Environ Geochem Health (2023) 45:8015–8030
https://doi.org/10.1007/s10653-023-01706-5

ORIGINAL PAPER

Dietary sources apportionment and health risk assessment for trace elements among residents of the Tethys-Himalayan tectonic domain in Tibet, China

Xue Gao · Jialu An · Chengqun Yu · Xinjie Zha · Yuan Tian

Received: 22 May 2023 / Accepted: 18 July 2023 / Published online: 31 July 2023

Abstract Dietary intake of toxic elements (TEs) and essential trace elements (ETEs) can significantly impact human health. This study collected 302 samples, including 78 food, 104 drinking water, 73 cultivated topsoil, and 47 sedimentary rock from a typical area of Tethys–Himalaya tectonic domain. These samples were used to calculate the average daily dose of oral intake (ADD_{oral}) and assess the health risks of five TEs and five ETEs. The results indicate that grain and meat are the primary dietary sources of TEs and ETEs for local residents. The intake of manganese (Mn) and copper (Cu) is mainly from local highland barley (66.90% and 60.32%, respectively), iron (Fe) is primarily from local grains (75.51%), and zinc (Zn) is mainly from local yak meat (60.03%). The ADD_{oral} of arsenic (As), Mn, Fe and Zn were found to be higher than the maximum oral reference dose in all townships of study area, indicating non-carcinogenic health risks for local residents. Additionally, lead (Pb) and nickel (Ni) in 36.36% townships, and Cu in 81.82% townships were above the maximum oral reference dose, while As posed a carcinogenic risk throughout the study area. The concentrations of As, mercury (Hg), Pb, Mn, Cu Fe and selenium (Se) in grains were significantly correlated with those in soils. Moreover, the average concentrations of As in *Proterozoic*, *Triassic*, *Jurassic* and *Cretaceous* was 43.09, 12.41, 15.86 and 6.22 times higher than those in the South Tibet shell, respectively. The high concentrations of TEs and ETEs in the stratum can lead to their enrichment in soils, which, in turn, can result in excessive intake by local residents through the food chain and biogeochemical cycles . To avoid the occurrence of some diseases caused by dietary intake, it is necessary to consume a variety of exotic foods, such as high-selenium foods, foreign rice and flour in order to improve the dietary structure.

Xue Gao and Jialu An have contributed equally to this work.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10653-023-01706-5.

X. Gao
State Key Laboratory of Hulless Barley and Yak Germplasm Resources and Genetic Improvement, Jinzhu Str.130, Chengguan District, Lhasa 850000, China

X. Gao
Tibet Academy of Agriculture and Animal Husbandry Sciences, Institute of Agricultural Resources and Environment, Jinzhu Str.130, Chengguan District, Lhasa 850000, China

J. An · X. Zha
Xi'an University of Finance and Economics, Changning Str. 360, Chang'an District, Xi'an 710100, China

C. Yu · Y. Tian (✉)
Key Laboratory of Ecosystem Network Observation and Modelling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Datun Str. 11A, Chaoyang District, Beijing 100101, China
e-mail: tiany.16b@igsnrr.ac.cn

Keywords Dietary intake sources · Toxic elements · Essential trace elements · Dietary structure · Health risk assessment · Tibet

Abbreviations

TEs	Toxic element
ETEs	Essential trace elements
As	Arsenic
Pb	Lead
Hg	Mercury
Cd	Cadmium
Ni	Nickel
Mn	Manganese
Fe	Iron
Cu	Copper
Zn	Zinc
Se	Selenium
WHO	World Health Organization
EFSA	European Food Safety Administration
USEPA	U.S. Environmental Protection Agency
MEE	Ministry of Ecology and Environment of the People's Republic of China
NHC	National Health Commission of the People's Republic of China
QTP	Qinghai–Tibet Plateau
KBD	Kashin-Beck disease
TH	Tethys–Himalaya
GPS	Global Position System
CAS	Chinese Academy of Sciences
ICP–MS	Inductively Coupled Plasma Mass Spectrometry
HG–AFS	Hydride Generation Atomic Fluorescence Spectrometry
CV–AAS	Cold Vapor Atomic Absorption Spectrometry
ADD	Average daily dose
C_g	The average concentration of trace elements in grain
C_f	The average concentration of trace elements in flour
C_r	The average concentration of trace elements in rice
C_v	The average concentration of trace elements in vegetable
C_m	The average concentration of trace elements in meat
C_w	The average concentration of trace elements in water
C_s	The average concentration of trace elements in soil
IR	Ingestion rate
EF	Exposure frequency
ED	Exposure duration
BW	Body weight
AT	Average time
HQ	Hazard quotient
RfD	Reference dose
CR	Carcinogenic risk

Introduction

Trace elements have been assigned definite biological functions in maintaining human health (Konikowska & Mandecka, 2018; Shayganfard, 2022; WHO, 1996). Some of these elements, such as arsenic (As), mercury (Hg), lead (Pb), nickel (Ni), and cadmium (Cd), are considered toxic elements (TEs), which can cause abnormal physiological functions and even several serious diseases at any concentration (Halder et al., 2020; Tian et al., 2022). On the other hand, others, such as manganese (Mn), copper (Cu), iron (Fe), selenium (Se), and zinc (Zn), are considered essential trace elements (ETEs), but their long-term dietary intake may pose health risks and potential toxicity when consumed excessively or insufficiently (Cannas et al., 2020; Tong et al., 2021; Xiao et al., 2019). The health effects of these trace elements are summarized in Table 1. Assessing the apportionment of dietary sources and the associated health risks of trace element consumption is crucial in determining contamination levels in an area (Antoniadis et al., 2019).

Direct dietary intake, such as food consumption and drinking water, is the primary way in which the general population ingests trace elements (Filippini et al., 2020; Pipoyan et al., 2019). However, soil and dust ingestion also pose a significant pathway for residents in agricultural and pastoral areas (USEPA, 2016). Due to the increasing industrialization and urbanization, it is necessary to comprehensively evaluate the dietary intake of trace elements, especially TEs and ETEs, to assess long-term public health risks in most countries, including China (Gao et al., 2019; Li et al., 2018; Tang et al., 2014; Tian et al., 2020a; Wu et al., 2016; Zheng et al., 2007). Many environmental health organizations worldwide have developed recommendation or limit standards for trace

Table 1 Health effects of TEs and ETEs

Trace elements	Health effects (Nordberg & Costa, 2022)	
	Deficiency	Overdose
TEs		
As	–	Skin lesions; Cardiovascular diseases; Carcinogenicity; etc
Pb	–	Central nervous system damage; Renal dysfunction; Decrease of IQ; etc
Hg	–	Minamata disease; Central nervous system damage; Death; etc
Cd	–	Itai-Itai disease; Kidney, liver and lungs damage; Carcinogenicity; etc
Ni	–	Haematotoxicity; Immunotoxicity; Carcinogenicity; etc
ETEs		
Mn	Impaired reproductive functions; Maldevelopment; etc	Increased hyperactive behavior; Neurological disorders; etc
Fe	Anemia; Decrease of IQ; Immunity decreased; etc	Gastrointestinal damage; Hemochromatosis; Cardiovascular disease; etc
Cu	Menkes disease; Central nervous system damage; Endocrine symptoms; etc	Wilson's disease Impaired reproductive functions; Kidney and liver damage; etc
Zn	Skin lesions; Neurological disorders; Immunity decreased; Growth retardation; Infertility; etc	Digestive system damage; Respiratory disorder; Altered lymphocyte function; Anemia; Carcinogenicity; etc
Se	Kaschin–Beck disease; Keshan disease Immunity decreased; etc	Chronic selenosis; Diabetes mellitus; Cardiovascular diseases; etc

elements and use health risk assessment as an effective approach to alleviate hidden hunger and some endemic diseases (EC, 2000; FAO & WHO, 2009; MEE, 2017a, 2017b; NHC, 2021; NHC & SA, 2006; NHC & SFDA, 2017; USEPA, 1996; USEPA, 2011; WHO, 2005; WHO, 2011).

The food consumption structure of rural residents in the Qinghai–Tibet Plateau (QTP) is relatively simple due to the region's natural geographical environment. Locally produced grain and meat products are the primary sources of protein, carbohydrate and fat intake (Dermience et al., 2017; Gao et al., 2017; Wang et al., 2021). Studies have confirmed that this simple food consumption structure is the main reasons behind endemic diseases such as endemic arsenic poisoning and Kashin-Beck disease in QTP (Dinh et al., 2018; Li et al., 2012). Therefore, studying dietary trace element intake in QTP have important reference value for assessing the health risk of residents. In recent decades, multiple methods have been used to analyze trace elements contents in the food–water system in parts of QTP (Tian et al., 2018; Wang et al., 2020; Zhang et al., 2021; Zhang et al., 2002). However, existing research on the health risk assessment of QTP has mainly focused on ETEs, especially Se (Dermience et al., 2017; Guo & Wang, 2012; Tian et al., 2016, ; Wang et al., 2020a, ; Zhang et al., 2011; Zhao et al., 2013).

Li et al. (2022) studied the water quality and health risks of trace elements in surface water in the northeast of the QTP, and the results showed that 96% of the water quality belonged to excellent status, the non-carcinogenic health risk of children was high, and Cr was the primary contributor element to the carcinogenic risk in water. Du et al. (2023) studied seven heavy metal concentrations in 126 topsoil samples on the QTP, and the results showed that the risk of Cd and As pollution in soil was high. Wu et al. (2018) collected 70 soil samples from the northeastern QTP to assess health risk. The results showed that the carcinogenic risk of adults and children was determined to be high and very high, while the non-cancer risk of children was higher, while the non-cancer risk of adults was lower. Li et al. (2023) collected and analyzed 130 pairs of representative soil-highland barley samples from the QTP, and the results showed that the Cd concentration in highland barley ranged from 0.57 to 13.62 μg/kg, with an average of 4.57 ± 0.17 μg/kg. According to the literature review, there are only a few systematic reports on the dietary intake of trace elements and their health risk assessment in QTP.

Against this backdrop, this study systematically collected food (including highland barley, wheat, vegetable and meat), drinking water, cultivated soil and sedimentary rock samples in a typical area of Tethys–Himalaya (TH) tectonic domain, and comprehensively analyze the concentration of five TEs (As, Hg, Pb, Ni and Cd) and five ETEs (Mn, Cu, Fe, Se and Zn). The primary objectives of this study are to (a) describe and analyze the concentration characteristics of TEs and ETEs in food, drinking water and soil in the study area; (b) calculate the oral intake dose and assess the dietary health risk of TEs and ETEs to local residents; and (c) estimate the proportion of different source of intake of TEs and ETEs and discuss their underlying impact mechanisms. The results of this cross-sectional study would provide a comprehensive understanding of basic data for effective management of residents' dietary intake, and have guiding significance and reference value for protecting residents' health and the sustainability of agricultural production in this region.

Materials and methods

Study area description

The study area, Longzi County, is located in the TH tectonic domain and can be located geographically using the coordinates 91°53′–93°06′ E and 28°07′–28°52′ N (see Fig. 1b). Longzi County is a significant area for agricultural and animal husbandry production in Tibet, with a total population of 33,570 comprising of Tibetan, Luoba, and Han nationalities. Longzi County straddles the Yarlung Zangbo River Suture Zone and Southern Tibetan Detachment System (Dhital, 2015; Zheng et al., 2000).

Samples preparation and analysis

In August 2019 and August 2020, a total of 78 food samples (including 60 highland barley, 6 wheat, 8 vegetables and 4 meat), 104 drinking water samples, 73 cultivated topsoil samples and 47 sedimentary rock samples, were collected in study area (Fig. 1c). The sample point coordinates were recorded by the handheld Global Position System manufactured by GARMIN. Each food sample weighing approximately 0.2 kg was collected and stored in a colorless polyethylene (PE) bag; Each drinking water sample was stored in a colorless PE bottle. The bottle were washed beforehand with deionized water and kept at 4 ℃; The cultivated topsoil samples were collected using the quartile method, with approximately 0.2 kg packed into each colorless PE bag; Each sedimentary rock sample weighing approximately 0.1 kg was collected from five blocks of the same outcrop and stored in a colorless PE bag.

The concentrations of Pb, Ni, Cd, Mn, Cu, Fe, and Zn in water samples were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP–MS). The concentrations of As and Se were determined using Hydride Generation Atomic Fluorescence Spectrometry (HG–AFS). The concentration of Hg was analyzed using Cold Vapor Atomic Absorption Spectrometry (CV–AAS). To determine the concentration of Cd, Cu, Fe, Mn, Ni, Pb, and Zn in topsoil, and sedimentary rock samples, the crushed and weighed sample was added to PTFE beaker mixed with acid of 3:3:1 HNO_3, HF and $HClO_4$, and heating the mixture at 180 ± 10℃ until the solution became transparent; the crushed food sample was added to glass beaker mixed with acid of 5:1 HNO_3 and $HClO_4$ and digested by heating (MEE, 2017a). The concentrations were then measured using ICP–MS. For the determination of As and Se, the crushed and weighed sample was added to aqua regia mixed with acid of a (1 + 1)

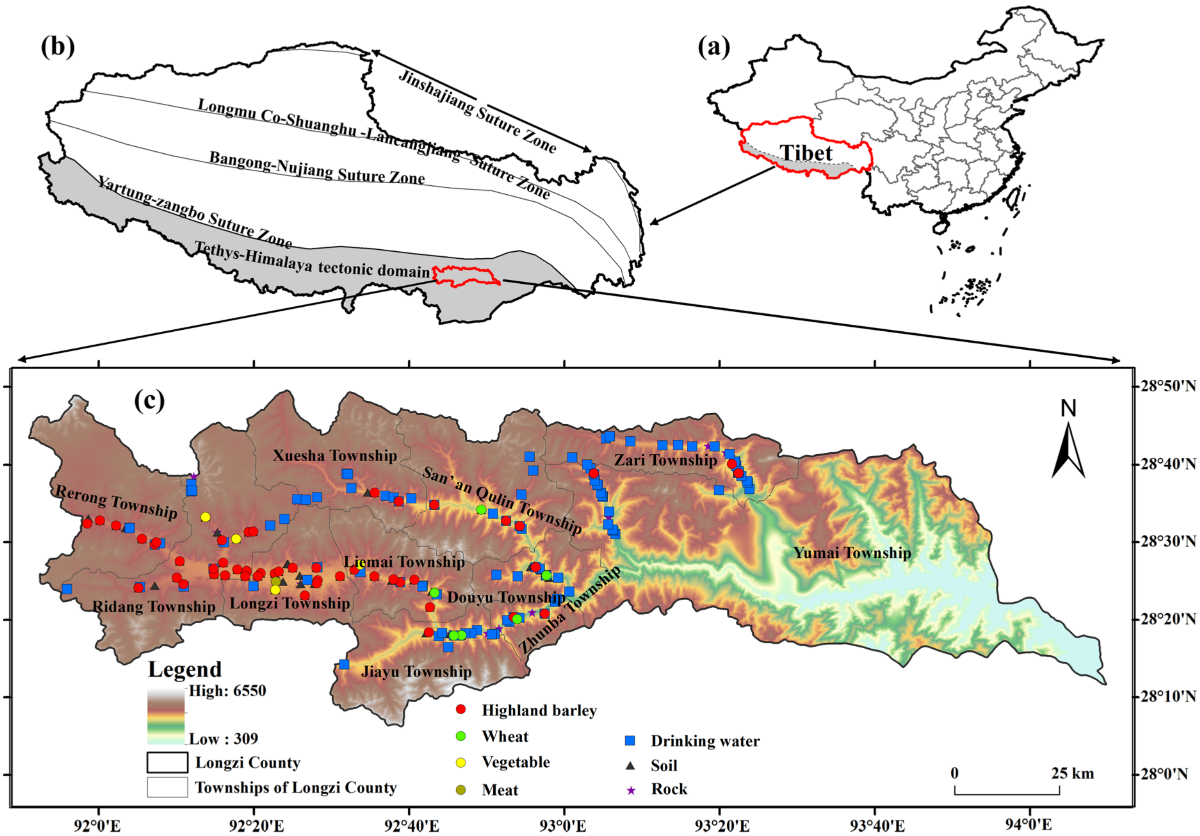


Fig. 1 Sampling locations in study area: **a** the location of Tibet in China; **b** the location of the study area in Tibet; **c** sampling points

aqua regia, and water bath digestion for three hours. Aqua regia is a mixture of concentrated nitric acid and concentrated hydrochloric acid at a ratio of 1:3 (volume ratio). After measuring Se, 3 mL of HCl, 5 mL of 5% thiourea solutions and 5 mL of 5% ascorbic acid solutions was added, shake well and take the supernatant to determine the As. The concentrations of As and Se were measured using HG–AFS. The concentration of Hg was determined using crushed and weighed sample via CV–AAS. More information regarding pretreatment and chemical analysis can be found in Appendix Material SA1 and SA2.

Estimated daily intake

Due to the particularity of the climate, the highland barley is the dominant crop in study area. Most of the farmlands are distributed in the Longzi river' middle reaches (Fig. 1c), and the rest are scattered in small plots around the villages.

Direct oral intake (food consumption, drinking water and soil/dust) by the general population is usually considered the main route of exposure (Marin et al., 2017; USEPA, 2016). In order to calculate the average daily dose of oral intake (ADD_{oral}), the Eq. (1) to Eq. (4) modified according to the equations of USEPA (2016) and NHC (2021) are used as follow:

$$ADD_d = \frac{(C_g \times IR_g + C_f \times IR_f + C_r \times IR_r + C_v \times IR_v + C_m \times IR_m) \times EF \times ED}{BW \times AT} \quad (1)$$

$$ADD_w = \frac{C_w \times IR_w \times EF \times ED}{BW \times AT} \quad (2)$$

$$ADD_s = \frac{C_s \times IR_s \times EF \times ED}{BW \times AT} \quad (3)$$

$$ADD_{oral} = ADD_d + ADD_w + ADD_s \quad (4)$$

where ADD_d, ADD_w and ADD_s are the ADD of food consumption, drinking water and soil/dust, respectively; C_g, C_f, C_r, C_v, C_m, C_s and C_w are the average concentrations of trace elements in grain (unit: mg/kg), flour (unit: mg/kg), rice (unit: mg/kg), vegetables (unit: mg/kg), meat (unit: mg/kg), soil (unit: mg/kg) and water (unit: μg /L), respectively; IR_g, IR_f, IR_r, IR_v, IR_m, IR_w and IR_s are the ingestion rates of grain, flour, rice, vegetables, meat, water and soil, respectively (Table 2); EF denotes frequency of exposure (unit: days/year), 365 days/year; ED represents duration of exposure (unit: years), according to MEP (2013) and adapted from the life expectancy of Tibet, 45 years for Tibet adults; BW refers to body weight (unit: kg), 55.3 kg for Tibet adults according to MEP (2013); AT is average time (unit: days), 16,425 days.

Human health risk assessment

The hazard quotient (HQ) of trace elements is calculated by Eq. (5) and Eq. (6) according to USEPA (2016) and NHC (2021):

$$HQ_e = \frac{ADD_{oral}}{RfD_e} \quad (5)$$

$$HQ_i = \frac{RfD_i}{ADD_{oral}} \quad (6)$$

where HQ_e refers to the excessive TEs and ETEs intake of HQ; HQ_i refers to the insufficient ETEs intake of HQ; RfD_e represents excessive reference dose of TEs and ETEs; RfD_i represents insufficient reference dose of ETEs. $HQ > 1$ indicates non-carcinogenic health risk, while $HQ < 1$ suggests no non-carcinogenic health risk. The RfD of each TE and ETE are listed in Table 2.

Carcinogenic risk (CR) of trace elements is calculated by Eq. (7) according to NHC (2021):

$$CR = ADD_{oral} \times SF \quad (7)$$

Table 2 *RfD* and *IR* for adults

Trace elements	unit	RfD_i	RfD_e	References
TEs				
As	mg/kg/day	–	0.0003	(USEPA, 2016)
Pb	mg/kg/day	–	0.004	
Hg	mg/kg/day	–	0.0003	
Cd	mg/kg/day	–	0.001	
Ni	mg/kg/day	–	0.020	
ETEs				
Mn	mg/kg/day	0.0743	0.1815	(CNS, 2013)
Fe	mg/kg/day	0.1485	0.6931	
Cu	mg/kg/day	0.0099	0.1320	
Zn	mg/kg/day	0.1361	0.6601	
Se	mg/kg/day	0.0008	0.0066	
IR				
Grain (highland barley)	kg/day	0.1335		According to the participatory rural assessment (PRA) data in Shannan City, Tibet (n = 231) by Wang et al. (2021)
Flour (wheat)	kg/day	0.1531		
Rice	kg/day	0.1006		
Vegetable	kg/day	0.4445		
Meat (animal food product)	kg/day	0.3619		
Water	L/day	3.5680		According to the PRA data in Tibet (n = 1143) by MEP (2013)
Soil	g/day	0.0500		(MEP, 2013)

where *SF* refers to the slop factor of carcinogenic risk (unit: mg/kg•day), 1.5 mg/kg•day, 0.0085 mg/kg•day, 0.061 mg/kg•day and 0.0028 mg/kg•day for As, Pb, Cd and Ni, respectively. Because USEPA (2016) and NHC (2021) do not mention the *SF* of Hg, *CR* only calculates the four elements As, Pb, Cd and Ni. $CR \leq 10^{-6}$ suggests the *CR* is negligible, $10^{-6} < CR \leq 10^{-4}$ indicates the *CR* is within the acceptable range, while $CR \geq 10^{-4}$ indicates a risk of cancer (CALEPA, 2019; NHC, 2021; USEPA, 2016).

Results

Levels of TEs and ETEs in food, drinking water and soil samples

The average concentrations of TEs and ETEs in food, drinking water and soil samples in study area are listed in Table 3. Based on the Food Safety Limits of Contaminants (NHC, 2022), grain, flour and meat samples were within the standard limits, but the concentration of Pb in vegetables was 1.34 times higher than the standard value limits of 0.1 mg/kg (Table 3). In addition, the average concentration of Cu in grain and flour were 1.71 and 2.21 times of the maximum recommended value of 10 mg/kg in the Limits of Eight Elements in Cereals, Legume, Tubes and its Products (MOA, 2004). In highland barley, the average concentrations of Pb, Ni, Mn, Fe, Zn and Cu were 1.12, 3.62, 3.58, 2.12, 1.28 and 4.47 times higher than those reported in some area of QTP, respectively (Che et al., 2019; Chi et al., 2011; Zhang et al., 2017). In meat, the average concentrations of Hg and Cd were 1.30 and 2.00 times higher than those found in Qinghai Province, while the concentrations of Mn, Zn and Fe were much higher than those in Shannan City (Wu, 2020; Xiang et al., 2021; Zhu et al., 2021). Therefore, it can be seen that most TEs and ETEs in food from the study area were slightly high, with the exception of Se, which was slightly low (Table 3).

The average concentrations of TEs and ETEs in drinking water were significantly lower than the limit prescribed by the Standards for Drinking Water Quality (SAMR and SA) (Table 3). Several studies have compared the average concentrations of TEs and

Table 3 Mean concentrations of TEs and ETEs in food, drinking water and soil

Trace elements	Grain (n = 60) mg/kg	Flour (n = 6) mg/kg	Vegetables (n = 8) mg/kg	Meat (n = 4) mg/kg	Water (n = 104) μg/L	Soil (n = 73) mg/kg	Rice of China mg/kg
TEs TEs							
As	0.1071	0.0237	0.1999	0.0980	0.6869	39.2865	0.114 (Liang et al., 2010)
Pb	0.1685	0.0563	0.1337	0.0750	0.0182	38.8490	0.100 (Fang et al., 2014)
Hg	0.0012	0.0012	0.0036	0.0013	0.0438	0.0368	0.002 (Fang et al., 2014)
Cd	0.0021	0.0036	0.0332	0.0020	0.0027	0.1232	0.080 (Fang et al., 2014)
Ni	0.9049	0.1384	1.4062	0.6604	0.9538	47.7660	0.422 (Wu et al., 2015)
ETEs							
Mn	4.1380	3.9252	4.3201	2.3570	0.4157	930.9054	7.700 (Qi et al., 2015)
Fe	97.224	48.328	194.926	174.447	85.278	46,259.030	18.200 (Liang et al., 2007)
Cu	17.0677	22.0973	19.6668	1.2587	0.1790	27.5000	3.990 (Herawati et al., 2000)
Zn	24.933	25.162	25.420	190.200	1.737	98.795	21.500 (Fang et al., 2008)
Se	0.0175	0.0092	0.0131	0.3948	0.4424	0.3771	0.088 (Williams et al., 2009)

ETEs in some QTP drinking water: The average concentration of Hg in study area was much higher (8.26 times) than that in the Rongna River in northern Tibet (Luo et al., 2022); The average concentrations of As and Ni in study area were slightly higher (1.72 and 1.64 times, respectively) than that in Tibet (Yi et al., 2021); The average concentrations of As, Zn and Fe in study area were higher (2.97, 1.44 and 1.53 times, respectively) than those in glacial meltwater runoff in the northeastern of QTP (Li et al., 2020; Qu et al., 2019); The average concentrations of Zn in drinking water of the study area was higher (2.16 times) than that in Luolong County (Zha et al., 2022). These results indicate that the concentrations of TEs and ETEs in drinking water of the study area are suitable, and the concentrations of As, Hg, Mn, Ni, Zn and Fe are higher than those in some parts of the QTP.

The average concentration of As, Pb, Hg, Cd, Ni, Mn, Cu and Zn in soil samples were 199%, 134%, 153%, 152%, 149%, 148%, 126% and 134% of the soil background values in Tibet, respectively (MEE, 1990). By comparing the Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land, it can be found that the average concentration of Pb, Hg, Cd, Ni, Cu and Zn in the soil samples of the study area did not exceed the screening value. However, the concentration of As was 131% of the screening value (SAMR and SA, 2018). The average concentration of Pb and Zn in soil samples was similar to that in Huzhu County of the QTP, while the average concentration of As in soil samples was 322% of that in Huzhu County (Zhang et al., 2022). These results indicating that the concentration of As in soil samples is markedly high.

Estimated daily oral intake of TEs and ETEs

In order to further consider the impact of TEs and ETEs in the daily diet of the study area on the health of local residents, the ADD_{oral} of TEs and ETEs at the township level in study area are calculated using formulas (1) to (4). The ADD_{oral} distribution of As, Pb, Hg and Cd in TEs showed similarities, with high value area of ADD_{oral} was primarily distributed in the eastern part of the study area. On the other hand, the high ADD_{oral} values of Fe, Cu, Zn and Se were mostly found in the northeast of the study area (Fig. S1). Furthermore, by calculating the proportion of ADD_{oral} from different sources of intake (Fig. 2, Table S1, Table S2, Table S3), it was discovered that ADD_d (including ADD_g, ADD_f, ADD_v and ADD_m) of TEs and ETEs accounted for more than 90% of ADD_{oral}. This suggests that food, particularly grain (highland barley) and meat, are the primary dietary sources of local residents.

The relationship between ADD_{oral} and RfD in the whole study area was shown in Fig. 3. The ADD_{oral} values of As varied from 0.003 mg/(kg·day) in Douyu Township to 0.005 mg/(kg·day) in Rerong Township, both of which exceeded the RfD_e. These results suggest that residents in all townships in the study area are exposed to excessive oral intake of As (Fig. 3a). For Hg and Cd, the ADD_{oral} value ranged from 5.10E-05 mg/(kg·day) in Xuesha Township to 9.17E-05 mg/(kg·day) in Douyu Township for Hg, and 4.45E-04 mg/(kg·day) in Rerong Township) to 5.47E-04 mg/(kg·day) in Douyu Township for Cd, respectively. In both cases, the ADD_{oral} values were lower than the RfD_e, indicating that the oral intake of Hg and Cd were suitable for the local residents (Fig. 3c, Fig. 3d). For Pb and Ni, The ADD_{oral} values ranged from 0.003 mg/(kg·day) in Jiayu Township to 0.011 mg/(kg·day) in Xuesha Township for Pb, and 0.017 mg/(kg·day) in Zhari Township) to 0.044 mg/(kg·day) in Longzi Township for Ni, respectively. Among the four townships, the ADD_{oral} values of Pb and Ni were higher than the RfD_e, suggesting that the oral intake of Pb and Ni were basically appropriate (Fig. 3b, Fig. 3e). The ADD_{oral} values of Mn and Zn ranged from 0.556 mg/(kg·day) in Douyu Township to 1.078 mg/(kg·day) in San'an Qulin Township for Mn, and 1.907 mg/(kg·day) in Longzi Township to 3.260 mg/(kg·day) in San'an Qulin Township for Zn, respectively. In both cases, the ADD_{oral} values exceeded the RfD_e, indicating excessive oral intake of Mn and Zn among the residents in the study area (Fig. 3f, Fig. 3i). The ADD_{oral} values of Fe ranged from 3.526 mg/(kg·day) in Douyu Township to 10.857 mg/(kg·day) in San'an Qulin Township, which were 5.090 to 15.660 times higher than the RfD_e. This indicated that the residents in all townships were exposed to extremely high levels of Fe through oral intake (Fig. 3g). The ADD_{oral} values of Cu anged from 0.115 mg/(kg·day) in Douyu Township and 0.175 mg/(kg·day) in San'an Qulin Township, which were higher than the RfD_e in nine townships. These results indicated that residents in most

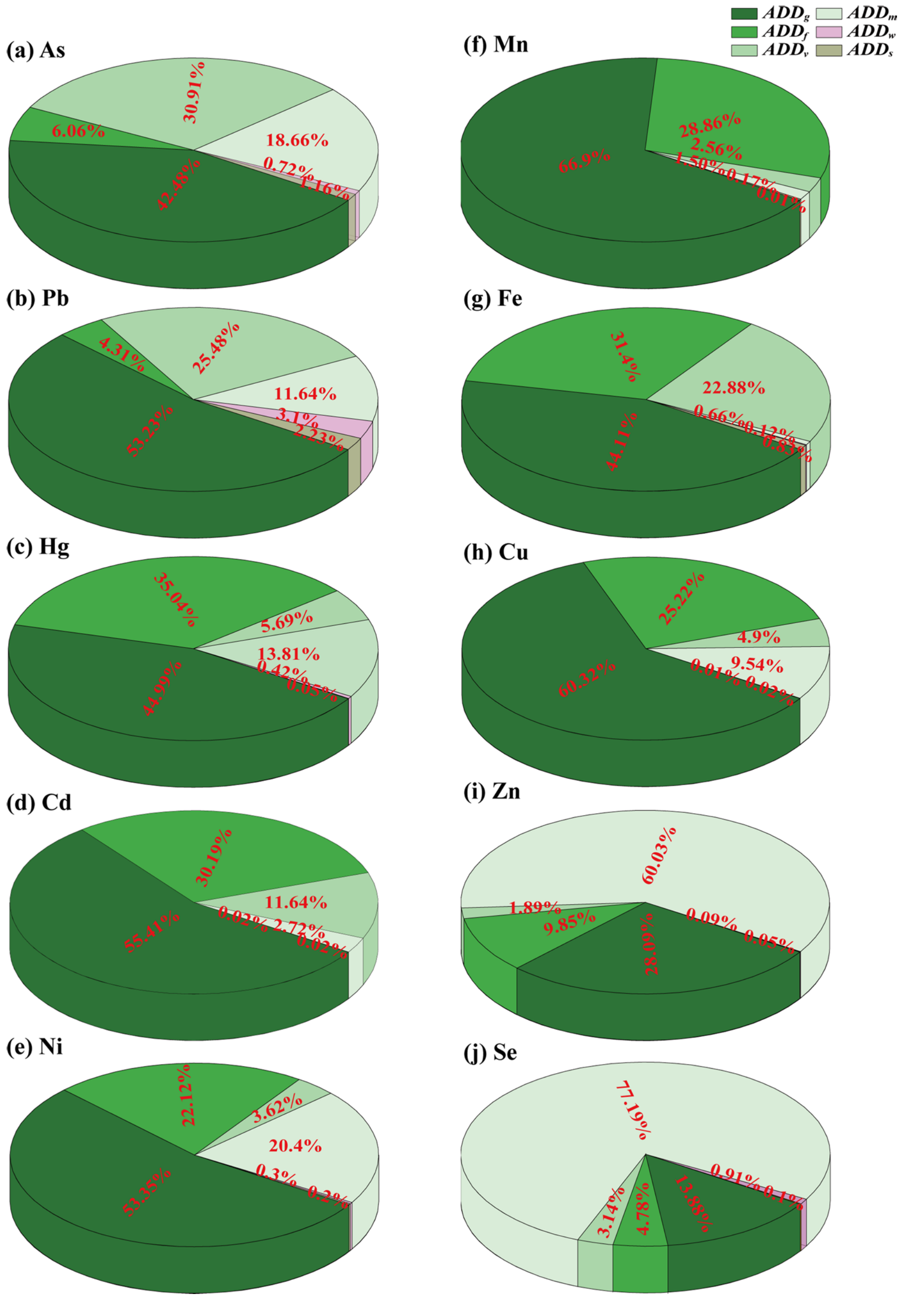


Fig. 2 The sources of ADD_{oral} intake of TEs and ETEs in Longzi County. **a** As, **b** Pb, **c** Hg, **d** Cd, **e** Ni, **f** Mn, **g** Fe, **h** Cu, **i** Zn, **j** Se

areas of Longzi County are exposed to excessive levels of Cu through oral intake (Fig. 3h). Finally, the ADD_{oral} values of Se ranged from 0.003 mg/(kg·day) in Jiayu Township to 0.005 mg/(kg·day) in San'an Qulin Township, which were higher than the RfD_i and lower than the RfD_e. These results suggest that the oral intake of Se was appropriate for residents in the study area (Fig. 3j).

Health risk assessment

The *HQ* of TEs and ETEs for each township was computed using Eqs. (5) and (6) (Table S5). In addition, The *CR* of As, Pb, Cd and Ni was calculated using formula (7) to assess the carcinogenic risk of these elements in each township in the study area (Table S6).

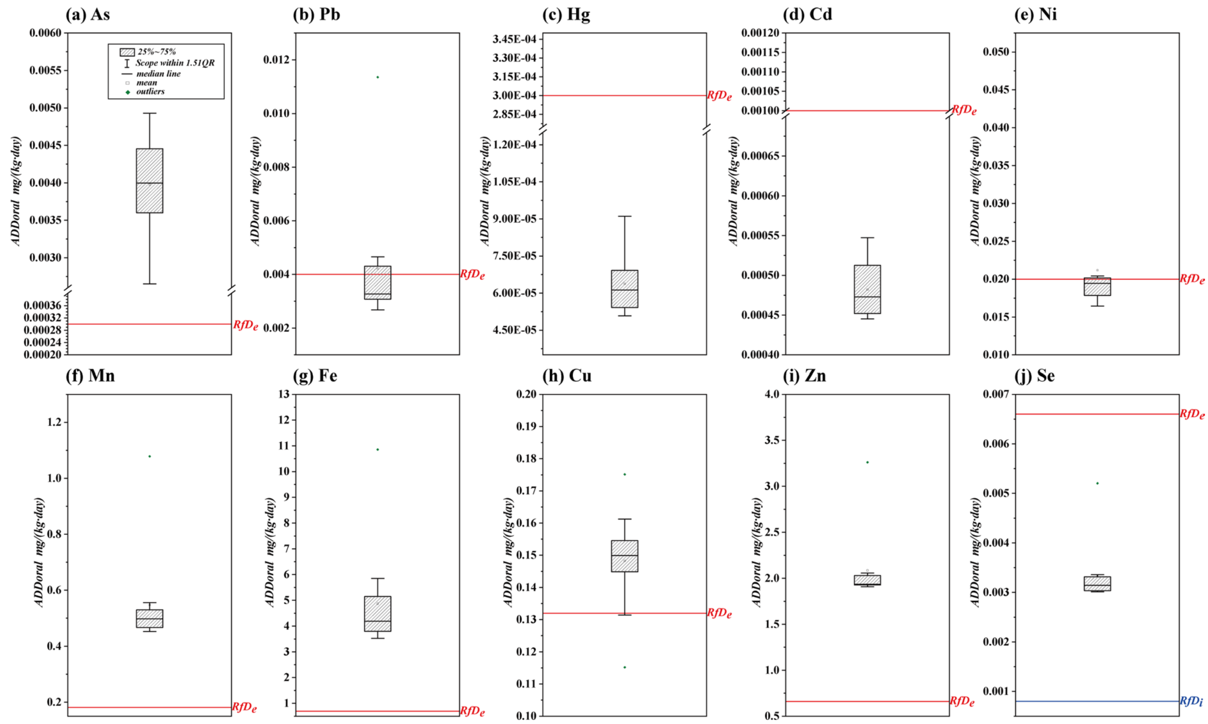


Fig. 3 The relationship between ADD_{oral} and *RfD* of TEs and ETEs in Longzi County. **a** As, **b** Pb, **c** Hg, **d** Cd, **e** Ni, **f** Mn, **g** Fe, **h** Cu, **i** Zn, **j** Se

The HQ_e of As was significantly higher than 1 in all township, and the *CR* of As was higher than 1×10^{-4} (Fig. 4a, Table S5, Table S6). For Pb, the HQ_e was 2.84 in Xuesha Township, while the HQ_e in remaining ten townships was slightly higher or lower than 1, and the *CR* were all between 1×10^{-6} and 1×10^{-4} (Fig. 4b, Table S5, Table S6). The HQ_e of Cd was lower than 1 in all townships, and the *CR* of Cd was lower than 1×10^{-4} (Fig. 3c, Table S5, Table S6). For Ni, the HQ_e was 2.22 in Longzi Township, and other ten townships was slightly higher or lower than 1, while the *CR* of Ni was between 1×10^{-6} and 1×10^{-4} (Fig. 4d, Table S5, Table S6). The HQ_e of Hg was lower than 1 in all townships (Fig. 4e, Table S5). The HQ_e of Mn, Fe and Zn were higher than 1 in all townships (Fig. 4f, Fig. 4g, Fig. 4i, Table S5). The HQ_e of Cu was higher than 1 in nine townships (Fig. 4h, Table S5). The HQ_i and HQ_e of Se were less than 1 in all townships (Fig. 4j, Table S5). These data indicated that there was a non-carcinogenic risk of excessive intake of As, Mn, Fe and Zn in all townships. The townships with non-carcinogenic risks of excessive intake of Pb and Ni accounted for 36.36%, while 81.82% of the townships had non-carcinogenic risks of excessive intake of Cu. There were no non-carcinogenic risks of Hg, Cd and Se in any townships in Longzi County. However, As posed a carcinogenic risk to the residents throughout the study area, while the carcinogenic risks of Pb, Hg and Ni were within the acceptable range. Consequently, high-concentrations food containing As, Mn, Fe, Cu and Zn should be reduced in the daily diet, and dietary distribution should be reasonably regulated to reduce and control the diseases caused by excessive intake of TEs and ETEs.

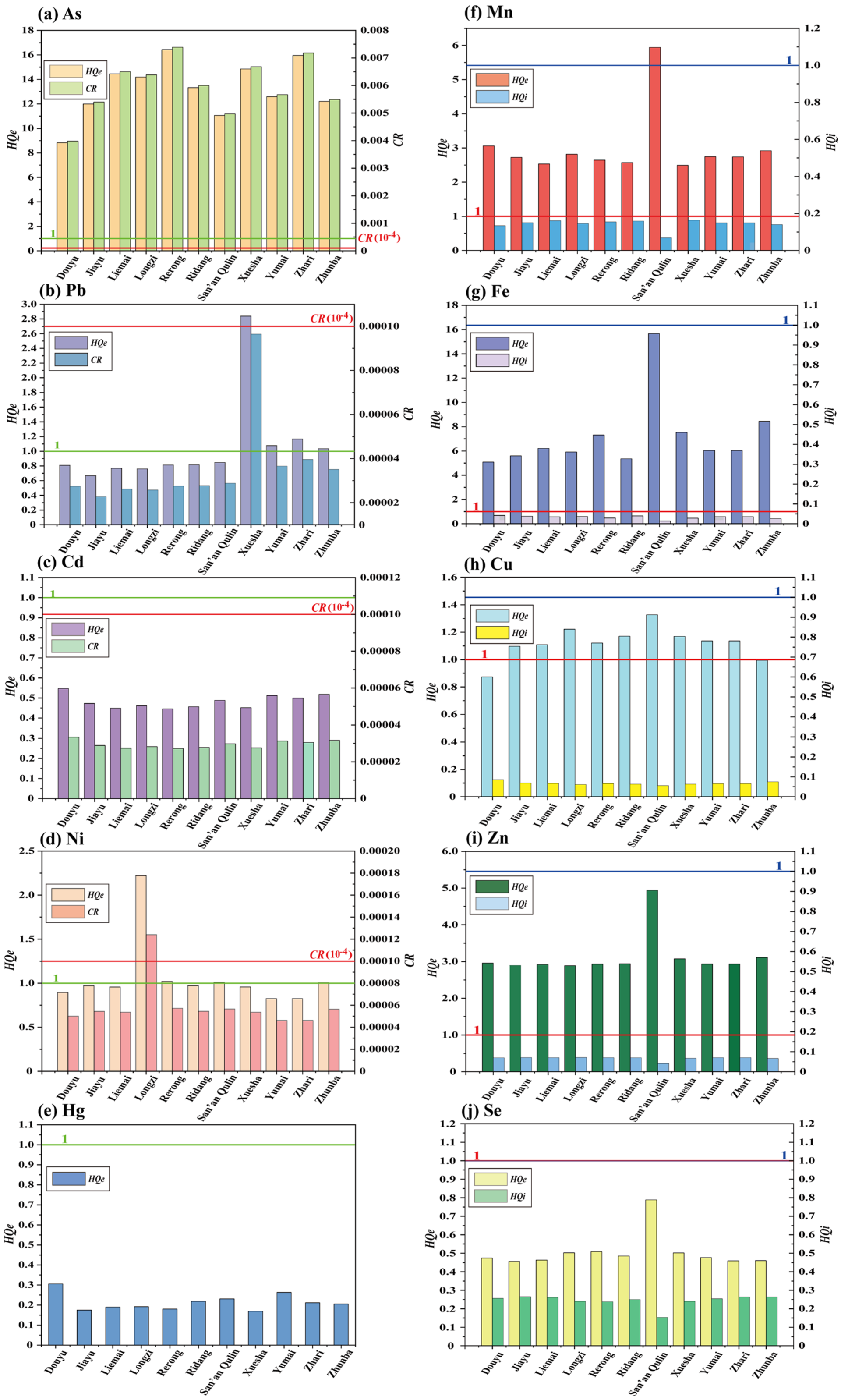
Discussions

Dietary intake is an important pathway for humans to consume TEs and ETEs (Rosinger, 2023; Shostak, 2023). Epidemiological studies have demonstrated a link between diet-related diseases and the biogeochemistry of trace elements, as discussed in the *Introduction*. By estimating the ADD_{oral} of TEs and ETEs, this study found that local residents have excessive intake of As, Mn, Fe, Cu and Zn. Grain and meat are the primary dietary sources for local residents' TEs and ETEs (Fig. 3, Table S4). In order to determine the sources of these elements in food, we conducted correlation analysis on these elements in matching samples between soil and grain. The results showed that there was a significant correlation between As, Pb, Hg, Mn, Fe, Cu and Se concentrations in grain and soil (r = 0.840^{***}, 0.911^{***}, 0.577^{*}, 0.820^{***}, 0.640^{**}, 0.614^{**} and 0.573^{*}, respectively), as shown in Fig. S2 and Table S7. Previous studies have confirmed that trace elements in grain are primarily absorbed by crop roots from cultivated soil (Abatemi-Usman et al., 2023; Chen et al., 2023). Thus, the enrichment of TEs or ETEs in local food is mainly on account of these high concentrations of TEs or ETEs in the soil.

Soil is mainly formed by weathering of stratum and soil forming parent material (loose debris formed by weathering of surface rocks), so stratum is the main source of trace elements in soil (Miguez-Macho & Fan, 2021). The eastern part of the study area is situated in the Collision zone between the Eurasian plate and the Indian Ocean plate, where with strong tectonic movement and extensive exposure of magmatic rocks (Liu et al., 2020; Tian et al., 2022). This also caused some "heavy" elements from earlier stratum and deep mantle to enter the surface (Wang et al., 2023). The geologic map and numerical age (Fig. S2) indicate that the stratum in the study area mainly comprises the Proterozoic (552–525 Ma), Triassic (201–252 Ma), Jurassic (145–210 Ma) and Cretaceous (66–145 Ma). When comparing the concentrations of TEs and ETEs in the stratum of the study area with the Southern Tibetan crust, it was found that the concentration of TEs in various stratum were higher than those in the Southern Tibetan crust. Notably, the concentrations of As in Proterozoic, Triassic, Jurassic and Cretaceous was 43.09, 12.41, 15.86 and 6.22 times that of the Southern Tibetan crust, respectively (Table S8). Our previous studies have confirmed that the spatial differentiation of heavy metals in the study area is mainly controlled by geological source factors (Tian et al., 2022). Therefore, the ADD_{oral} among local residents is mainly influenced by the concentrations of TEs and ETEs under different geological backgrounds. The high concentration of TEs or ETEs in the geological background leads to the high concentration of these elements in the soil, which in turn causes excessive intake of these elements by local residents through the food chain and biogeochemical cycle. This also explains the spatial differentiation of these elements in the soil.

By reason of the limitations imposed by the natural geographical environment, the food consumption structure of local residents in the TH tectonic domain is relatively homogeneous (Jing et al., 2023). Through analysis of the intake sources of TEs and ETEs, it was found that Mn and Cu were mainly come from local highland barley, while Fe primarily comes from local grains (highland barley and flour accounting for over 75%), and Zn mainly comes from local yak meat (Fig. 2f, g, h and i). Ma et al. (2022) reported that local agricultural activities, such as pesticide spraying and excessive application of chemical fertilizer, could significantly increase the concentration of Cu in the soil. Duncan et al. (2023) have concluded that the concentration of Fe and Zn in livestock feed is generally high, and the excessive use of feed may also be the responsible for the high concentrations of Fe and Zn in local meat products. Therefore, reasonable fertilization and planning the use of livestock feed are effective measures to reduce and prevent health problems caused by excessive consumption by local residents. Besides, balancing the intake of TEs and ETEs by consuming diverse exotic foods and improving the dietary structure (such as increasing intake of vegetables and fruits) can help local residents avoid the health risks associated with excessive intake of TEs and ETEs.

In summary, this study comprehensively analyzed the concentrations characteristics of five TEs and five ETEs in food, drinking water and soil samples, calculating the proportion of ADD_{oral} from different intake source in typical area of TH tectonic domain. The non-carcinogenic and carcinogenic risks of these elements were also assessed. In addition, based on the calculation results, we briefly explained the spatial distribution trend of ADD_{oral}, and discussed the relationship between the concentrations of five TEs and five ETEs in sedimentary rocks of the study area and Southern Tibetan crust. Finally, we clarified and identified the health risks caused by dietary intake of local residents, and proposed dietary recommendations to reduce such risks. However, accurate *IR* data was not obtained from the questionnaire survey when calculating the ADD_{oral} of five TEs and five ETEs in the study area. Thus, the average intake of various foods for the residents of Shannan City, obtained from the relevant literature, was used, which may cause some


(a) As
(b) Pb
(c) Cd
(d) Ni
(e) Hg
(f) Mn
(g) Fe
(h) Cu
(i) Zn
(j) Se
HQe
HQi
CR
CR (10^-4)
Douyu
Jiayu
Liemai
Longzi
Rerong
Ridang
San'an Qulin
Xuesha
Yumai
Zhari
Zhunba

◂**Fig. 4** The *Health Risk* of TEs and ETEs in Longzi County, **a** As, **b** Pb, **c** Cd, **d** Ni, **e** Hg, **f** Mn, **g** Fe, **h** Cu, **i** Zn and **j** Se

deviation between the calculation results of ADD_{oral} and the actual situation in the study area. The follow-up studies could further carry out a systematic participatory rural assessment of local residents' dietary intake to obtain more accurate *IR* values. By reason of the foregoing, this study can provide comprehensive basic data for the effective management of healthy dietary intake among residents in TH tectonic domain, with reference value for the health risk assessment and endemic disease prevention and control decision-making among local and even Tibetan residents.

Conclusions

The dietary assessment of typical areas of in the TH tectonic domain is crucial for promoting the health, safety and sustainable development of local residents. The concentrations of several TEs and ETEs in food, drinking water and soil in the study area were higher than those in the QTP and its surrounding areas. Moreover, highland barley and meat were the primary sources of oral intake of TEs and ETEs for local residents. In addition, the non-carcinogenic health risks of Hg, Cd and Se were negligible, whereas the remaining seven elements posed certain non-carcinogenic health risks. Among these elements, As posed both significant non-carcinogenic and carcinogenic health risks throughout the study area. The high concentration of TEs and ETEs in the geological background of the study area pose health risks to local residents through the food chain and biogeochemical cycle. Therefore, it is necessary to increase the intake of vegetables and fruits and consume some exotic food to improve the dietary structure among the local residents in order to avoid the occurrence dietary intake-related diseases.

Acknowledgements This research was jointly funded by the National Natural Science Foundation of China (Grant No. 42207515), the Central Government Guides Local Science and Technology Development Program (Grant No. XZ202201YD0014C), the Key R&D Program of Tibet (Grant No. XZ202001ZY0050G and XZ202001ZY0042N) and the China (Xi' an) Silk Road Research Institute Scientific Program (Grant No. 2019YB06).

Author contributions XG: Sample collection and pretreatment, provision of article ideas, article writing. JA: Data collation, draft production, write the first draft of the article. CY: Resources, project administration. XZ: Sample collection and analysis, project support. YT: The provision of article ideas, revision and improvement of articles after writing, project support. All authors have read and agreed to the published version of the manuscript.

Data availability The data are available for other researchers upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known conflict financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abatemi-Usman Sa, Akindele O, Ayanlade A, Perez M, Attahiru Ii, Norton G, et al. (2023). Trace elements concentrations in soil contaminate corn in the vicinity of a cement-manufacturing plant: potential health implications. Journal of Exposure Science & Environmental Epidemiology. https://doi.org/10.1038/s41370-023-00548-8

Antoniadis, V., Golia, E. E., Liu, Y.-T., Wang, S.-L., Shaheen, S. M., & Rinklebe, J. (2019). Soil and maize contamination by trace elements and associated health risk assessment in the industrial area of Volos, Greece. *Environment International, 124*, 79–88. https://doi.org/10.1016/j.envint.2018.12.053

Cannas, D., Loi, E., Serra, M., Firinu, D., Valera, P., & Zavattari, P. (2020). Relevance of Essential Trace Elements in Nutrition and Drinking Water for Human Health and Autoimmune Disease Risk. *Nutrients, 12*(7), 2074. https://doi.org/10.3390/nu12072074

CALEPA (2019). California Environmental Protection Agency. Sacramento, CA, USA. https://calepa.ca.gov.

Che, F., Feng, S., Li, S., Chen, Z., Niu, J., Qi, W., et al. (2019). Differences in trace components of highland barley of different varieties from different regions. *Liquor-Making Science Technology., 11*, 113–118. https://doi.org/10.13746/j.njkj.2019244

Chen, L., Wang, F., Zhang, Z., Chao, H., He, H., Hu, W., et al. (2023). Influences of arbuscular mycorrhizal fungi on crop growth and potentially toxic element accumulation in contaminated soils: A meta-analysis. *Critical Reviews in Environmental Science and Technology*. https://doi.org/10.1080/10643389.2023.2183700

Chi, X., Xing, Y., Dong, Q., & Hu, F. (2011). Determination contents of twenty elements in different cultivars of naked barley by ICP-AES. *Food Science, 32*(10), 130–132.

CNS. (2013). *Chinese dietary reference intakes handbook*. Standards Press of China.

Dermience, M., Mathieu, F., Li, X. W., Vandevijvere, S., Claus, W., Maertelaer, V. D., et al. (2017). Minerals and trace elements intakes and food consumption patterns of young children living in rural areas of tibet autonomous

region. *PR China: A Cross-Sectional Survey. Healthcare., 5*(1), 12. https://doi.org/10.3390/healthcare5010012
Dhital, M. R. (2015). *Introduction to Tethys Himalaya*. Switzerland: Springer, Cham. https://doi.org/10.1007/978-3-319-02496-7_21
Dinh, Q. T., Cui, Z., Huang, J., Tran, T. A. T., Wang, D., Yang, W., et al. (2018). Selenium distribution in the Chinese environment and its relationship with human health: A review. *Environment International, 112*, 294–309. https://doi.org/10.1016/j.envint.2017.12.035
Du, H., Wang, J., Wang, Y., Yao, Y., Liu, X., & Zhou, Y. (2023). Contamination characteristics, source analysis, and spatial prediction of soil heavy metal concentrations on the Qinghai-Tibet Plateau. *Journal of Soils and Sediments., 23*, 2202–2215. https://doi.org/10.1007/s11368-023-03462-6
Duncan, A. J., Lukuyu, B., Mutoni, G., Lema, Z., & Fraval, S. (2023). Supporting participatory livestock feed improvement using the Feed Assessment Tool (FEAST). *Agronomy for Sustainable Development., 43*, 34. https://doi.org/10.1007/s13593-023-00886-9
EC (2000). White Paper on Food Safety. European Commission, Brussels. Doi: https://doi.org/10.1108/bfj.2000.070102
Fang, Y., Sun, X., Yang, W., Ma, N., Xin, Z., Fu, J., et al. (2014). Concentrations and health risks of lead, cadmium, arsenic, and mercury in rice and edible mushrooms in China. *Food Chemistry, 147*, 147–151. https://doi.org/10.1016/j.foodchem.2013.09.116
Fang, Y., Wang, L., Xin, Z., Zhao, L., An, X., & Hu, Q. (2008). Effect of foliar application of zinc, selenium, and iron fertilizers on nutrients concentration and yield of rice grain in China. *Journal of Agricultural and Food Chemistry, 56*(6), 2079–2084. https://doi.org/10.1021/jf800150z
FAO, WHO (2009). Principles and Methods for the Risk Assessment of Chemicals in Food. Environmental Health Criteria 240. WHO, Geneva. ISSN: 0250–863X.
Filippini, T., Tancredi, S., Malagoli, C., Malavolti, M., Bargellini, A., Vescovi, L., et al. (2020). Dietary estimated intake of trace elements: Risk assessment in an Italian population. *Exposure and Health, 12*(4), 641–655. https://doi.org/10.1007/s12403-019-00324-w
Gao, B., Gao, L., Gao, J., Xu, D., Wang, Q., & Sun, K. (2019). Simultaneous evaluations of occurrence and probabilistic human health risk associated with trace elements in typical drinking water sources from major river basins in China. *Science of the Total Environment, 666*, 139–146. https://doi.org/10.1016/j.scitotenv.2019.02.148
Gao, L., Xu, Z., Cheng, S., Xu, S., Zhang, X., Yu, C., et al. (2017). Food consumption structure and dietary nutrition of residents in rural Tibet. *Resources Science, 39*, 168–174. https://doi.org/10.18402/resci.2017.01.17
Guo, Q., & Wang, Y. (2012). Hydrochemical anomaly of drinking waters in some endemic Kashin-Beck disease areas of Tibet. *China. Environmental Earth Sciences, 65*(3), 659–667. https://doi.org/10.1007/s12665-011-1113-x
Halder, D., Saha, J. K., & Biswas, A. (2020). Accumulation of essential and non-essential trace elements in rice grain: Possible health impacts on rice consumers in West Bengal. *India. Science of the Total Environment, 706*, 135944. https://doi.org/10.1016/j.scitotenv.2019.135944
Herawati, N., Suzuki, S., Hayashi, K., Rivai, I. F., & Koyama, H. (2000). Cadmium, copper, and zinc levels in rice and soil of Japan, Indonesia, and China by soil type. *Bulletin of Environmental Contamination and Toxicology, 64*(1), 33–39. https://doi.org/10.1007/s001289910006
Jing, L., Jianping, W., Lihua, F., Kai, C., Ting, Y., Changzai, W., et al. (2023). Characteristics of azimuthal anisotropy in SE Tibetan plateau and its relationship with the background of block structure. *Frontiers in Earth Science*. https://doi.org/10.3389/feart.2023.1065911
Konikowska, K., & Mandecka, A. (2018). *Trace Elements in Human Nutrition*. Wiley-Blackwell. https://doi.org/10.1002/9781119133780
Li, M., Du, Y., Chen, L., Liu, L., & Duan, Y. (2018). Assessment of trace elements in terminal tap water of Hunan Province, South China, and the potential health risks. *Environmental Monitoring & Assessment, 190*(6), 318. https://doi.org/10.1007/s10661-018-6684-5
Li, M., Sun, X., & Li, S. (2020). Advances on inorganic hydrochemistry of glacial meltwater runoff in the Qinghai-Tibet Plateau and its surrounding areas. *Journal of Glaciology Geocryology, 42*(2), 562–574. https://doi.org/10.7522/j.issn.1000-0240.2020.0052
Li, R., Zhang, R., Yang, Y., & Li, Y. (2023). Accumulation characteristics, driving factors, and model prediction of cadmium in soil-highland barley system on the Tibetan Plateau. *Journal of Hazardous Materials., 453*, 131407. https://doi.org/10.1016/j.jhazmat.2023.131407
Li, S., Wang, M., Yang, Q., Wang, H., Zhu, J., Zheng, B., et al. (2013). Enrichment of arsenic in surface water, stream sediments and soils in Tibet. *Journal of Geochemical Exploration, 135*(6), 104–116. https://doi.org/10.1016/j.gexplo.2012.08.020
Liang, F., Li, Y., Zhang, G., Tan, M., Lin, J., Liu, W., et al. (2010). Total and speciated arsenic levels in rice from China. *Food Additives & Contaminants: Part A, 27*(6), 810–816. https://doi.org/10.1080/19440041003636661
Liang, J., Han, B., Han, L., Nout, M. R., & Hamer, J. R. (2007). Iron, zinc and phytic acid content of selected rice varieties from China. *Journal of the Science of Food and Agriculture, 87*, 504–510. https://doi.org/10.1002/jsfa.2747
Liu, Y., Dai, J., Wang, C., Li, H., Wang, Q., & Zhang, L. (2020). Provenance and tectonic setting of upper Triassic turbidites in the eastern tethyan Himalaya: Implications for early-stage evolution of the Neo-Tethys. *Earth-Science Reviews., 200*, 103030. https://doi.org/10.1016/j.earscirev.2019.103030
Luo, Y., Rao, J., & Jia, Q. (2022). Heavy metal pollution and environmental risks in the water of Rongna River caused by natural AMD around Tiegelongnan copper deposit, Northern Tibet. *China. Public Library of Science, 17*(4), e0266700. https://doi.org/10.1371/journal.pone.0266700
Ma, Y., Wang, Q., Su, W., Cao, G., Fu, G., & Du, W. (2022). Potential sources, pollution, and ecological risk assessment of potentially toxic elements in surface soils on the north-eastern margin of the Tibetan Plateau. *Toxics, 10*(7), 2–15. https://doi.org/10.3390/toxics10070368
Marin, S., Pardo, O., Baguena, R., Font, G., & Yusa, V. (2017). Dietary exposure to trace elements and health risk assessment in the region of Valencia, Spain: A total diet study. *Food Additives Contaminants: Part A, 34*(2),

228–240. https://doi.org/10.1080/19440049.2016.1268273
MEE (1990). Background value of soil elements in China. Beijing: China Environmental Science: China National Environmental Monitoring Centre.
MEE (2017b). Technical guideline for population exposure assessment of environmental pollutant. HJ 875–2017b. MEE, Beijing.
MEE. (2017a). *Soil and sediment-Digestion of total metal elements-Microwave assisted acid digestion method*. Ministry of Ecology and Environment of the People's Republic of China.
MEP. (2013). *Exposure Factors Handbook of Chinese Population*. China Environmental Press.
Miguez-Macho, G., & Fan, Y. (2021). Spatiotemporal origin of soil water taken up by vegetation. *Nature, 598*(7882), 624–628. https://doi.org/10.1038/s41586-021-03958-6
MOA (2004). Limits of Eight Elements in Cereals, Legume, Tubes and its Products (NY 861–2004). Minsistry of Agriculture and Rural Affairs of the People's Republic of China, ChengDu.
NHC (2021a). Technical guide for environmental health risk assessment of chemical exposure (WS/T 777–2021a). National Health Commission of the People's Republic of China Beijing.
NHC, SA (2006). Standards for drinking water quality. GB 5749–2006. China Standards Press Beijing.
NHC, SFDA (2017). Limits of contaminants in food. National Food Safety Standard. GB 2762–2017. NHC/SFDA, Beijing.
NHC. (2022). *National Standards for Food Safety Limits of Contaminants in Food (GB 2762–2022)*. National Health Commission of the People's Republic of China.
Nordberg, G. F., & Costa, M. (2022). Handbook on the Toxicology of Metals. In G. F. Nordberg (Ed.), *Specific Metals*. London: Academic Press. Elsevier.
Pipoyan, D., Stepanyan, S., Stepanyan, S., Beglaryan, M., & Merendino, N. (2019). Health risk assessment of potentially toxic trace and elements in vegetables grown under the impact of Kajaran mining complex. *Biological Trace Element Research, 192*(2), 336–344. https://doi.org/10.1007/s12011-019-01675-w
Qi, Y., Cui, Y., Shimojo, C., & Yoshida, M. (2015). Manganese and molybdenum contents in rice. *Biomedical Research on Trace Elements, 26*, 23–26.
Qu, B., Zhang, Y., Kang, S., & Sillanpaa, M. (2019). Water quality in the Tibetan Plateau: Major ions and trace elements in rivers of the "Water Tower of Asia." *Science of the Total Environment, 649*, 571–581. https://doi.org/10.1016/j.scitotenv.2018.08.316
Rosinger, A. Y. (2023). Water Needs, Water Insecurity, and Human Biology. *Annual Review of Anthropology*. https://doi.org/10.1146/annurev-anthro-052721-090331
SAMR, SA (2018). Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land (GB15618–2018). State Administration for Market Regulationof the People's Republic of China and Standardization Administration of the People's Republic of China, Beijing.
SAMR, SA (2022). Standards for Drinking Water Quality (GB5749–2022). State Administration for Market Regulationof the People's Republic of China and Standardization Administration of the People's Republic of China, Beijing.
Shayganfard, M. (2022). Are essential trace elements effective in modulation of mental disorders? update and perspectives. *Biological Trace Element Research, 200*(3), 1032–1059. https://doi.org/10.1007/s12011-021-02733-y
Shostak, S. (2023). Food and inequality. *Annual Review of Sociology, 49*, 112747. https://doi.org/10.1146/annurev-soc-031021-112747
Tang, J., Huang, Z., & Pan, X. (2014). Exposure assessment of heavy metals (Cd, Hg, and Pb) by the intake of local foods from Zhejiang. *China. Environmental Geochemistry & Health, 36*(4), 765–771. https://doi.org/10.1007/s10653-014-9594-7
Tian, Y., Yu, C., Zha, X., Wu, J., Gao, X., Feng, C., et al. (2016). Distribution and potential health risks of arsenic, selenium, and fluorine in natural waters in Tibet. *China. Water, 8*(568), 1–16. https://doi.org/10.3390/w8120568
Tian, Y., Yu, C., Zha, X., Wu, J., Gao, X., & Feng, C. (2018). Geographical and Botanical Variation in Concentrations of Molybdenum in Natural Pasture Plants and Surface Water and Yak Molybdenum Ingestion in North Tibet. *China. Journal of Resources and Ecology, 9*(5), 545–553. https://doi.org/10.5814/j.issn.1674-764x.2018.05.012
Tian, Y., Zha, X., Gao, X., Dai, E., & Yu, C. (2020a). Spatial analysis and biogeochemical cycles: a comparative study of Kashin-Beck disease villages and non-disease villages in Linzhou County. *Tibet. Journal of Resources and Ecology, 11*(2), 232–246. https://doi.org/10.5814/j.issn.1674-764x.2020.02.011
Tian, Y., Zha, X., Gao, X., & Yu, C. (2022). Geochemical characteristics and source apportionment of toxic elements in the Tethys−Himalaya tectonic domain, Tibet. *China. Science of the Total Environment, 831*, 154863. https://doi.org/10.1016/j.scitotenv.2022.154863
Tong, S., Li, H., Tudi, M., Yuan, X., & Yang, L. (2021). Comparison of characteristics, water quality and health risk assessment of trace elements in surface water and groundwater in China. *Ecotoxicology and Environmental Safety, 219*, 112283. https://doi.org/10.1016/j.ecoenv.2021.112283
USEPA (1996). Safe Drinking Water Act. In: Water EsOoGWaD, editor. United States Environmental Protection Agency, Washington DC.
USEPA (2011). Exposure Factors Handbook: 2011 Edition. EPA/600/R-09/052F. U.S. Environmental Protection Agency, Washington, DC.
USEPA. (2016). *Exposure Factors Handbook*. U.S. Environmental Protection Agency.
Wang, J., Zhao, S., Yang, L., Gong, H., Li, H., & Nima, C. (2020a). Assessing the health loss from Kashin-Beck disease and its relationship with environmental selenium in Qamdo district of Tibet, China. *International Journal of Environmental Research and Public Health, 18*, 1–11. https://doi.org/10.3390/ijerph18010011
Wang, L., Guo, J., Feng, L., Luo, Y., Zhang, X., Fan, Y., et al. (2021). The structure and characteristics of resident food consumption in rural areas of the Tibetan Plateau: Taking Three-Rivers Region in Tibet as an example. *Acta*

Geographica Sinica, 76(9), 2104–2117. https://doi.org/10.11821/dlxb202109005
Wang, X., Dan, Z., Cui, X., Zhang, R., Zhou, S., Wenga, T., 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 G, Lv Q, Wei W, Fang H, Zhang Y, Zhang X, et al. (2023). The formation mechanism of the Cona Woka rift in Eastern Himalaya and its influence on the Tethyan Himalayan polymetallic deposits revealed by magnetotelluric imaging. Tectonophysics. 860: 229918. https://doi.org/10.1016/j.tecto.2023.229918
WHO. (1996). *Trace elements in human nutrition and health*. World Health Organization.
WHO (2005). Dietary exposure assessment of chemicals in food. Report of a Joint FAO/WHO Consultation. Joint FAO/WHO Expert Committe on Food Additives, Geneva.
WHO. (2011). *Guidelines for drinking-water quality*. World Health Organization.
Williams, P. N., Lombi, E., Sun, G.-X., Scheckel, K., Zhu, Y.-G., Feng, X., et al. (2009). Selenium Characterization in the Global Rice Supply Chain. *Environmental Science Technology, 43*(15), 6024–6030. https://doi.org/10.1021/es900671m
Wu, J., Lu, J., Li, L., Min, X., & Luo, Y. (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
Wu, M., Wang, G., James, B., Chen, Y., Hu, Z., & Zheng, C. (2015). Accumulation of Soil Nickel in the Grains of Different Indica Rice. *Chinese Journal of Tropical Crops, 36*(9), 1574–1579. https://doi.org/10.3969/j.issn.1000-2561.2015.09.005
Wu, X. (2020). Correlation analysis of mineral elements in yak meat and herbage in seven regions of Tibet. *Tibet Journal of Agricultural Sciences, 42*(04), 14–17.
Wu, Y., Zhang, H., Liu, G., Zhang, J., Wang, J., Yu, Y., et al. (2016). Concentrations and health risk assessment of trace elements in animal-derived food in southern China. *Chemosphere, 144*, 564–570. https://doi.org/10.1016/j.chemosphere.2015.09.005
Xiang, Y., Hao, L., & Chai, S. (2021). Using stable isotope and mineral element fingerprint combination technology to trace yak meat from different origins. *Chinese Qinghai Journal of Animal and Veterinary Sciences, 51*(02), 36–42. https://doi.org/10.3969/j.issn.1003-7950.2021.02.007
Xiao, J., Wang, L., Deng, L., & Jin, Z. (2019). Characteristics, sources, water quality and health risk assessment of trace elements in river water and well water in the Chinese Loess Plateau. *Science of the Total Environment, 650*, 2004–2012. https://doi.org/10.1016/j.scitotenv.2018.09.322
Yi, K., Wang, J., Yang, C., Wang, S., Wei, S., Li, G., et al. (2021b). Determination of 35 trace elements in Tibet drinking natural water by inductively coupled plasma mass spectrometry. *Modern Food*. https://doi.org/10.16736/j.cnki.cn41-1434/ts.2021.23.057
Zha, X., An, J., Gao, X., & Tian, Y. (2022). Dietary and drinking water intake of essential trace elements in a typical Kashin-Beck disease endemic area of Tibet. *China. Environmental Health, 21*(01), 1–12. https://doi.org/10.1186/s12940-022-00898-0
Zhang, B., Jia, T., Peng, S., Yu, X., & She, D. (2022). Spatial distribution, source identification, and risk assessment of heavy metals in the cultivated soil of the Qinghai-Tibet Plateau region: Case study on Huzhu County. *Global Ecology and Conservation, 35*, e02073. https://doi.org/10.1016/j.gecco.2022.e02073
Zhang, B., Yang, L., Wang, W., Li, Y., & Li, H. (2011). Environmental selenium in the Kaschin-Beck disease area, Tibetan plateau. *China. Environmental Geochemistry & Health, 33*(5), 495–501. https://doi.org/10.1007/s10653-010-9366-y
Zhang, T., Yu, Y., & La, Q. (2017). Evaluation of the qualitative differences among different Tibetan highland barley varieties. *Barley and Cereal Science, 34*(01), 28–32. https://doi.org/10.14069/j.cnki.32-1769/s.2017.01.007
Zhang, X., Deng, W., & Yang, X. (2002). The background concentrations of 13 soil trace elements and their relationships to parent materials and vegetation in Xizang (Tibet), China. *Journal of Asian Earth Sciences, 21*, 167–174. https://doi.org/10.1016/S1367-9120(02)00026-3
Zhang, T., Wang, Q., Li, J., Zhao, S., Qie, M., Wu, X., et al. (2021). Study on the origin traceability of Tibet highland barley (Hordeum vulgare L) based on its nutrients and mineral elements. *Food Chemistry, 346*, 128928. https://doi.org/10.1016/j.foodchem.2020.128928
Zhao, Z., Li, Q., Yang, P., Wang, H., Kong, L., Wang, L., et al. (2013). Selenium: A protective factor for Kaschin-Beck disease in Qing-Tibet plateau. *Biological Trace Element Research, 153*(1), 1–4. https://doi.org/10.1007/s12011-013-9686-8
Zheng, D., Zhang, Q., & Wu, S. (2000). *Mountain Geoecology and Sustainable Development of the Tibetan Plateau*. Springer.
Zheng, N., Wang, Q., Zhang, X., Zheng, D., Zhang, Z., & Zhang, S. (2007). Population health risk due to dietary intake of heavy metals in the industrial area of Huludao City, China. *Science of the Total Environment, 387*, 96–104. https://doi.org/10.1016/j.scitotenv.2007.07.044
Zhu, Q., Tan, L., Zhao, J., Gao, X., et al. (2021). Analysis of nutritional compositions and quality evaluation of yak meat from Qinghai-Plateau regions. *Journal of Food Science and Biotechnology, 40*(11), 97–111. https://doi.org/10.3969/j.issn.1673-1689,2021.11.013