *Water*

Research, 14, 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

He, X. W., Fang, Z. Q., Wang, Y. X., Jia, M. Y., Song, J. Y., & Cheng, Y. J. (2016). Pollution characteristics, potential ecological risk and health risk assessment of heavy metal in a sewage treatment plant in Beijing. *Acta Scientiae Circumstantiae, 36*, 1092–1098. https://doi.org/10.13671/j.hjkxxb.2015.0562

Huang, J., Minasny, B., McBratney, A., Padarian, J., & Triantafilis, J. (2018). The location- and scale- specific correlation between temperature and soil carbon sequestration across the globe. *Science of the Total Environment, 615*, 540–548. https://doi.org/10.1016/j.scitotenv.2017.09.136

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*, 60–72. https://doi.org/10.2478/intox-2014-0009

Kang, J. H., Choi, S. D., Park, H., Baek, S. Y., Hong, S., & Chang, Y. S. (2009). Atmospheric deposition of persistent organic pollutants to the East Rongbuk Glacier in the Himalayas. *Science of the Total Environment, 408*, 57–63. https://doi.org/10.1016/j.scitotenv.2009.09.015

Karunanidhi, D., Aravinthasamy, P., Subramani, T., & Chandrajith, R. (2022). Provincial and seasonal influences on heavy metals in the Noyyal River of South India and their human health hazards. *Environmental Research, 204*, 111998. https://doi.org/10.1016/j.envres.2021.111998

Li, Y. X., Huang, Y., Wang, N., Yang, J., Xu, M. M., Su, B., & Gao, F. W. (2014). Pollution characteristics and health risk assessment of heavy metals for an open dumping site in inner suburbs in Shandong Province. *Environmental Chemistry, 33*, 1476–1483.

Li, W., Zhang, N., Xiong, J., et al. (2022). Distribution characteristics and pollution assessment of heavy metals in soil of Mitika wetland. *Applied Chemical Industry, 51*, 3514–3518+3523. https://doi.org/10.16581/j.cnki.issn1671-3206.20221031.012

Li, W., Sun, J., Xiong, J., Zhang, N., Gao, H. T., Zhang, Q. Y., & lv, X.B. (2023). Distribution characteristics and risk assessment of heavy metals in the surface soil of Lhalu Wetland, Tibe. *Environmental Science & Technology, 46*, 92–100. https://doi.org/10.19672/j.cnki.1003-6504.1640.22.338

Li, X. M. (2022). Distribution characteristics and influencing factors of heavy metals in alpine grassland ecosystem in central and eastern Qinghai-Tibet plateau. Dissertation, Southwest University

Liu, C., & Wu, X. W. (2011). Factors influencing municipal solid waste generation in China: A multiple statistical analysis study. *Waste Management & Research., 29*, 371–378. https://doi.org/10.1177/0734242X10380114

Liu, S. J., Wang, W. Y., Han, Y. M., & Xue, H. Y. (2022). Assessment of Heavy Metal Pollution Situation of Farmland Soil Located in Zhangmai Village, Nyingchi City. *Journal of Plateau Agriculture, 6*, 349–355. https://doi.org/10.19707/j.cnki.jpa.2022.04.005

Martín, J. A. R., Ramos-Miras, J. J., Boluda, R., & Gil, C. (2013). Spatial relations of heavy metals in arable and greenhouse soils of a Mediterranean environment region (Spain). *Geoderma, 200*, 180–188. https://doi.org/10.1016/j.geoderma.2013.02.014

National Bureau of statistics of the People's Republic of China (NBSPRC). (2021). *China Statistical Yearbook*. China Statistics Press.

Nemerow, N. (1974). *Scientific Stream Pollution Analysis*. McGrow Hill.

Niu, B., Shanshan, E., Xu, Z., & Guo, J. (2023). How to efficient and high-value recycling of electronic components mounted on waste printed circuit boards: Recent progress, challenge, and future perspectives. *Journal of Cleaner Production, 415*, 137815. https://doi.org/10.1016/j.jclepro.2023.137815

Obiri-Nyarko, F., Duah, A. A., Karikari, A. Y., Agyekum, W. A., Manu, E., & Tagoe, R. (2021). Assessment of heavy metal contamination in soils at the Kpone landfill site, Ghana: Implication for ecological and health risk assessment. *Chemosphere, 282*, 131007. https://doi.org/10.1016/j.chemosphere.2021.131007

Qiao, P., Wang, S., Li, J., Shan, Y., Wei, Y., Zhang, Z., & Lei, M. (2023). Quantitative analysis of the contribution of sources, diffusion pathways, and receptor attributes for the spatial distribution of soil heavy metals and their nested structure analysis in China. *Science of the Total Environment, 882*, 163647. https://doi.org/10.1016/j.scitotenv.2023.163647

Sun, S., Bao, C., & Tang, Z. (2019). Tele-connecting water consumption in Tibet: Patterns and socio-economic driving factors for virtual water trades. *Journal of Cleaner Production, 233*, 1250–1258. https://doi.org/10.1016/j.jclepro.2019.06.141

US EPA (1992) Guidelines for exposure assessment. United States Environmental Protection Agency, Washington

US EPA (2000) Handbook for non-cancer health effects evaluation. United States Environmental Protection Agency, Washington

US EPA (2002) Supplemental guidance for developing soil screening levels for superfund sites. United States Environmental Protection Agency, Washington

US EPA (2011) Exposure factor handbook. United States Environmental Protection Agency, Washington

US EPA (2012) Municipal Solid Waste Generation, Recycling and Disposal in United Sates. United States Environmental Protection Agency, Washington

van der Ent, A., & Reeves, R. D. (2015). Foliar metal accumulation in plants from copper-rich ultramafic outcrops: Case studies from Malaysia and Brazil. *Plant and Soil, 389*, 401–418. https://doi.org/10.1007/s11104-015-2385-9

Wang, M. G., Li, S. H., Wang, H., Xiao, T. F., & Zheng, B. S. (2012). Distribution of arsenic in surface water in Tibet. *Environmental Science, 33*, 3411–3416.

Wang, X., Luo, J., Yin, R. S., et al. (2017). Using mercury isotopes to understand mercury accumulation in the montane forest floor of the Eastern Tibetan Plateau. *Environmental Science & Technology, 51*, 801–809. https://doi.org/10.1021/acs.est.6b03806

Wang, F. F., Guan, Q. Y., Tian, J., Lin, J. K., Yang, Y. Y., Yang, L. Q., & Pan, N. H. (2020a). Contamination characteristics, source apportionment, and health risk assessment of heavy metals in agricultural soil in the Hexi Corridor. *CATENA, 191*, 104573. https://doi.org/10.1016/j.catena.2020.104573

Wang, X. T., Dan, Z., Cui, X. Q., et al. (2020b). Contamination, ecological and health risks of trace elements in soil of landfill and geothermal sites in Tibet. *Science of the Total Environment, 715*, 136639. https://doi.org/10.1016/j.scitotenv.2020.136639

Wang, S., Han, Z., Wang, J., He, X., Zhou, Z., & Hu, X. (2022). Environmental risk assessment and factors influencing heavy metal concentrations in the soil of municipal solid waste landfills. *Waste Management, 139*, 330–340. https://doi.org/10.1016/j.wasman.2021.11.036

Wang, R., Zhang, Z., Chen, X., Zhan, L., & Xu, Z. (2023). Research on compound pollution characteristics and health risk evaluation of particulate matter and heavy metals in waste glass recycling process. *Environmental Pollution, 337*, 122570. https://doi.org/10.1016/j.envpol.2023.122570

Wang, Y.H. (2018) Distribution characteristics, sources and ecological risk assessment of heavy metals in soils of Qinghai-Tibet Platesu. Dissertation, Tianjin Normal University

Wen, Z., Song, K., Liu, G., Shang, Y., Hou, J., Yu, L., & Fang, C. (2019). Impact factors of dissolved organic carbon and the transport in a river-lake continuum in the Tibet Plateau of China. *Journal of Hydrology, 579*, 124202. https://doi.org/10.1016/j.jhydrol.2019.124202

Wu, J., Lu, J., Li, L. M., Min, X. Y., & Luo, Y. M. (2018). Pollution, ecological-health risks, and sources of heavy metals in soil of the northeastern Qinghai-Tibet Plateau. *Chemosphere, 201*, 234–242. https://doi.org/10.1016/j.chemosphere.2018.02.122

Xiao, C., Kang, S. C., Qin, D., Yao, T. D., & Ren, J. W. (2002). Transport of atmospheric impurities over the Qinghai-Xizang (Tibetan) Plateau as shown by snow chemistry. *Journal of Asian Earth Sciences, 20*, 231–239. https://doi.org/10.1016/S1367-9120(01)00065-7

Xiao, Z., He, P. J., Shao, L. M., Li, G. J., Yu, J. Y., Chen, Z. F., & Xu, Y. E. (2005). Effect of the total amount and speciation of heavy metals on its mobility in municipal solid waste landfill. *Environmental Chemistry, 03*, 265–269.

Xie, S. R., Peng, B., Tang, X. Y., Yu, C. X., & Wu, F. C. (2008). Characteristics of Heavy Metal Contamination of Soils Derived from Black Shale in the Contral Hunan, China. *Chinese Journal of Soil Science, 01*, 137–142.

Xu, Y., Li, S. Q., Guo, S. H., Li, H. F., & Liu, W. T. (2008). Comparison of assessment methods of heavy metal pollution in soil. *Journal of Anhui Agricultural Sciences, 36*, 4615–4617.

Xu, Q. Y., Dai, L. L., Peng, Z. G., Zhang, J., Xiao, K. Q., Gong, H., Wu, H. H. (2023) Characteristics and health risk evaluation of soil heavy metals in Longshan County, Hunan Province. Geology in China. https://link.cnki.net/urlid/11.1167.P.20230815.1025.002. Accessed 21 Aug 2023.

Zhang, Z., Li, W., Wang, Y., Qian, B., Li, K., Zhang, J., Gao, Y., Guo, Z., & You, M. (2015). Geological and Geochemical Characteristics of Mafic-ultramafic Intrusions in the Hualong Area, Southern Qilian Mountains and Its Ni-Cu Mineralization. *Acta Geologica Sinica, 89*, 632–644.

Zhang, C., Nie, S., Liang, J., Zeng, G., & Wu, H. (2016). Effects of heavy metals and soil physicochemical properties on wetland soil microbial biomass and bacterial community structure. *Science of the Total Environment, 557*, 785–790. https://doi.org/10.1016/j.scitotenv.2016.01.170

Zhang, X., Wei, S., Sun, Q., Wadood, S., & Guo, B. (2018). Source identification and spatial distribution of arsenic and heavy metals in agricultural soil around Hunan industrial estate by positive matrix factorization model, principle components analysis and geo statistical analysis. *Ecotoxicological and Environmental Safety, 159*, 354–362. https://doi.org/10.1016/j.ecoenv.2018.04.072

Zhang, R., Chen, T., Zhang, Y., Hou, Y. H., & Chang, Q. R. (2020). Health risk assessment of heavy metals in agricultural soils and identification of main influencing factors in a typical industrial park in northwest China. *Chemosphere, 252*, 126591. https://doi.org/10.1016/j.chemosphere.2020.126591

Zhang, M., Liu, Y., Chen, A., Liang, K., Yang, Y., & Xu, W. (2023a). The tectonic links between Palaeozoic eclogites and mafic magmatic Cu-Ni-Co mineralization in East Kunlun orogenic belt, western China. *International Geology Review, 65*, 1158–1178. https://doi.org/10.1080/00206814.2021.1885504

Zhang, T., Wang, P., Wang, M., Liu, J., Gong, L., & Xia, S. (2023b). Spatial distribution, source identification, and risk assessment of heavy metals in riparian soils of the Tibetan plateau. *Environmental Research, 237*, 116977. https://doi.org/10.1016/j.envres.2023.116977

Zhang, X. (2005) Geochemical characteristics and environmental effects of heavy metal element release and migration in Tongling mining area, Anhui Province. Dissertation, Hefei Polytechnic University

Zhong, W., Zhang, D., & Hou, L. (2021). The Potential Ecological Risk Assessment in Different Functional Areas of Nyingchi. *Journal of Plateau Agriculture, 5*, 367–373. https://doi.org/10.19707/j.cnki.jpa.2021.04.006

Zhou, P. (2020a) Analysis and evaluation of groundwater environment in landfill sites: A case study in Shigatse, Tibet. Dissertation, Tibet University.

Zhou, W. W. (2020b) Study on status and risk assessment of heavy metals in soil of Shannan landfill in Tibet (2020) Dissertation, Tibet University.

Zhou, W. W., Chen, G. Y., Qiongda, Z. M., Zhou, P., & Wang, J. (2020). Health risk assessment of groundwater quality in Lhasa landfill. *Environmental Chemistry, 39*, 1513–1522.

Zhou, W. W., Dan, Z., Zhou, P., Chen, G. Y., & Meng, D. A. (2022). Study on health risk assessment of potentially toxic elements in the soil around landfill in Shannan City, Tibet. *Environmental Pollutants & Bioavailability, 34*, 365–373. https://doi.org/10.1080/26395940.2022.2118832

Zhou, W. W., Dan, Z., Meng, D. A., et al. (2023). Distribution characteristics and potential ecological risk assessment of heavy metals in soils around Shannan landfill, Tibet. *Environmental Geochemistry and Health, 45*, 393–407. https://doi.org/10.1007/s10653-022-01349-y