



Deterministic and Probabilistic Health Risk Assessment of Toxic Metals in the Daily Diets of Residents in Industrial Regions of Northern Ningxia, China

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Abstract

This study was designed to investigate the toxic metal (aluminum (Al), arsenic (As), chromium (Cr), cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn)) concentrations in drinking water and different foodstuffs meat (pork, beef, and mutton), cereals (rice, flour, corn, millet), beans (cowpeas, tofu), potatoes (potato, sweet potato), solanaceous fruits (pepper, eggplant, bitter melon, cucumber), vegetables (cabbage, cauliflower, spinach), and fruits (apples, watermelons, pears, grapes)) and then estimate the potential health risks of toxic metal consumption to local residents in industrial regions of northern Ningxia, China. As in drinking water, Cr in meat, Pb in cereals, Pb in beans, As and Pb in potatoes, Pb in solanaceous fruits, Cr and Ni in vegetables, and Ni and Pb in fruits were the most contaminated heavy metals in the corresponding food with over-standard rates of 16.7%, 12.5%, 5.1%, 60%, 50%, 50%, 38.2%, 44.4%, 44.4%, 31.8%, and 31.8%, respectively.

The results of the deterministic assessment of health risks showed that the total noncarcinogenic risk value of dietary intake of toxic metals by the local population was 5.6106, indicating that toxic metals pose a high noncarcinogenic risk. The order of the non-carcinogenic risk is $HI_{\text{cereal}} (1.2104) > HI_{\text{solanaceous fruit}} (0.9134) > HI_{\text{vegetables}} (0.8726) > HI_{\text{fruit}} (0.8170) > HI_{\text{meat}} (0.7269) > HI_{\text{drinking water}} (0.6139) > HI_{\text{beans}} (0.2991) > HI_{\text{potatoes}} (0.1573)$. The total carcinogenic health risk from exposure to toxic metals through dietary intake was 9.98×10^{-4} , indicating that the total cancer risk value of residents is beyond the acceptable range (10^{-4}) under the current daily dietary exposure and implies a high risk of cancer. The order of the carcinogenic risk is $R_{\text{drinking water}} (2.34 \times 10^{-4}) > R_{\text{meat}} (2.11 \times 10^{-4}) > R_{\text{solanaceous fruit}} (1.89 \times 10^{-4}) > R_{\text{fruit}} (1.88 \times 10^{-4}) > R_{\text{cereal}} (1.36 \times 10^{-4}) > R_{\text{potatoes}} (2.44 \times 10^{-5}) > R_{\text{vegetables}} (1.51 \times 10^{-5}) > R_{\text{beans}} (0)$. The probabilistic assessment results showed that 98.83% of the population is exposed to severe noncarcinogenic risk and 87.02% is exposed to unacceptable carcinogenic risk. The sensitivity analysis showed that drinking water, local cereals, vegetables, and fruits were the major contributors to health risks. Our results indicated that the daily dietary exposure of residents in industrial regions of northern Ningxia poses a serious threat to human health, and it is suggested that relevant departments should strengthen monitoring and control of the current situation of toxic metal pollution in the environment and continue to pay attention and take measures to reduce the exposure of toxic metals in the diets of residents in this area.

Keywords Dietary intake · Health risk assessment · Monte Carlo simulation · Toxic metals

Introduction

Toxic metal pollution refers to the contamination of the environment by toxic metals or their compounds mainly as a result of human activities, such as mining, waste gas discharge, sewage irrigation, and the use of products containing heavy metals [1, 2]. Toxic metals in the environment are difficult to degrade and are widely distributed in the atmosphere, water, soil, and organisms. Toxic metals are easily absorbed and accumulated by crops and subsequently enter the human body through the food chain. After entering the

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Table 1 Reference dose values of various heavy metals in drinking water and food

	Drinking water	Food
Al	1.0000	0.0005
As	0.0003	0.0003
Cr	0.0030	0.0030
Cd	0.0050	0.0010
Cu	0.0400	0.0370
Ni	0.0200	0.0200
Pb	0.0014	0.0037
Zn	0.3000	0.3000

human body, toxic metals accumulate and can cause acute and chronic damage, in addition to causing potential carcinogenic, teratogenic, and mutagenic hazards. Therefore, toxic metal pollution has raised widespread concern among researchers worldwide [3, 4]. Many studies have investigated toxic metal exposure through the daily diets of residents near industrial parks, with most focusing on economically developed areas, such as smelting and mining areas in Hunan and Guangdong provinces and industrial areas in coastal cities in Zhejiang province, among others. However, few studies have focused on the northern Ningxia region [5–7]. Therefore, it is necessary to investigate the concentrations of toxic metals in the daily diets of residents near the industrial regions of Ningxia.

Health risk assessment refers to the probability estimation of the impact of toxic and harmful substances on human health and safety, which is determined by collecting and analyzing toxicological and epidemiological data, identifying environmental and exposure factors, and other relevant data [8, 9]. The assessment is directly expressed by the degree of health risk, which indicates the possibility of damage to human health [10]. A comprehensive review of the literature has revealed that China's health risk research is predominantly based on deterministic risk assessment, and probabilistic risk assessment is rarely conducted. However, few studies have used a combination of both approaches to evaluate the exposure levels of toxic metal pollutants in the diets of residents in specific regions [11–13].

Ningxia is located in the inland region of Northwest China in the Yellow River system. Owing to a unique natural environment and resource conditions, several industrial enterprises and industrial parks, including mineral smelting and metal processing, electroplating, electronics, and battery manufacturing industries, were built in northern Ningxia. On the one hand, industrial areas promote economic development; on the other hand, environmental pollution has increased in such areas [14, 15]. In recent years, researchers have observed increased heavy metal pollution in northern Ningxia. Liu et al. [16] analyzed heavy metal pollution in eight categories of foods sold in major supermarkets and farmers' markets in Ningxia and found that heavy metals,

including Pb, Cd, Hg, and Al, were present in the major foods consumed in Ningxia, and their levels exceeded the standard limits to varying degrees. Al had the highest concentration, and its over-standard rate was the highest, indicating the severity of the environmental pollution problem in the area. Therefore, research on Al contamination with regard to food safety risk assessment should be strengthened. Zhao et al. [17] assessed the potential health risks of five heavy metals in water samples obtained from the Qingshui River Basin in Ningxia and observed that the Amaranth River was the most polluted, with the main pollutant being Fe. In addition, the highest total health risk of the five heavy metals was 3.13×10^{-7} , and Cd, as a carcinogenic pollutant, had the highest health risk index. However, information on the health risk assessment studies of toxic metals through the consumption of foodstuffs is quite limited in the Ningxia industrial region. Moreover, most of the previous studies have only focused on a single or a few kinds of foodstuffs. Thus, a comprehensive risk assessment of toxic metals in the diets of the local residents is urgently needed.

Therefore, the purpose of the present study was to investigate the toxic metal content in the daily diet of residents in the industrial region of Ningxia. In this case, the inductively coupled plasma-atomic emission spectrometry (ICP–AES) method was used to quantify the heavy metal content in drinking water and various food samples because it has the advantages of a fast analysis speed, high analysis accuracy and precision, and wide determination range. A questionnaire on the dietary consumption of foodstuffs was conducted to obtain region-specific exposure parameters, and the hazard quotient (HQ) and hazard index (HI) were used to assess noncarcinogenic health risks from individual metals and the combined health risk from eight metals, respectively. In addition, the carcinogenic risk (R) was used to assess the carcinogenic risk of As in the diet of local residents. Deterministic and probabilistic risk assessment methods were used to evaluate potential health risks to local residents following dietary exposure to selected toxic metals. A sensitivity analysis was performed to identify the major contributors to the health risks.

Materials and Methods

Sample Collection and Preparation

Drinking water and various food samples were collected from nearby villages and towns (38°58' to 39°54'N, 116°23' to 106°35'E) in the industrial regions of northern Ningxia, China, in September 2017. Samples were taken after obtaining the relevant permission from families. The 187 samples included 36 drinking water samples and 151 food samples. The 151 food samples included 8 portions of meat (pork,

Table 2 Concentrations of heavy metals in drinking water and food

		Al	As	Cr	Cd	Cu	Ni	Pb	Zn
Drinking water $n = 36$ (mg/L)	Mean	0.0997	0.0056	0.0005	0.0000	0.0012	0.0054	0.0037	0.0296
	SD	0.1342	0.0111	0.0006	0.0001	0.0024	0.0226	0.0040	0.0549
	Mix	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Max	0.5429	0.0456	0.0022	0.0004	0.0120	0.1361	0.0121	0.2372
	Safe limits	0.2	0.01	0.05	0.005	1.0	0.02	0.01	1.0
	Over-limit ratio	11.1%	16.7%	0%	0%	0%	5.6 %	11.1%	0%
Meat $n = 8$ (mg/Kg)	Mean	0.0202	0.2183	0.4719	0.0000	1.0747	0.0000	0.0780	46.3887
	SD	0.0533	0.1581	0.4061	0.0000	0.5379	0.0000	0.0816	19.4477
	Mix	0.0000	0.0000	0.0000	0.0000	0.4116	0.0000	0.0000	15.4314
	Max	0.1613	0.4269	1.0140	0.0000	2.2011	0.0000	0.1960	73.5856
	Safe limits	10	0.5	1.0	0.1	10	0.2	0.2	100
	Over-limit ratio	0%	0%	12.5%	0%	0%	0%	0%	0%
Cereal $n = 59$ (mg/Kg)	Mean	0.0055	0.0158	0.2564	0.0128	0.2820	0.1125	0.0453	5.3166
	SD	0.0388	0.0276	0.2363	0.0142	0.2017	0.1987	0.0745	3.5065
	Min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Max	0.3005	0.0989	0.7701	0.0656	0.6861	1.2914	0.2835	12.1507
	Safe limits	100	0.5	1.0	0.1	10	0.4	0.2	50
	Over-limit ratio	0%	0%	0%	0%	0%	1.7%	5.1 %	0%
Beans $n = 10$ (mg/Kg)	Mean	1.7096	0.0000	0.7536	0.0045	1.9198	0.4792	0.4636	8.5279
	SD	1.1480	0.0000	0.8636	0.0091	1.7087	0.6002	0.3877	7.1609
	Min	0.3980	0.0000	0.0550	0.0000	0.4282	0.0000	0.0000	1.7347
	Max	4.1777	0.0000	2.2808	0.0301	4.6906	1.6047	1.0014	22.1708
	Safe limits	100	0.5	1.0	0.2	20	3.0	0.2	100
	Over-limit ratio	0%	0%	40%	0%	0%	0%	60%	0%
Potatoes $n = 4$ (mg/Kg)	Mean	0.4319	0.1475	0.0322	0.0000	0.1316	0.1579	0.1798	0.2276
	SD	0.1784	0.1475	0.0187	0.0000	0.0674	0.0683	0.1894	0.3941
	Mix	0.1349	0.0000	0.0155	0.0000	0.0287	0.0895	0.0000	0.0000
	Max	0.5866	0.2984	0.0611	0.0000	0.2097	0.2639	0.4436	0.9102
	Safe limits	10	0.2	0.5	0.1	6	0.3	0.2	5
	Over-limit ratio	0%	50%	0%	0%	0%	0%	50%	0%
Solanaeous fruit $n = 34$ (mg/Kg)	Mean	0.0872	0.0965	0.2728	0.0185	0.8822	0.1461	0.1659	5.3943
	SD	0.1180	0.1237	0.2676	0.0262	0.8868	0.1732	0.2390	4.3754
	Mix	0.0000	0.0000	0.0000	0.0000	0.0885	0.0000	0.0000	0.0000
	Max	0.3590	0.3722	0.9064	0.1096	3.3155	0.6618	0.8709	15.8353
	Safe limits	10	0.5	0.5	0.05	10	0.3	0.1	20
	Over-limit ratio	0%	0%	26.5%	17.6%	0%	11.8%	38.2%	0%
Vegetables $n = 18$ (mg/Kg)	Mean	0.0064	0.0042	0.5642	0.0277	0.9527	0.5560	0.1603	6.7956
	SD	0.0143	0.0173	0.4771	0.0237	0.9718	0.9483	0.4142	5.5740
	Mix	0.0000	0.0000	0.0440	0.0000	0.0197	0.0000	0.0000	1.3239
	Max	0.0549	0.0753	1.5511	0.0722	2.8231	3.4651	1.8107	16.6289
	Safe limits	10	0.5	0.5	0.2	10	0.3	0.3	20
	Over-limit ratio	0%	0%	44.4%	0%	0%	44.4%	11.1%	0%
Fruit $n = 22$ (mg/Kg)	Mean	0.0171	0.0473	0.0673	0.0173	0.3318	0.2458	0.1496	4.4962
	SD	0.0555	0.1438	0.0303	0.0210	0.2118	0.3922	0.2136	10.6937
	Mix	0.0000	0.0000	0.0093	0.0000	0.1261	0.0000	0.0000	0.0000
	Max	0.2420	0.6893	0.1172	0.0759	1.0795	1.5844	0.5846	50.6054
	Safe limits	15	0.5	0.5	0.05	10	0.2	0.1	5
	Over-limit ratio	0%	4.5%	0%	4.5%	0%	31.8%	31.8%	13.6%

beef, and mutton), 59 portions of cereals (rice, flour, corn, millet), 10 portions of beans (cowpeas, tofu), 4 portions of potatoes (potato, sweet potato), 34 portions of solanaceous fruits (pepper, eggplant, bitter melon, cucumber), 18 portions of vegetables (cabbage, cauliflower, spinach), and 22 portions of fruits (apples, watermelons, pears, grapes). Five food samples were collected at each site, with every five replicates forming a large sample. Samples of drinking water were placed in plastic bottles. The food samples were dried in a 60 °C oven (DHG-9030A, thermostatic air drying oven, China) to remove moisture. Then the dried samples were crushed and ground, packed into polyethylene bags, and immediately transported to the laboratory for Al, As, Cr, Cd, Cu, Ni, Pb, and Zn analysis.

Laboratory Analyses of Toxic Metals in Water and Food Samples

Twenty milliliters of each water sample were transferred into a test tube. All samples were initially evaporated in an ED54-iTouch high-temperature digestion furnace (LaiBoT, China), and 5 mL (100%) concentrated nitric acid (HNO₃) was added to the evaporated samples. Afterward, the samples were digested in a high-temperature digestion furnace. Using a three-step temperature procedure, under the condition of the maximum power of the high-temperature digestion furnace, first, the temperature was increased linearly to 6 °C for 20 min; second, the temperature was increased to 120 °C and maintained for 30 min; and finally, the temperature was increased to 180 °C for 1~2 h. The digested samples were dissolved in deionized water and diluted to 10 mL.

Samples of meat, vegetables, and fruits (0.5000 g) were weighed in test tubes, and 20 mL of mixed acid (v:v, HNO₃:HClO₄ = 4:1) was added to each sample. After 1 day of cold digestion, the test tubes were placed in a high-temperature

digester for heat digestion. The digested samples were subsequently dissolved in deionized water and diluted to 10 mL.

Cereal samples were digested with 10 mL HNO₃, and the rest of the steps were the same as those for the other food samples.

All samples used in the present study were analyzed using inductively coupled plasma-atomic emission spectrometry to determine their Al, As, Cr, Cd, Cu, Ni, Pb, and Zn concentrations. Blank reagents and multielement standard solutions were used for each batch. The accuracy of the methods was validated by three replicate measurements. Quality control was performed to ensure the precision and accuracy of the experiment. The correlation coefficients of the standard curves of the elements were better than 0.9990. Recovery analysis was performed using standard reference plant materials (GBW10014) (from the National Research Center for Standards in China) to ensure the reliability of sample analysis. The recoveries of the elements ranged from 85 to 110%. Each sample was analyzed three times, with relative standard deviations (RSDs) of the repeated analyses below 5%, indicating that the precision and accuracy of the experiment met the requirements.

Collection of Data on the Diets of Residents in Ningxia Villages and Towns Using Questionnaires

A questionnaire-based survey of village residents was conducted during sampling. The food frequency method was used to design the questionnaires used in the present study. Considering the age distribution and gender balance of the population, a total of 97 completed questionnaires were judged to be effective. Information, including food types, food consumption frequency, food source, age, gender, and the number of household members, was recorded.

Table 3 A summary of the concentrations of heavy metals in drinking water from different countries

Concentration of metal (ug/L) in the drinking water								Country	Author and year of publication
Al	As	Cr	Cd	Cu	Ni	Pb	Zn		
		1.6	0.1		1.6	0.9		India [45]	Prasad M, et al. (2022)
	2.185		0.002			0.11		Thailand [46]	Wongsasuluk P, et al. (2018)
		0.37	0.42					Malaysia [47]	Ahmed MF, Mokhtar MB. (2020)
	0.18	4.49			1.69	0.58		Iran [48]	Alidadi H, et al. (2019)
	0.97	0.48		0.1	0.36	0.1	4.26	China [49]	Yan M, et al. (2018)
		15.0	1.25	515.0	17.0	8.0	785.0	Ethiopia [50]	Haftu Z, et al. (2020)
	0.35	4.13	0.03	16.10	1.10	2.03		Pakistan, Swabi [51]	Hussain S, et al. (2019)
	< 1		< 1	< 1	2.0	< 1	20.0	China, Beijing [23]	Xie, et al. (2021)
			10-20					South Africa [52]	Madilonga RT, et al. (2021)
			3.79	4.74				Africa [53]	Ali S, et al. (2022)

Table 4 A summary of the concentrations of heavy metals in various types of food

Type of food	Concentration of metal (mg/Kg)								Country	Author and year of publication
	Al	As	Cr	Cd	Cu	Ni	Pb	Zn		
Meat										
Baked ham			0.15	0.01	1.08		0.22	6.02	Italy [54]	Barone G, et al. (2021)
Raw ham			0.19	0.01	1.11		0.30	5.71		
Mortadella			0.20	0.02	1.13		0.34	6.03		
Meat			0.87		0.95			43.30	Spain [55]	Perelló G, et al. (2015)
Meat			0.019	0.002	0.74		0.004	22.50	Swedish [56]	Becker W, et al. (2011)
Meat			0.21	0.004					India [57]	Dubey VK, et al. (2016)
Beef			1.24			0.25		121.27	Nigeria [58]	Ihedioha JN, et al. (2014)
Fresh meat		0.018	0.061	0.002	0.801	0.055	0.029		China [59]	Han JL, et al. (2022)
Mutton		349	362	0.301				0.482	Kuwait [60]	Abd-Elghany SM, et al. (2020)
Sheep		0.23	1.66	2.79	5.56	0.54	11.79	233.10	Iran [61]	Raeeszadeh M, et al. (2022)
Beef		0.2	1.83	4.31	5.75	1.17	7.01	234.6		
Cereal, beans, and potatoes										
Wheat	0.111	0.094	0.016	2.640	0.275	0.044	21.528		Iran [62]	Ghanati K, et al. (2019)
Flour	0.004		0.043			0.067			Poland [63]	Bielecka J, et al. (2022)
Rice		0.41	0.13		0.84	< 0.05			Nigeria [64]	Orisakwe OE, et al. (2015)
Wheat		0.42	0.16		0.41	< 0.05				
Grain	0.028		0.018			0.103			China [65]	Liu, et al. (2019)
Grain	0.087	0.082	0.001	0.032		0.013			Malaysia [66]	Zulkafflee NS, et al. (2022)
Rice		1.98	0.08		1.50	0.15	13.92		Burkina Faso [67]	Bazié BSR, et al. (2022)
Maize	0.53	1.2	0.12		0.080	0.46			Bangladesh [68]	Rahman M, et al. (2019)
Pea	0.61	0.64	0.23		0.60	0.97				
Beans	0.042	0.120	0.025	1.466		0.117	4.363		China [69]	Qi, et al. (2022)
Beans	< dl	< dl	0.04	9.2	2.45	0.25	72.0		Croatia [70]	Stančić Z, et al. (2016)
White potato	0.027	< dl	0.23	8.2	0.31	0.36	57.4			
Red potato	0.053	< dl	0.28	5.9	< dl	0.17	60.4			
Potato		1.13	0.6	4.8	0.89	3.04	37.66		Pakistan [71]	Din AU, et al. (2013)
potato	0.448		0.135	0.015		0.613	4.674		China [72]	Zhou, et al. (2016)
Vegetable and fruit										
Cabbage			4.33	1.79			7.14		Iran [73]	Jafarian-Dehkordi A, et al. (2013)
Lettuce			6.00	1.79			5.16			
Carrot	1.82	8.80	0.15	6.80	0.00	6.96	2.87		Colombia [74]	Lizarazo MF, et al. (2020)
Mushroom	2.58	12.8	0.16	19.4	0.00	5.69	3.31			
Spinach				29.65		14.61	137.84		India [75]	Sonu K, et al. (2019)
Cabbage				6.30		24.2	80.02			
Vegetable	0.025	0.127	0.140	0.600		0.171	3.725		China [69]	Qi, et al. (2022)
Solanaceous vegetables	0.019	0.083	0.031	0.546		0.058	2.101			
Cabbage	6.36	4.50	1.00	15.96	3.06	6.70	34.4		Ethiopia [76]	Bayissa LD, et al. (2021)
Grapes		1.06		3.21	0.31				Egypt [77]	Amer MM, et al. (2019)
Apple	0.003		0.002			0.068			India [78]	Mawari G, et al. (2022)
Fruit				63.8	8.8		47.8		French [79]	Cherfi A, et al. (2016)
Grape		0.002	0.003		0.001	0.04			Bangladesh [80]	Afrin S, et al. (2021)
Apple		0.002	0.001		0.001	0.05				
Orange		0.002	0.001		0.002	0.06				
Strawberry			0.050			0.10			Poland [81]	Rusin M, et al. (2021)
Raspberry			0.050			0.10				
Assembling	8.162	0006	0.286	0.001	0.416	0.041	0.411		China [82]	Nie, et al. (2021)

Health Risk Assessment

Deterministic Estimation of Health Risks

Of the eight toxic metals studied, Al, Cr, Cd, Cu, Ni, Pb, and Zn posed noncarcinogenic health risks through oral exposure, whereas As posed both noncarcinogenic and carcinogenic health risks through oral exposure. The daily exposure to toxic metals was calculated using Eqs. 1 and 2 as follows [18, 19]:

$$EXPO_{As} = \frac{C \times DI \times EF \times ED}{BW \times LT} \tag{1}$$

$$EXPO = \frac{C \times DI \times EF \times ED}{BW \times LT} \tag{2}$$

where EXPO is the daily exposure to toxic metals; C (mg/kg) is the concentration of toxic metals in drinking water and foods; DI (g/day) is the daily intake of different types of food; EF (day/year) is the exposure frequency, which was obtained from the questionnaire; ED (years)

is the duration of exposure; BW (kg) is the average body weight of the resident, which was also determined from the questionnaire; and LT is the average exposure time of the resident, which was assumed to be 70 years [20].

The hazard quotient (HQ) was calculated to assess the noncarcinogenic risk of individual toxic metals. An $HQ \geq 1$ indicates that the risk is serious, whereas an $HQ < 1$ indicates that it is not serious. HQ was calculated using Eq. 3 as follows [21, 22]:

$$HQ = \frac{EXPO}{RfD} \tag{3}$$

where RfD (mg/(kg-d)) is the reference dose of noncarcinogenic pollutants, as recommended by the United States Environmental Protection Agency (US EPA) and the World Health Organization (WHO) [23]. The RfD values are listed in Table 1.

When exposure to multiple noncarcinogenic substances occurs simultaneously, regardless of their interactions, an overall hazard index (HI) can be obtained by summing the cumulative noncarcinogenic risk of each pollutant. The

Table 5 Exposure factors associated with drinking water and various foods

	Daily intake of food (g/day)	Exposure frequency (day/year)	Exposure duration (year)	Average weight (Kg)
Drinking water	1546.39	365	70 [84]	54.93
Meat	42.41	304.09		
Cereal	313.92	365		
Beans	23.75	64.35		
Potatoes	17.24	128.17		
Solanaceous fruit	111.28	235.31		
Vegetables	152.69	316.46		
Fruit	240.59	220.86		
Data sources	Questionnaire	Questionnaire	Document literature	Questionnaire

Table 6 Noncarcinogenic risk hazard quotients (HQ), toxic metal hazard indices (HI), and carcinogenic risk (R) values of dietary intake of arsenic based on the deterministic estimation method

	Non-carcinogenic risk (HQ)									Carcinogenic risk (R) As
	Al	As	Cr	Cd	Cu	Ni	Pb	Zn	HI	
Drinking water	0.0028	0.5210	0.0045	0.0002	0.0008	0.0076	0.0742	0.0028	0.6139	2.34×10^{-4}
Meat	0.0259	0.4080	0.1012	0.0000	0.0187	0.0000	0.0136	0.0995	0.7269	2.11×10^{-4}
Cereal	0.0627	0.3018	0.4884	0.0734	0.0806	0.0321	0.0700	0.1013	1.2104	1.36×10^{-4}
Beans	0.2621	0.0000	0.0191	0.0003	0.0040	0.0018	0.0096	0.0022	0.2991	0.0000
Potatoes	0.0952	0.0542	0.0012	0.0000	0.0004	0.0009	0.0054	0.0001	0.1573	2.44×10^{-5}
solanaceous fruit	0.2277	0.4201	0.1187	0.0242	0.0311	0.0095	0.0586	0.0235	0.9134	1.89×10^{-4}
Vegetables	0.0310	0.0336	0.4532	0.0667	0.0621	0.0670	0.1044	0.0546	0.8726	1.51×10^{-5}
Fruit	0.0904	0.4180	0.0595	0.0459	0.0238	0.0326	0.1072	0.0397	0.8170	1.88×10^{-4}

Table 7 Statistics of probabilistic estimation of hazard indices (HI) and carcinogenic risk (R) values

	Non-carcinogenic risk (HI)				Carcinogenic risk (R) ($\times 10^{-4}$)					
	Distribution	Parameters	10%	50%	90%	Distribution	Parameters	10%	50%	90%
Drinking water	Lognormal	Location:0.00, Mean:0.95, SD:2.01	0.00	0.65	2.93	Lognormal	Location:0.00, Mean:3.58, SD:8.91	0.00	2.43	12.21
Meat	Lognormal	Location:0.00, Mean:1.14, SD:1.12	0.34	0.77	2.39	Lognormal	Location:0.00, Mean:3.31, SD:3.96	0.71	2.07	7.00
Cereal	Lognormal	Location:0.00, Mean:1.69, SD:2.38	0.00	1.25	4.34	Lognormal	Location:0.00, Mean:1.52, SD:7.52	0.00	1.66	8.56
Beans	Lognormal	Location:0.00, Mean:0.47, SD:0.48	0.12	0.31	0.97	-*	-	-	-	-
Potatoes	Lognormal	Location:0.00, Mean:0.25, SD:0.24	0.08	0.17	0.51	Lognormal	Location:0.00, Mean:0.39, SD:0.64	0.06	0.21	0.86
Solanaceous fruit	Lognormal	Location:0.00, Mean:1.39, SD:1.96	0.00	1.05	3.44	Lognormal	Location:0.00, Mean:2.56, SD:7.09	0.00	2.32	9.15
Vegetables	Lognormal	Location:0.00, Mean:1.39, SD:1.58	0.33	0.88	2.98	Lognormal	Location:0.00, Mean:0.27, SD:1.83	0.00	0.04	0.48
Fruit	Lognormal	Location:0.00, Mean:1.35, SD:9.06	0.22	0.68	2.62	Lognormal	Location:0.00, Mean:3.24, SD:40.50	0.05	0.71	6.21

HI was calculated using Eq. 4 and used to assess the total noncarcinogenic health risk: an HI value ≤ 1 means that the exposed population is unlikely to experience notable adverse effects, and if the value is > 1 , there may be non-carcinogenic effects on human health [24, 25].

$$HI = \sum_1^n HQ_n \tag{4}$$

This index is used for the total risk caused by several constituents in a material or the sum of more than one HQ for a specific constituent that enters the body through various pathways. In this study, HI was used to assess the cumulative health risk to humans from exposure to eight toxic metals in food.

The metal As is a carcinogen, and its carcinogenic risk (R) can be calculated using Eq. 5 as follows [26]:

$$R = SF \times EXPO \tag{5}$$

where SF is the carcinogenic risk slope factor [mg/(kg·d)], and the US EPA recommends an SF of 1.5 [mg/(kg·d)] for As. The negligible carcinogenic risk level recommended by the US EPA is 10^{-6} , while the level recommended by the WHO is 10^{-5} ; the maximum acceptable level recommended by the US EPA is 10^{-4} [27, 28].

Probabilistic Assessment and Sensitivity Analysis

Uncertainty analysis in health risk assessment mainly includes two components: determining the probabilistic results and evaluating the contribution of each variable to the results. Monte Carlo simulation was used to analyze the uncertainty of the results [29]. First, the best-fitting probability distribution type of the exposure factors was simulated by Anderson-Darling and chi-square tests. Subsequently, stable exposure distribution results were obtained from 10,000 iterations, and the values at different quantiles (e.g., 10th, 50th, and 90th) of the exposure distribution results were used to assess the probabilistic risk. The degrees of contribution of the exposure factors to the results were assessed by performing sensitivity analysis. A positive value indicated that the exposure factor was positively correlated with health risks; otherwise, it was negatively correlated [30–32].

Statistical Analysis

The mean, standard deviation (SD), and over-standard rates were calculated using MS Excel 2010 (Microsoft Corp, Redmond, WA, USA). The determination of the best-fitting distribution for each parameter, Monte Carlo simulation, and sensitivity analysis were performed using the Crystal Ball.

Fig. 1 Cumulative distribution of hazard indices for total dietary intake of toxic metals (red area represents the probability of exceeding the maximum acceptable levels, which is 98.83%)

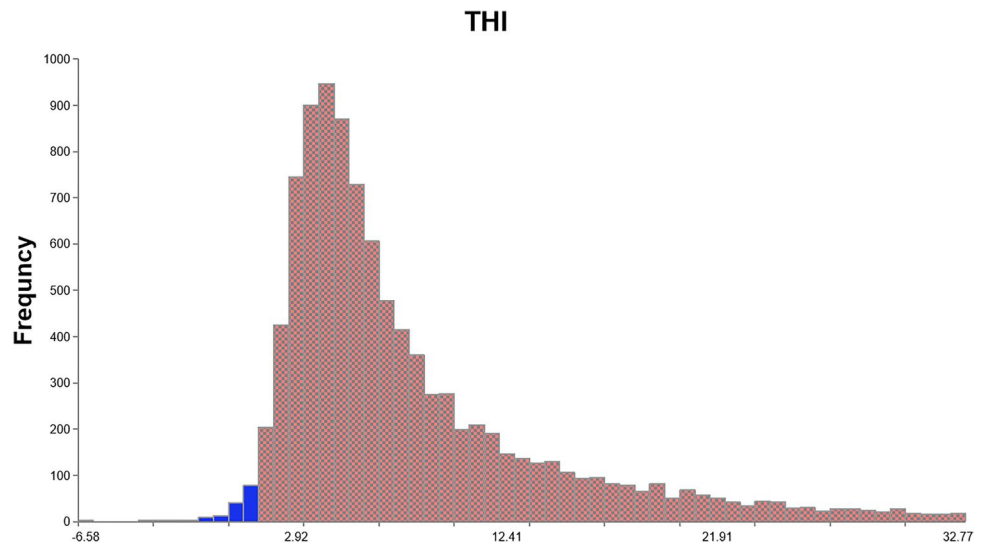
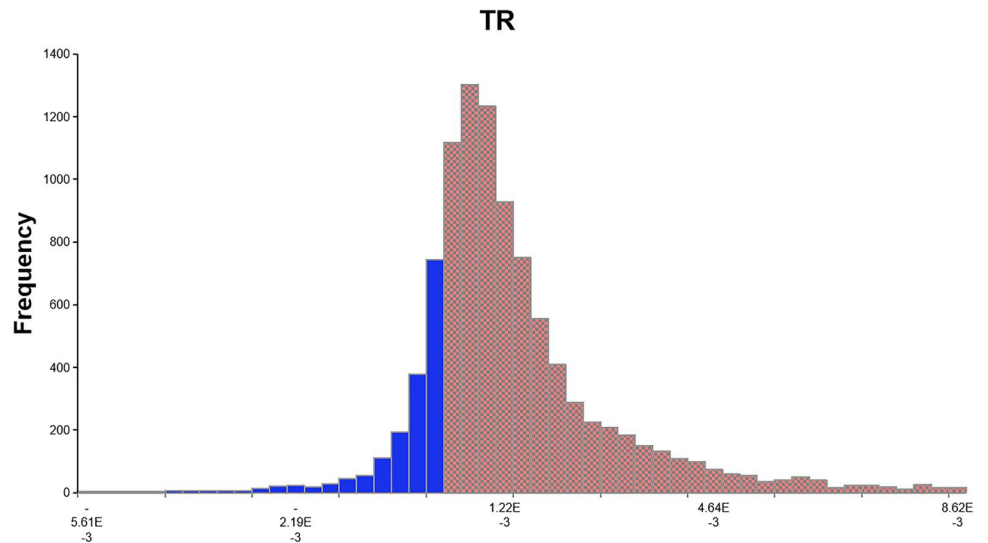


Fig. 2 Cumulative distribution of carcinogenic risk (R) of total dietary intake of arsenic (red area represents the probability of exceeding the maximum acceptable levels, which is 87.02%)



Results and Discussion

Heavy Metal Concentrations in Drinking Water and Various Food Samples

The average concentrations of the eight toxic metals (Al, As, Cr, Cd, Cu, Ni, Pb, and Zn) and their corresponding SD values are listed in Table 2. In the present study, the over-standard rates of Al, As, Ni, and Pb in drinking water samples were 11.1%, 16.7%, 5.6%, and 11.1%, respectively, and As exhibited the highest level of pollution. The ingestion of trace amounts of As over a long period may be detrimental to human health because of its non-biodegradable nature [33]. Ahmed et al. [34] reported

high concentrations of As in the transboundary Langat River in Malaysia. Therefore, it is important to manage drinking water sources to minimize human health risks associated with As exposure.

Excessive amounts of Cr were detected in meat samples, with the metal content exceeding the recommended limit by 12.5%. Previous studies have also reported that Cr concentrations in commercial livestock meat exceeded the standard value, although the over-standard rates of Cr varied among different livestock meats. Animals ingest heavy metals that are added to their feed, which once in the body are difficult to remove.

Our results showed that the Pb and Ni contents in cereal samples exceeded the standard limits by 5.1% and 1.7%, respectively. Nawaz et al. [37] investigated Ni accumulation

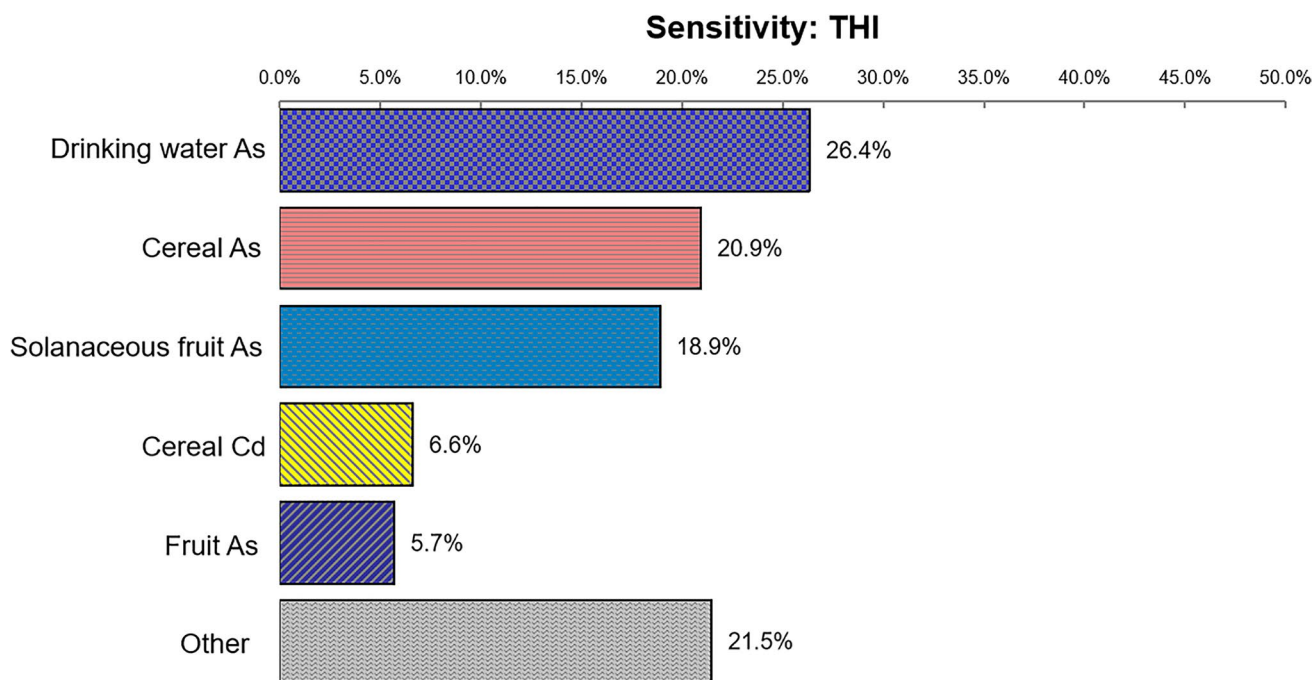


Fig. 3 Sensitivity analysis of noncarcinogenic risk from dietary intake of toxic metals

in cereals irrigated with wastewater and observed that high concentrations of irrigation wastewater improved the bioavailability of Ni in crops and in turn increased its accumulation in the edible parts of crops. Román-Ochoa et al. [38] examined the heavy metal content of cereals and grain-processed foods in Arequipa, Peru, and found that lead concentrations in quinoa, corn, and rice products increased sequentially due to processing. Therefore, the high Pb and Ni concentrations in cereals should be addressed, and their monitoring should be enhanced.

According to the results of the present study, the Cr and Pb concentrations in soybean were high, and their over-standard rates were 40% and 60%, respectively. These results are consistent with those obtained by Huang et al. [39], who reported that the Cr and Pb concentrations in soybean were 0.03–1.05 mg/kg and 0.11–0.85 mg/kg, respectively, and the Pb concentration was high, with an over-standard rate of 97.4%. The As and Pb concentrations in potato samples exceeded the standard limits, and their over-standard rate was 50%. Tubers, such as potatoes, are prone to heavy metal contamination. Furthermore, tubers are the most heavily metal-enriched plant parts. Bao et al. [40] assessed the heavy metal contents of potatoes planted in an experimental area of the Qinghai University Academy of Agriculture and Forestry Sciences, and the results showed that the respective average contents of Cd, Cr, Pb, and Ni in the potato tubers were 3.20-fold, 1.58-fold, 9.4-fold, and 1.7-fold higher than the limit values of the metal

contents in potato tubers. Bao et al. observed that the Pb content exceeded the standard limit and exhibited the highest level of pollution, which is consistent with the results of the present study.

The over-standard rates of Cr, Cd, Ni, and Pb in solanaceous fruit samples were 26.5%, 17.6%, 11.8%, and 38.2%, respectively. The order of heavy metal contamination in solanaceous fruits from the highest to the lowest was Pb > Cr > Cd > Ni. However, vegetables are easily contaminated by heavy metals, such as Pb and Cd, and the phenomenon of exceeding their standard limits is common. Luo et al. [41] investigated the health risks of heavy metals in solanaceous fruits in Beijing, China. The results showed that the average Pb, Cd, Cu, and Zn contents in solanaceous fruits in Beijing were 0.082, 0.021, 0.996, and 0.590 mg/kg, respectively. Based on the national food safety standard limits of China, the over-standard rate of Pb in solanaceous fruits in Beijing was 5.8%, and its pollution level was the highest. The results obtained by Luo et al. are similar to those of the present study.

The over-standard rates of Cr, Ni, and Pb in vegetable samples were 44.4%, 44.4%, and 11.1%, respectively. The results showed that the pollution levels of Cd, Ni, and Zn in leafy vegetables were relatively high. Frazana et al. [42] reported results similar to those of this study. The report stated that heavy metal concentrations were measured in vegetables commonly eaten in industrial areas of Bangladesh. Pb, Cd, Cr, and Ni were detected in

most of the vegetables analyzed, and some samples had Pb, Cd, and Ni concentrations that exceeded the FAO/WHO maximum permissible concentrations for Pb, Cd, and Ni. Previous studies have shown that the accumulation capacity of heavy metals in vegetables is usually ranked as vegetables > legumes > solanaceous fruits. The variations in the distribution of heavy metal pollutants in various types of vegetables were associated with the differences in the biological characteristics of the vegetables.

Our results showed that As, Cd, Ni, Pb, and Zn were detected in the fruit samples, and their concentrations were higher than those reported in related studies, suggesting that the fruits in the northern region of Ningxia are highly polluted with heavy metals. Further analysis suggested that the cause of the over-standard concentrations could be severe heavy metal pollution in soils adjacent to the industrial park, where most of the fruits are planted by the local residents.

The heavy metal concentrations in the drinking water and various foods analyzed in the present study were observed to have the following order: drinking water (Al > Zn > As > Ni > Pb > Cu > Cr > Cd), meat (Zn > Cu > Cr > As > Pb > Al > Ni = Cd), cereals (Zn > Cu > Cr > Ni > Pb > As > Cd > Al), beans (Zn > Cu > Al > Cr > Ni > Pb > Cd > As), potatoes (Al > Zn > Pb > Ni > As > Cu > Cr > Cd), solanaceous fruits (Zn > Cu > Cr > Pb > Ni > As > Al > Cd), vegetables (Zn > Cu > Cr > Ni > Pb > Cd > Al > As), and fruits (Zn > Cu > Ni > Pb > Cr > As > Cd > Al). A summary of the concentrations of heavy metals in drinking water from different countries is presented in Table 3, whereas a summary of heavy metals in various types of food is presented in Table 4.

Exposure Factors

The daily intake and frequency of exposure to toxic metals through drinking water and various foods are presented in Table 5. The consumption of drinking water, meat, cereals, beans, potatoes, solanaceous fruits, vegetables, and fruit was 1546.39 mL, 42.41 g, 313.92 g, 23.75 g, 17.24 g, 111.28 g, 152.69 g, and 240.59 g, respectively, which satisfied the recommendations of the Dietary Guidelines for Chinese Residents (2022 edition) [83]. The average weight of the participants was 54.93 kg.

Human Health Risk Assessment

Determination of the Assessment

The results of the deterministic assessments of the health risks of exposure to toxic metals through drinking water

and food are presented in Table 6. For noncarcinogenic risk, an HQ value of individual metals < 1 indicates that the metal poses no significant noncarcinogenic risk through drinking water or various foods. Among the eight toxic metals, Al in beans and potatoes posed higher noncarcinogenic risks than the other metals. The As in drinking water, meat, solanaceous fruits, and fruits posed the highest noncarcinogenic risk. Cr had the highest HQ value in cereals and vegetables. The HI values of drinking water and different foods were as follows: cereals (1.2104) > solanaceous fruits (0.9134) > vegetables (0.8726) > fruits (0.8170) > meat (0.7269) > drinking water (0.6139) > beans (0.2991) > potatoes (0.1573). With regard to the carcinogenic risks posed by As, the order of *R* values was as follows: drinking water (2.34×10^{-4}) > meat (2.11×10^{-4}) > solanaceous fruits (1.89×10^{-4}) > fruits (1.88×10^{-4}) > cereals (1.36×10^{-4}) > potatoes (2.44×10^{-5}) > vegetables (1.51×10^{-5}) > beans (0.00). The *R* values of drinking water, meat, solanaceous fruits, fruits, and cereals were greater than 1.0×10^{-4} , indicating that dietary intake poses a significant carcinogenic risk to residents. The *R* values of potatoes and vegetables ranged between 10^{-5} and 10^{-4} , indicating that there is a certain level of carcinogenic risk. The *R* value of beans was 0 because As was not detected in beans, and the total carcinogenic risk value attributed to As in the daily diet of residents was greater than 1.0×10^{-4} , which indicates that local residents may be exposed to potential carcinogenic risks through the diet.

We assessed potential health risks by comparing the HI values of drinking water and various foods, and the results were as follows. The HI value of cereals was > 1, indicating that there may be significant potential health risks associated with the consumption of cereals alone among the local residents in northern Ningxia. Zhang et al. [85] reported that the total target hazard quotient (TTHQ) value of cereals in Binzhou, China, was 0.914, indicating that the combined exposure risk of Pb, Cd, and As intake in cereals was within the acceptable intake levels, although there were potential risks. If multiple heavy metals were monitored, the risk of TTHQ in cereals was greater than one, which verifies the results of the present study. Therefore, the monitoring of multiple heavy metals in cereals should be strengthened, and more comprehensive risk assessments should be carried out. Except for cereals, the HI values for residents who consumed any of the other foodstuffs were generally < 1, indicating that there is no significant potential health risk for residents by consuming individual foodstuffs. The potential health risk of consuming beans or potatoes was the lowest. Xu et al. [86] reported that the health risks of commercially available legumes in Guizhou Province, China, were low and posed no apparent health hazards to humans. Yang et al. [87] reported that local residents in

Henan Province, China, were slightly exposed to Pb contamination through grains and potatoes, and the health risks from their exposure were within the acceptable levels. Farzana et al. [42] reported that the Cd levels in all vegetables analyzed in the study were above the threshold for cancer risk and were a potential carcinogenic risk for both adults and children. The noncarcinogenic risk results showed that the THQ values of Pb, Cd, Cr, and Ni in most vegetable samples were all less than 1.0, meaning that there were no harmful health effects on exposed consumers and their health was not compromised. Sadia et al. [80] tested the extent of heavy metal contamination in grapes, apples, oranges, bananas, and pomegranates widely consumed in supermarkets in Dhaka, Bangladesh, to assess their health risk to humans, and the results showed that the lifetime increased risk of cancer from Cd and Pb in bananas, apples, grapes, oranges, and pomegranates for children and adults exceeded the threshold, posing a potential cancer risk to human health, and heavy metal contamination in all types of fruit did not pose a potential noncarcinogenic risk to humans. However, when individual health risks for all toxic metals ingested through drinking water, cereals, meat, vegetables, and fruits were added together, the TTHQ value was 5.6106, suggesting that residents living in northern Ningxia may have adverse health effects. Liang et al. [88] investigated heavy metal pollution and health risks for residents near tailing ponds in Guangdong province in southern China and observed that the total noncarcinogenic HI value of all metals considered through multiple exposure routes was 26.6, which was significantly higher than the acceptable level. In addition, As accounted for the highest cancer risk when cancer risk was considered, and the total cancer risk value was higher than the acceptable range. The results obtained in the present study are consistent with those of Liang et al. Notably, the THQ value is a highly conservative and relative index, and a TTHQ value exceeding one does not imply that local residents have been exposed to adverse health effects. However, according to our results, the potential health risks of As in drinking water were the highest. Therefore, it is necessary to enhance the monitoring of As levels in foodstuffs and issue a consumption advisory note.

Probabilistic Assessment

The toxic metal contents in drinking water and various foods analyzed were fitted to lognormal distributions. The DI, EF, and BW values of all the residents were fitted to lognormal distributions. The BWs of males and females were fitted to Poisson and negative binomial distributions, respectively.

The results of the probabilistic estimation of health risks are summarized in Table 7. All HI values for the

noncarcinogenic risk were fitted to lognormal distributions. The 10th percentile of the HI values for drinking water and various foods did not exceed the limit value of 1, indicating that 10% of the residents did not have significant noncarcinogenic risk caused by dietary exposure to the toxic metals. The 50th percentile of the HI values for cereals (1.25) and solanaceous fruits (1.05) were greater than the limit value of 1, indicating that 50% of the residents may have significant noncarcinogenic risks from the consumption of cereals and solanaceous fruits. The 90th percentile of the HI values for drinking water, meat, cereals, solanaceous fruits, vegetables, and fruits were 2.93, 2.39, 4.34, 3.44, 2.98, and 2.62, respectively, indicating that these foods are likely to cause significant health hazards to local residents. The percentage of target hazard index values > 1 (Fig. 1) was 98.83%, indicating that 98.83% of the local residents were exposed to severe noncarcinogenic risk.

To determine the carcinogenic risk, the *R* values for drinking water and various foods were fitted to lognormal distributions. The 90th percentile of *R* values for beans, potatoes, and vegetables were 0.00×10^{-4} , 0.86×10^{-4} , and 0.48×10^{-4} , respectively, with none of them exceeding the maximum acceptable level of 1.0×10^{-4} . According to the probability estimation results, the 10th, 50th, and 90th percentiles of *R* values were 0.00×10^{-4} , 2.43×10^{-4} , and 12.21×10^{-4} for drinking water; 0.71×10^{-4} , 2.07×10^{-4} , and 7.00×10^{-4} for meat; 0.00×10^{-4} , 1.66×10^{-4} , and 8.56×10^{-4} for cereals; 0.00×10^{-4} , 2.32×10^{-4} , and 9.15×10^{-4} for solanaceous fruits; and 0.05×10^{-4} , 0.71×10^{-4} , and 6.21×10^{-4} for fruits. Therefore, we can conclude that the intake of the types of food analyzed in the present study by residents leads to varying degrees of carcinogenic risk, and the risk levels are significantly different. Approximately, 87.02% of the local residents had a total risk (TR) exposure value greater than 1.0×10^{-4} (Fig. 2), indicating that they experienced unacceptable carcinogenic risk due to the dietary intake of As.

*Arsenic was not detected in beans, so the distribution could not be modeled

Sensitivity Analysis

The results of the sensitivity analysis are shown in Fig. 3 and Fig. 4. For the total noncarcinogenic risk, As in drinking water was the most notable contributor to the health risk, accounting for 26.4%, followed by As in cereals, As in solanaceous fruits, Cd in cereals, and As in fruits, with proportions of 20.9%, 18.9%, 6.6%, and 5.7%, respectively. Regarding the total carcinogenic risk, As in drinking water, cereals, solanaceous fruit, and fruits contributed the most to the output variance, with proportions

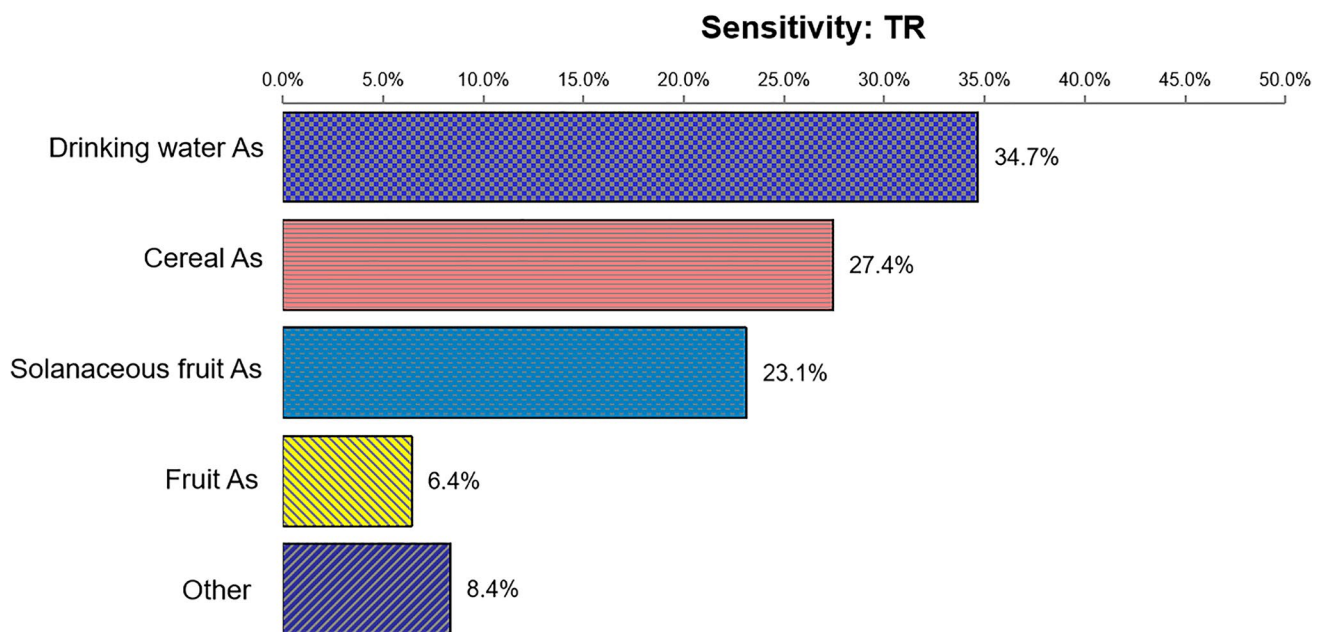


Fig. 4 Sensitivity analysis of carcinogenic risk from dietary intake of toxic metals

of 34.7%, 27.4%, 23.1%, and 6.4%, respectively. The results imply that As in drinking water is the most sensitive factor for both noncarcinogenic and carcinogenic risks, and monitoring As concentrations could effectively reduce the health risk it poses to local residents.

Conclusion

The concentrations of Al, As, Cr, Cd, Cu, Ni, Pb, and Zn in drinking water and seven types of food exceeded the corresponding standard limits at different levels. The most harmful metals, especially Pb, exceeded the standard limits in fruits. The dietary ingestion of these eight toxic metals could pose serious noncarcinogenic risks, with As posing the highest carcinogenic risk to residents in the northern Ningxia region. The As in drinking water was the most sensitive factor affecting health risk results among the various exposure factors evaluated. Therefore, monitoring the concentration of toxic metals in both drinking water and food is necessary. Moreover, the constant monitoring of toxic metals in all food commodities is needed to evaluate whether any potential health risks from heavy metal exposure exist, ensure food safety, and protect residents from food that might pose a risk to their health. However, there are some uncertainties in this study, and the bioavailability of toxic metals in food after being processed and entering the human body was not considered in the assessment. The dietary structure and eating habits of different consumers may also affect their exposure to toxic metals

through their diets. A more accurate risk exposure assessment can be carried out in future studies. The results of the present study can serve as an important reference for future research in related fields.

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Author Contribution Meilin Zhu conceived and designed the experiments. Yan Wang and Deyan Cao performed the experiments. Jiaqi Qin and Siyuan Zhao analyzed the data. Jianzai Zhang, Xi Zhang, and Junji Wang provided the analysis tools. Yan Wang wrote the manuscript. Meilin Zhu critically revised the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate The study was approved by the institutional research ethics committee of Ningxia Medical University, and written informed consent was obtained from each participant.

Consent for Publication The authors confirm that the human study participants provided informed consent for any data in the manuscript.

Competing Interests The authors declare no competing interests.

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References

- Qin G, Niu Z, Yu J, Li Z, Ma J, Xiang P (2021) Soil heavy metal pollution and food safety in China: effects, sources and removing technology. *Chemosphere* 267:129205. <https://doi.org/10.1016/j.chemosphere.2020.129205>
- Bi X, Zhang M, Wu Y, Fu Z, Sun G, Shang L, Li Z, Wang P (2020) Distribution patterns and sources of heavy metals in soils from an industry undeveloped city in Southern China. *Ecotoxicol Environ Saf* 205:111115. <https://doi.org/10.1016/j.ecoenv.2020.111115>
- Rehman K, Fatima F, Waheed I, Akash MSH (2018) Prevalence of exposure of heavy metals and their impact on health consequences. *J Cell Biochem* 119(1):157–184. <https://doi.org/10.1002/jcb.26234>
- Fu Z, Xi S (2020) The effects of heavy metals on human metabolism. *Toxicol Mech Methods* 30(3):167–176. <https://doi.org/10.1080/15376516.2019.1701594>
- Fan Y, Zhu T, Li M, He J, Huang R (2017) Heavy metal contamination in soil and brown rice and human health risk assessment near three mining areas in central China. *J Healthc Eng* 2017:4124302. <https://doi.org/10.1155/2017/4124302>
- Han JL, Pan XD, Chen Q, Huang BF (2021) Health risk assessment of heavy metals in marine fish to the population in Zhejiang. *China. Sci Rep* 11(1):11079. <https://doi.org/10.1038/s41598-021-90665-x>
- Xu DM, Yan B, Chen T, Lei C, Lin HZ, Xiao XM (2017) Contaminant characteristics and environmental risk assessment of heavy metals in the paddy soils from lead (Pb)-zinc (Zn) mining areas in Guangdong Province, South China. *Environ Sci Pollut Res Int* 24(31):24387–24399. <https://doi.org/10.1007/s11356-017-0052-9>
- Choudri BS, Al-Nasiri N, Charabi Y, Al-Awadhi T (2020) Ecological and human health risk assessment. *Water Environ Res* 92(10):1440–1446. <https://doi.org/10.1002/wer.1382>
- Vermeire T, Stevenson H, Peiters MN, Rennen M, Slob W, Hakker BC (1999) Assessment factors for human health risk assessment: a discussion paper. *Crit Rev Toxicol* 29(5):439–490. <https://doi.org/10.1080/104084499991349249>
- Hoang HG, Chiang CF, Lin C, Wu CY, Lee CW, Cheruiyot NK, Tran HT, Bui XT (2021) Human health risk simulation and assessment of heavy metal contamination in a river affected by industrial activities. *Environ Pollut* 285:117414. <https://doi.org/10.1016/j.envpol.2021.117414>
- Manea DN, Ienciu AA, Ștef R, Șmuleac IL, Gergen II, Nica DV (2020) Health risk assessment of dietary heavy metals intake from fruits and vegetables grown in selected old mining areas—a case study: the Banat area of southern Carpathians. *Int J Environ Res Public Health* 17(14):5172. <https://doi.org/10.3390/ijerph17145172>
- Jiang DM (2007) Study on dietary structure and heavy metal intake level of urban and rural residents in Chongqing. Southwest University
- Wei J, Cen K (2020) Contamination and health risk assessment of heavy metals in cereals, legumes, and their products: a case study based on the dietary structure of the residents of Beijing, China. *J Clean Prod* 260:121001. <https://doi.org/10.1016/j.jclepro.2020.121001>
- Wang JY, Zhang SZ, Yong J, Zhang ZJ, Chen YH (2021) Characteristics and causes of heavy pollution in typical industrial city in Ningxia in January 2020. *Res Environ Sci* 34(08):1802–1811. <https://doi.org/10.13198/j.issn.1001-6929.2021.05.26>
- Wang ME, Peng C, Chen WP (2016) Impacts of industrial zone in arid area in Ningxia province on the accumulation of heavy metals in agricultural soils. *Huan Jing Ke Xue* 37(9):3532–3539. <https://doi.org/10.13227/j.hjkk.2016.09.035>
- Liu JX, Yuan XJ, Shu XJ, Gong R, Zhang YH (2013) Investigation and evaluation of heavy metal contamination in primary food in Ningxia. *Ningxia Med J* 35(05):412–413. <https://doi.org/10.13621/j.1001-5949.2013.05.003>
- Zhao ZF, Shi W, Qiu XZ, Ouyang H, Wang SQ, Sun XY, Li SL (2021) Distribution characteristics and health risk assessment of five heavy metals in the water of Qingshuihe river basin. *Adm Tech Environ Monit* 33(03):35–40. <https://doi.org/10.19501/j.cnki.1006-2009.2021.03.008>
- Bridges J (2003) Human health and environmental risk assessment: the need for a more harmonised and integrated approach. *Chemosphere* 52(9):1347–1351. [https://doi.org/10.1016/s0045-6535\(03\)00469-7](https://doi.org/10.1016/s0045-6535(03)00469-7)
- Zhu ML, Zhu XZ, Feng NC (2016) Evaluation of health risks and determination of limited concentrations of heavy metals in *Glycyrrhizae Radix et Rhizoma*. *Chinese Tradit Patent Med* 38(08):1771–1776
- Gruszecka-Kosowska A (2019) Human health risk assessment and potentially harmful element contents in the fruits cultivated in the southern Poland. *Int J Environ Res Public Health* 16(24):5096. <https://doi.org/10.3390/ijerph16245096>
- Aghlmand R, Rasi Nezami S, Abbasi A (2021) Evaluation of chemical parameters of urban drinking water quality along with health risk assessment: a case study of Ardabil province, Iran. *Int J Environ Res Public Health* 18(10):5179. <https://doi.org/10.3390/ijerph18105179>
- Kiani A, Arabameri M, Moazzen M, Shariatifar N, Aeenehvand S, Khaniki GJ, Abdel-Wahhab M, Shahsavari S (2022) Probabilistic health risk assessment of trace elements in baby food and milk powder using ICP-OES method. *Biol Trace Elem Res* 200(5):2486–2497. <https://doi.org/10.1007/s12011-021-02808-w>
- Xie S, Yuan R, Ding WB (2021) Leves and health risk assessment of 10 kinds of metal /metalloid elements in drinking water in Dongcheng District of Beijing from 2018 to 2020. *Journal of Hygiene Research* 50(06):932–937. <https://doi.org/10.19813/j.cnki.weishengyanjiu.2021.06.010>
- Ekosse GI, Nkeng GE, Bukalo N, Oyebanjo O (2021) Geophagic clays from Cameroon: provenance, metal contamination and health risk assessment. *Int J Environ Res Public Health* 18(16):8315. <https://doi.org/10.3390/ijerph18168315>
- Ilechukwu I, Osuji LC, Okoli CP, Onyema MO, Ndukwe GI (2021) Assessment of heavy metal pollution in soils and health risk consequences of human exposure within the vicinity of hot mix asphalt plants in Rivers State Nigeria. *Environ Monit Assess* 193(8):461. <https://doi.org/10.1007/s10661-021-09208-6>
- Menon M, Sarkar B, Hufton J, Reynolds C, Reina SV, Young S (2020) Do arsenic levels in rice pose a health risk to the UK

- population? *Ecotoxicol Environ Saf* 197:110601. <https://doi.org/10.1016/j.ecoenv.2020.110601>
27. USEPA (2005) Guidelines for carcinogen risk assessment, NCEA-F-0644. United States Environmental Protection Agency, Risk Assessment Forum, Washington (DC)
 28. Satpathy D, Reddy MV, Dhal SP (2014) Risk assessment of heavy metals contamination in paddy soil, plants, and grains (*Oryza sativa* L.) at the East Coast of India. *Biomed Res Int* 2014:545473. <https://doi.org/10.1155/2014/545473>
 29. Jiang C, Zhao Q, Zheng L, Chen X, Li C, Ren M (2021) Distribution, source and health risk assessment based on the Monte Carlo method of heavy metals in shallow groundwater in an area affected by mining activities China. *Ecotoxicol Environ Saf* 224:112679. <https://doi.org/10.1016/j.ecoenv.2021.112679>
 30. Guo G, Zhang D, Wang Y (2019) Probabilistic human health risk assessment of heavy metal intake via vegetable consumption around Pb/Zn smelters in Southwest China. *Int J Environ Res Public Health* 16(18):3267. <https://doi.org/10.3390/ijerph16183267>
 31. Yang S, Zhao J, Chang SX, Collins C, Xu J, Liu X (2019) Status assessment and probabilistic health risk modeling of metals accumulation in agriculture soils across China: a synthesis. *Environ Int* 128:165–174. <https://doi.org/10.1016/j.envint.2019.04.044>
 32. Hu W, Wang H, Dong L, Huang B, Borggaard OK, Bruun Hansen HC, He Y, Holm PE (2018) Source identification of heavy metals in peri-urban agricultural soils of southeast China: an integrated approach. *Environ Pollut* 237:650–661. <https://doi.org/10.1016/j.envpol.2018.02.070>
 33. Hull EA, Barajas M, Burkart KA, Fung SR, Jackson BP, Barrett PM, Neumann RB, Olden JD, Gawel JE (2021) Human health risk from consumption of aquatic species in arsenic-contaminated shallow urban lakes. *Sci Total Environ* 770:145318. <https://doi.org/10.1016/j.scitotenv.2021.145318>
 34. Ahmed MF, Lim CK, Mokhtar MB, Khiretdin RPK (2021) Predicting arsenic (As) exposure on human health for better management of drinking water sources. *Int J Environ Res Public Health* 18(15):7997. <https://doi.org/10.3390/ijerph18157997>
 35. Korish MA, Attia YA (2020) Evaluation of heavy metal content in feed, litter, meat, meat products, liver, and table eggs of chickens. *Animals (Basel)* 10(4):727. <https://doi.org/10.3390/ani10040727>
 36. Okoye EA, Bocca B, Ruggieri F, Ezejiofor AN, Nwaogazie IL, Domingo JL, Rovira J, Frazzoli C, Orisakwe OE (2021) Metal pollution of soil, plants, feed and food in the Niger Delta, Nigeria: health risk assessment through meat and fish consumption. *Environ Res* 198:111273. <https://doi.org/10.1016/j.envres.2021.111273>
 37. Nawaz H, Anwar-Ul-Haq M, Akhtar J, Arfan M (2021) Cadmium, chromium, nickel and nitrate accumulation in wheat (*Triticum aestivum* L.) using wastewater irrigation and health risks assessment. *Ecotoxicol Environ Saf* 208:111685. <https://doi.org/10.1016/j.ecoenv.2020.111685>
 38. Román-Ochoa Y, Choque Delgado GT, Tejada TR, Yucra HR, Durand AE, Hamaker BR (2021) Heavy metal contamination and health risk assessment in grains and grain-based processed food in Arequipa region of Peru. *Chemosphere* 274:129792. <https://doi.org/10.1016/j.chemosphere.2021.129792>
 39. Huang CS, Hu GC, Chen MB, Zhang LJ, Qiu RL (2017) Heavy metal content characteristics and risk assessment of household cereal and beans from mining areas. *China Environ Sci* 37(03):1171–1178
 40. Bao YH, Ma XH, Yan SF, Xiao M, Cui MM (2021) Detection and health risk assessment of heavy metal in potato and cultivated soil. *Journal of Food Safety and Quality* 12(23):9149–9156. <https://doi.org/10.19812/j.cnki.jfsq11-5956/ts.2021.23.024>
 41. Luo HX, Li ZM, Wang XW, Li XH, Zhang J (2017) Security analysis of heavy metals residues in solanaceous vegetables in Beijing. *Food Res Dev* 38(06):112–115
 42. Sulaiman FR, Ibrahim NH, Ismail SNS (2020) Heavy metal (As, Cd, and Pb) concentration in selected leafy vegetables from Jengka, Malaysia, and potential health risks. *SN App Sci* 2(8):1430. <https://doi.org/10.1007/s42452-020-03231-x>
 43. Mi B, Liu F, Xie L, Zhou H, Wu F, Dai X (2019) Evaluation of the uptake capacities of heavy metals in Chinese cabbage. *Ecotoxicol Environ Saf* 171:511–517. <https://doi.org/10.1016/j.ecoenv.2019.01.022>
 44. Pan SF, Ji XH, Xie YH, Liu SH, Tian FX, Liu XL (2022) Influence of soil properties on cadmium accumulation in vegetables: thresholds, prediction and pathway models based on big data. *Environ Pollut* 304:119225. <https://doi.org/10.1016/j.envpol.2022.119225>
 45. Prasad M, Aswal RS, Joshi A, Kumar GA, Ramola RC (2022) A systematic study on occurrence, risk estimation and health implications of heavy metals in potable water from different sources of Garhwal Himalaya, India. *Sci Rep* 12(1):20419. <https://doi.org/10.1038/s41598-022-24925-9>
 46. Wongsasuluk P, Chotpanarat S, Siri Wong W, Robson M (2018) Using urine as a biomarker in human exposure risk associated with arsenic and other heavy metals contaminating drinking groundwater in intensively agricultural areas of Thailand. *Environ Geochem Health* 40(1):323–348. <https://doi.org/10.1007/s10653-017-9910-0>
 47. Ahmed MF, Mokhtar MB (2020) Assessing cadmium and chromium concentrations in drinking water to predict health risk in Malaysia. *Int J Environ Res Public Health* 17(8):2966. <https://doi.org/10.3390/ijerph17082966>
 48. Alidadi H, Tavakoly Sany SB, Zarif Garaati Oftadeh B, Mohamad T, Shamszade H, Fakhari M (2019) Health risk assessments of arsenic and toxic heavy metal exposure in drinking water in north-east Iran. *Environ Health Prev Med* 24(1):59. <https://doi.org/10.1186/s12199-019-0812-x>
 49. Yan M, Nie H, Wang W, Huang Y, Wang J (2018) Occurrence and toxicological risk assessment of polycyclic aromatic hydrocarbons and heavy metals in drinking water resources of Southern China. *Int J Environ Res Public Health* 15(7):1422. <https://doi.org/10.3390/ijerph15071422>
 50. Haftu Z, Sathishkumar P (2020) Determination of physicochemical parameters and heavy metals concentration in drinking water at Asgedo Tsimbila district, Tigray, Ethiopia. *Chem Afr* 3:419–426. <https://doi.org/10.1007/s42250-020-00129-4>
 51. Hussain S, Habib-Ur-Rehman M, Khanam T, Sheer A, Kebin Z, Jianjun Y (2019) Health risk assessment of different heavy metals dissolved in drinking water. *Int J Environ Res Public Health* 16(10):1737. <https://doi.org/10.3390/ijerph16101737>
 52. Madilonga RT, Edokpayi JN, Volenzo ET, Durwoju OS, Odiyo JO (2021) Water quality assessment and evaluation of human health risk in Mutangwi River, Limpopo Province, South Africa. *Int J Environ Res Public Health* 18(13):6765. <https://doi.org/10.3390/ijerph18136765>
 53. Ali S, Méité N, Kouyaté A, Irankunda E, Kouamé A, Koffi A, Bohousou K, Kouakou L (2022) Assessing levels and health risks of fluoride and heavy metal contamination in drinking water. *J Geosci Environ Protect* 10:15–34. <https://doi.org/10.4236/gep.2022.1011002>
 54. Barone G, Storelli A, Quaglia NC, Garofalo R, Meleleo D, Busco A, Storelli MM (2021) Trace metals in pork meat products marketed in Italy: occurrence and health risk characterization. *Biol Trace Elem Res* 199(8):2826–2836. <https://doi.org/10.1007/s12011-020-02417-z>
 55. Perelló G, Vicente E, Castell V, Llobet JM, Nadal M, Domingo JL (2015) Dietary intake of trace elements by the population of Catalonia (Spain): results from a total diet study. *Food Addit Contam Part A Chem Anal Control Expo Risk Assess* 32(5):748–755. <https://doi.org/10.1080/19440049.2015.1018844>
 56. Becker W, Jorhem L, Sundström B, Grawé KP (2011) Contents of mineral elements in Swedish market basket diets. *J Food Compos Anal* 24:279–287

57. Dubey VK, Agnihotri MK, Shukla A (2016) Determination of heavy metals in selected meat and meat products from meat market of Singrauli. *J Appl Chem* 9(11):52–54. <https://doi.org/10.9790/5736-0911015254>
58. Ihedioha JN, Okoye CO, Onyechi UA (2014) Health risk assessment of zinc, chromium, and nickel from cow meat consumption in an urban Nigerian population. *Int J Occup Environ Health* 20(4):281–288. <https://doi.org/10.1179/2049396714y.0000000075>
59. Han JL, Pan XD, Chen Q (2022) Distribution and safety assessment of heavy metals in fresh meat from Zhejiang China. *Sci Rep* 12(1):3241. <https://doi.org/10.1038/s41598-022-07214-3>
60. Abd-Elghany SM, Mohammed MA, Abdelkhalek A, Saad FSS, Sallam KI (2020) Health risk assessment of exposure to heavy metals from sheep meat and offal in Kuwait. *J Food Prot* 83(3):503–510. <https://doi.org/10.4315/0362-028x.Jfp-19-265>
61. Raeeszadeh M, Gravandi H, Akbari A (2022) Determination of some heavy metals levels in the meat of animal species (sheep, beef, turkey, and ostrich) and carcinogenic health risk assessment in Kurdistan province in the west of Iran. *Environ Sci Pollut Res Int* 29(41):62248–62258. <https://doi.org/10.1007/s11356-022-19589-x>
62. Ghanati K, Zayeri F, Hosseini H (2019) Potential health risk assessment of different heavy metals in wheat products. *Iran J Pharm Res* 18(4):2093–2100. <https://doi.org/10.22037/ijpr.2019.1100865>
63. Bielecka J, Markiewicz-Żukowska R, Puścion-Jakubik A, Grabia M, Nowakowski P, Soroczyńska J, Socha K (2022) Gluten-free cereals and pseudocereals as a potential source of exposure to toxic elements among Polish residents. *Nutrients* 14(11):2342. <https://doi.org/10.3390/nu14112342>
64. Orisakwe OE, Mbagwu HO, Ajaezi GC, Edet UW, Uwana PU (2015) Heavy metals in seafood and farm produce from Uyo, Nigeria: levels and health implications. *Sultan Qaboos Univ Med J* 15(2):e275–282
65. Liu MW, Yang HH, Zhao YP, Hui QF, Guo X, Wei MM (2019) The heavy metal contamination in 8 types of food in Weinan City from 2013 to 2017. *J Hyg Res* 48(1):136–139. <https://doi.org/10.19813/j.cnki.weishengyanjiu.2019.01.019>
66. Zulkafflee NS, Mohd Redzuan NA, Nematbakhsh S, Selamat J, Ismail MR, Praveena SM, Yee Lee S, Abdull Razis AF (2022) Heavy metal contamination in *Oryza sativa* L. at the eastern region of Malaysia and its risk assessment. *Int J Environ Res Public Health* 19(2):739. <https://doi.org/10.3390/ijerph19020739>
67. Bazié BSR, Compaoré MKA, Bandé M, Kpoda SD, Méda NR, Kangambega TMO, Iboudo I, Sandwidi BY, Nikiema F, Yakoro A, Bassolé IHN, Hien H, Kabré E (2022) Evaluation of metallic trace elements contents in some major raw foodstuffs in Burkina Faso and health risk assessment. *Sci Rep* 12(1):4460. <https://doi.org/10.1038/s41598-022-08470-z>
68. Rahman M, Islam MA (2019) Concentrations and health risk assessment of trace elements in cereals, fruits, and vegetables of Bangladesh. *Biol Trace Elem Res* 191(1):243–253. <https://doi.org/10.1007/s12011-018-1596-3>
69. Qi H, Zhuang J, Zhuang Z, Wang Q, Wan YN, Li HF (2022) Enrichment characteristics of heavy metals and health risk in different vegetables. *Environ Sci:1-12*. <https://doi.org/10.13227/j.hjcx.202207036>
70. Stančić Z, Vujević D, Gomaz A, Bogdan S, Vinček D (2016) Detection of heavy metals in common vegetables at Varaždin City Market Croatia. *Arh Hig Rada Toksikol* 67(4):340–350. <https://doi.org/10.1515/aiht-2016-67-2823>
71. Din AU, Abdel-Reheem MAT, Ullah H, Ahmad I, Waseem A, Ullah R, Shah AUHA (2013) Assessment of heavy metals in onion and potato in imported and local variety of Pakistan and Afghanistan. *Life Sci J* 10:198–204
72. Zhou H, Yang WT, Zhou X, Liu L, Gu JF, Wang WL, Zou JL, Tian T, Peng PQ, Liao BH (2016) Accumulation of heavy metals in vegetable species planted in contaminated soils and the health risk assessment. *Int J Environ Res Public Health* 13(3):289. <https://doi.org/10.3390/ijerph13030289>
73. Jafarian-Dehkordi A, Alehashem M (2013) Heavy metal contamination of vegetables in Isfahan. *Iran. Res Pharm Sci* 8(1):51–58
74. Lizarazo MF, Herrera CD, Celis CA, Pombo LM, Teherán AA, Piñeros LG, Forero SP, Velandia JR, Díaz FE, Andrade WA, Rodríguez OE (2020) Contamination of staple crops by heavy metals in Sibate. *Colombia. Heliyon* 6(7):e04212. <https://doi.org/10.1016/j.heliyon.2020.e04212>
75. Sonu K, Chandra Yadav I, Kumar A, Devi NL (2019) Dataset on assessment of heavy metals contamination in multi-environmental samples from Patna. *India. Data Brief* 25:104079. <https://doi.org/10.1016/j.dib.2019.104079>
76. Bayissa LD, Gebeyehu HR (2021) Vegetables contamination by heavy metals and associated health risk to the population in Koka area of central Ethiopia. *PLoS One* 16(7):e0254236. <https://doi.org/10.1371/journal.pone.0254236>
77. Amer MM, Sabry BA, Marrez DA, Hathout AS, Fouzy ASM (2019) Exposure assessment of heavy metal residues in some Egyptian fruits. *Toxicol Rep* 6:538–543. <https://doi.org/10.1016/j.toxrep.2019.06.007>
78. Mawari G, Kumar N, Sarkar S, Daga MK, Singh MM, Joshi TK, Khan NA (2022) Heavy metal accumulation in fruits and vegetables and human health risk assessment: findings from Maharashtra India. *Environ Health Insights* 16:11786302221119152. <https://doi.org/10.1177/11786302221119151>
79. Cherfi A, Cherfi M, Maache-Rezzoug Z, Rezzoug SA (2016) Risk assessment of heavy metals via consumption of vegetables collected from different supermarkets in La Rochelle France. *Environ Monit Assess* 188(3):136. <https://doi.org/10.1007/s10661-016-5140-7>
80. Afrin S, Alam MK, Ahmed MW, Parven A, Jubayer MF, Megharaj M, Meftaul IM, Khan MSI (2022) Determination and probabilistic health risk assessment of heavy metals in widely consumed market basket fruits from Dhaka city Bangladesh. *International J Environ Anal Chem* 5(1):1–16. <https://doi.org/10.1080/03067319.2021.2018578>
81. Rusin M, Domagalska J, Rogala D, Razzaghi M, Szymala I (2021) Concentration of cadmium and lead in vegetables and fruits. *Sci Rep* 11(1):11913. <https://doi.org/10.1038/s41598-021-91554-z>
82. Nie RR, Gu MH, Dong WJ, He WB, He GZ, Shen J, Dai JB, Li HH, Cai ZT (2021) Metallic element analysis and dietary risk assessment of Meizhou golden pomelo. *Journal of Food Safety and Quality* 12(12):4742–4749. <https://doi.org/10.19812/j.cnki.jfsq11-5956/ts.2021.12.006>
83. Society CN (2022) Dietary guidelines for Chinese resident: 2022. People's Health Publishing House, Beijing
84. USEPA (US Environmental Protection Agency) (2002) Supplemental guidance for developing soil screening levels for superfund sites. Office of emergency and remedial response, Washington
85. Zhang XH, Zhao Q, Lu XL (2021) The exposure and risk assessment of lead, cadmium and arsenic in cereals and vegetables in Binzhou City. *Chinese J Health Lab Sci* 31(07):877–879+883
86. Xu MH, Zhu M, Zhou FQ, You YD, Ran MQ, Jiao YZ (2021) Lead and cadmium pollutions and health risk assessment of commercial beans from Guizhou province. *Food Ind* 42(12):484–487
87. Yang L, Ye B, Han H, Li S, Yuan P, Fu PY, Yuan P, Zhang SF (2022) Monitoring and exposure risk assessment of lead pollution in commercially cereal and tuber products in Henan, 2015–2019. *Mod Prev Med* 49(01):37–40+52
88. Liang Y, Yi X, Dang Z, Wang Q, Luo H, Tang J (2017) Heavy metal contamination and health risk assessment in the vicinity of a tailing pond in Guangdong, China. *Int J Environ Res Public Health* 14(12):1557. <https://doi.org/10.3390/ijerph14121557>

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