Accumulation characteristics and evaluation of heavy metals in soils and vegetables of plastic-covered sheds in typical red soil areas of China

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RESEARCH ARTICLE

Abstract

The degree of pollution and potential ecological risk of heavy metals (HMs) in the soil of plastic-covered sheds in Jiangxi Province were evaluated by the Nemerow index and potential ecological risk index. The bioconcentration factor and total target hazard quotient (TTHQ) were used to evaluate the enrichment ability and health risk of HMs in vegetables. The mean contents of arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg) and lead (Pb) in soil were 5.99, 0.373, 17.8, 5.94E-02, and 28.9 mg kg^{-1}, respectively; Cd exceeded the background value and the maximum limit. Most soils had no extremely strong ecological risk. The concentration of Pb in root vegetables was 0.204 mg kg^{-1}, with the highest concentration of Cd (0.147 mg kg^{-1}) in Ganzhou leafy vegetables. The Hg concentration of leafy vegetables in Jiujiang was 1.41E-02 mg kg^{-1}, which exceeded the maximum limit. The bioconcentration factor of HMs was negatively correlated with pH ($P \leq 0.05$). The migration ability of Cd in root vegetables was 1.7-fold to that of leafy vegetables, and was strongest. The TTHQ of all vegetables was less than 1.0, which indicated that there was no significant noncarcinogenic risk in adults. The TTHQ of root vegetables was highest, with Pb in vegetables being major health risk factors. In conclusion, fruit and solanaceous vegetables may be more suitable for planting in plastic-covered shed than root and leafy vegetables; Cd and Pb were identified as the priority control metals under plastic-covered sheds in Jiangxi Province.

Keywords: plastic-covered shed; red soil; vegetable; heavy metal accumulation; evaluation

Introduction

Vegetables are rich in nutrients and are one of the main sources of food for humans (Wang *et al.*, 2022). Heavy metals (HMs) in vegetables can accumulate in the body through food, which leads to diseased attributes. HMs do not degrade naturally; therefore, they accumulate in the soil and may cause potential risks (Tariq *et al.*, 2019). In recent years, HM pollution of agricultural products has increased rapidly due to human activities and related factors (Wang *et al.*, 2021; Wen *et al.*, 2020). Researchers are seriously concerned about HM pollution in the soil and vegetables. HM pollution in vegetables has been frequently reported globally, with arsenic (As), cadmium (Cd), chromium (Cr) and lead (Pb) often exceeding maximum limits. A high content of HMs in the soil and vegetables is a possible threat to human health (Tariq, 2021). Mercury (Hg), Cd, Pb, Cr and copper (Cu) have led to

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pollution in vegetables, HMs in vegetables exceed the critical levels, and there are obvious health risks (Cheshmazar *et al.*, 2018; Gupta *et al.*, 2021; Hossain *et al.*, 2021; Ji *et al.*, 2018; Liu *et al.*, 2021; Quispe, 2021; Tomno *et al.*, 2020). Cd is a ubiquitous and predominant pollutant in vegetables, and vegetable intake health risks are unacceptable (Su *et al.*, 2023). Vegetables pose a noncarcinogenic health risk because of HMs (Sadee and Rasul, 2022).

China's vegetable production and consumption is huge, and plastic-covered sheds have developed rapidly in south China. Although plastic-covered sheds can increase vegetable supply, they can cause the risk of environmental pollution. Plastic is composed of various types of polymers (Yuan *et al.*, 2022). These are hard to degrade and can form particles by physical and biological processes (O'Kelly *et al.*, 2021). They are carriers for organic pollutants and HMs (Bhagat *et al.*, 2021). They affect the biophysical properties of the soil (Yang *et al.*, 2021) and harm soil organisms, and animal growth, development, and reproduction. HMs and plastics in the soil negatively affect soil quality and show synergistic or antagonistic effects (Kumar, *et al.*, 2022). At the same time, multiple cropping and excess chemical fertilization have led to pollution problems (Chen *et al.*, 2021; Huang *et al.*, 2018; Kianpoor Kalkhajeh *et al.*, 2020), and HM pollution in the soil and vegetables is very serious in China (Hu *et al.*, 2017). Concentrations of Cd and Pb being 72.4% and 35.5%, respectively, in the soil samples have exceeded maximum limits in northern China (Fan *et al.*, 2017). Cd, Cu and zinc (Zn) were more than background values in Hebei Province, northern China (Meng *et al.*, 2021). Cd content in some soil samples was more than the limits, with the maximum values being 3.77-fold higher than the limits in northwest China (Chen *et al.*, 2021). Cr and Pb exceeded 1.86–2.63-fold higher than the limits of Chinese and World Health Organization (WHO)/Food and Agriculture Organization (FAO) in southwest China (Wang *et al.*, 2022). Liu *et al.* (2021) studied the accumulation of eight HMs in plastic-covered shed soils and vegetables across Chinese provinces (except Jiangxi Province) and confirmed that HM accumulation is a serious question. Soil acidity in plastic-covered sheds is significant (Bai *et al.*, 2020), and acidic soil promotes the enrichment of HMs (Meng *et al.*, 2021).

A large number of studies have been carried out on HM pollution in the soil and vegetables. Fan *et al.* (2017) used the bioconcentration factor (BCF) and total target hazard quotient (TTHQ) to evaluate HM pollution in greenhouse vegetables in north China and found that the transport coefficients of As, Cr and Pb were higher in leafy and fruit vegetables than in tuber vegetables. The accumulation of HMs under greenhouse conditions could cause risk to human health through fruit and leafy vegetables. Sawut *et al.* (2018) used the Nemerow integrated pollution index to evaluate HM pollution in greenhouse soil in northwest China and used the TTHQ to evaluate the noncarcinogenic risk assessment of vegetables. The results showed that Cd and Hg were the primary pollutants, and the noncarcinogenic risk for adults was low. By collecting data, Meng *et al.* (2021) evaluated the soil and vegetables in Chinese greenhouses using transfer factor and target hazard quotient (THQ), and found that the relatively high transfer factor and hazard index values of Cd in spinach should be considered. Gupta *et al.* (2019) evaluated BCF and health risk of the soil and vegetables in northern India. The results showed that HM transport coefficient of leafy vegetable was higher than fruit vegetable, the TTHQ for Pb, manganese (MN), and Cd was more than 1 because of the consumption of fenugreek and spinach, and the THQ for all investigated metals was less than unity because of the consumption of eggplant and chilli. Jalali and Meyari (2022) evaluated the transfer factor and health risk of soil and vegetables in west Iran. The transfer factor values of the studied HMs were ordered based on the mean values: Cd > Zn > Pb > Cu > Mn > nickel (Ni) > iron (Fe), and the health risk index (RI) values for adults were less than 1, except for Cd and Pb. Birghila *et al.* (2023) evaluated the transfer factor and health risk of the soil and tomato in southeastern Romania. The BCF was less than 1, indicating that tomato did not accumulate HMs. The THQ and hazard index value were below the acceptable level. Laboni *et al.* (2023) evaluated vegetables grown in the industrial areas of Bangladesh, and found THQ < 1.0, indicating that it had no noncarcinogenic risk. The soil–vegetable system of historical wastewater irrigation in Kaifeng City, central China, was evaluated by the Nemerow integrated pollution index, BCF and heath risk assessment. The Nemerow pollution index of Cd was highest, and most soil samples were slightly or moderately polluted by HMs. The transfer factor of Cd was highest, and risk assessment revealed that local vegetable consumers suffered health risks (Ruan *et al.*, 2023). Many studies evaluated the soil pollution status by using the geoaccumulation index (Liu *et al.* 2021; Meng *et al.* 2021; Su *et al.* 2023). It is a quantitative indicator to study HMs in the sediments of water environments based on the relationship between total concentration of HMs and background value.

With increasing awareness of human health, increasing attention has been given to HM pollution of plastic-covered shed vegetables. Thus, to protect the dietary safety and health of residents, it is essential to study the accumulation and potential risk of HMs in the soil and vegetables under plastic-covered sheds.

Jiangxi is located in southeastern China and is a typical red soil area. Owing to climate differences, hothouses are mainly plastic-covered sheds, and red soil is characterized by strong acidity and biological enrichment.

No relevant studies have been reported about the soil and vegetables under plastic-covered sheds in Jiangxi. To provide a reference for the development of plastic-covered shed vegetables in Jiangxi Province and ensure vegetable consumption security, the pollution index, health risk, and probabilistic risk assessment were investigated.

The aims of this research were as follows: (1) to determine the content of HMs (Cd, Pb, Cr, As, Hg) in the soil and vegetables, evaluate the soil pollution degree by the Nemerow index and potential ecological RI, and study the HM safety status of planting soil; (2) to investigate the HM enrichment capacity of vegetables by BCF to explore differences in HM accumulation in different vegetables. We explored the relationship between pH in red soil and HM accumulation in vegetables under plastic-covered sheds to study the effect of red soil on HMs in vegetables; (3) we estimated the health risk of plastic-covered shed vegetables in adults and confirmed the safety of plastic-covered shed vegetables for consumption. This work would be useful for providing supervision and management for plastic-covered shed vegetable production and decreasing human health risks.

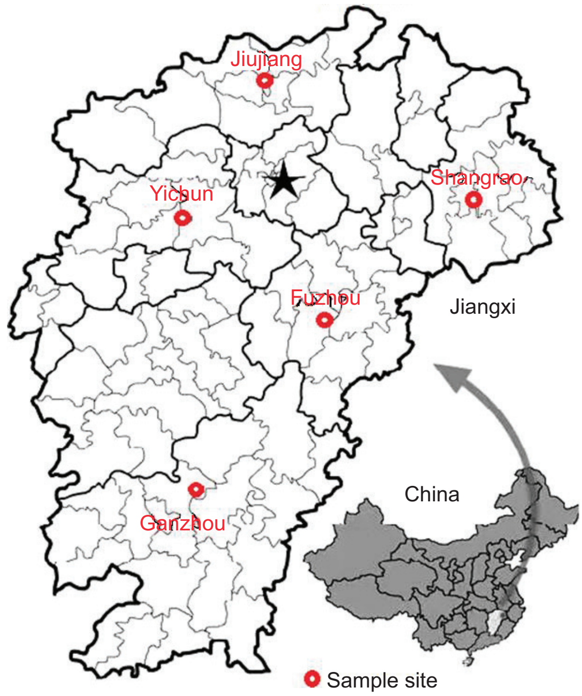

Figure 1. Distribution of sampling locations in the study areas.

Materials and Methods

Study area

Jiangxi Province is located in southeastern China, bounded between 113°34'36"–118°28'58" E and 24°29'14"–30°04' 41" N. In recent years, Jiangxi has made great efforts to speed up the development of vegetable bases and has become the main production base for vegetables in China's southeast coastal region. The study area included parts of Jiujiang city, Shangrao city, Fuzhou city, Yichun city and Ganzhou city in Jiangxi Province (Figure 1). Jiujiang is located in northern, Shangrao city in northeastern, Fuzhou city in western, and Ganzhou city in southern Jiangxi Province.

Sample collection

In all, 52 soil (surface 0–20 cm) and 119 vegetable samples were collected from plastic-covered sheds in mentioned five cities of Jiangxi Province. The sample quantity distribution is shown in Tables 1 and 2. A representative sample was collected from each site with five soil and vegetable subsamples.

Sample analysis

Soil samples were dried at room temperature, finely ground, and passed through a 10-mesh sieve. A portion of soil that was passed through a 100-mesh sieve was used to determine the concentrations of HMs. Distilled water was used to wash vegetable samples, and vegetable samples were dried at room temperature. To determine the concentrations of HMs, samples (0.1 g) were digested with microwave digestion apparatus (CEM mars6, USA), soil samples were digested with HNO_3-H_2O_2-HF (guaranteed reagent [GR]), and vegetable samples were digested with HNO_3-H_2O_2 (GR) (Chen *et al.*, 2021; Wang *et al.*, 2022). Temperature rise program: 120°C, kept for 3 min, 150°C, kept for 3 min, 190°C, kept for 30 min, and heating at 105°C until the remaining 1 mL. The concentration of HMs was determined by ICP–MS (NexION2000, PerkinElmer, USA). The operating parameters of ICP-MS were as follows: argon as a carrier gas, methane as a reaction gas (purity >99.999%), flow rate of 0.1–1.0 mL/min, step length of 0.1 mL/min, RPq value of 0.45–0.80, RF power 400–1,600 W, lens voltage 6.25 V, analog stage voltage -3,000 V, and pulse stage voltage 2,500 V. Dynamic reaction cell (DRC) operating parameters were as follows: mode CPV-21V, mode QRO-6.5V, and mode CRO-1V. The soil pH was determined at a soil–water ratio of 1:2.5 using a pH meter (s470k, Mettler Toledo, China). Quality control was ensured with the use of reagent blanks and certified reference materials (GBW07405 [GSS-5]) for soil, spinach (GBW10015 [GSB-6] for vegetables), and certified reference materials produced by the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences. Each sample was determined from three replicates of parallel experiments, and the mean value was the final determination.

Table 1. Soil properties, concentrations of HMs and background values in various regions.

HMs	As (mg kg^{-1})	Cd (mg kg^{-1})	Cr (mg kg^{-1})	Hg (mg kg^{-1})	Pb (mg kg^{-1})	pH
Jiujiang city						
Mean (n = 10)	7.03	0.502	17.0	3.01E-02	45.3	6.33
Range	2.19–11.1	8.93E-02–2.73	8.44–27.4	2.03E-03–758E-02	12.4–161	4.30–6.85
Standard deviation	2.56	0.790	5.63	2.71E-02	46.5	0.83
Coefficient of variation (CV), %	36.0	158	33.0	91.0	103	13.2
Shangrao city						
Mean (n = 15)	6.56	0.221	15.0	0.0480	24.7	6.33
Range	2.90–14.6	4.21E-02–0.537	7.93–21.7	1.46E-03–0.191	14.2–38.7	4.43–7.27
Standard deviation	2.98	0.124	4.62	0.0631	8.56	0.91
Coefficient of variation (CV), %	45.1	56.2	31.0	191.0	35.3	14.4
Fuzhou city						
Mean (n = 10)	3.43	0.173	15.9	0.0912	27.9	6.33
Range	2.10–4.93	4.58E-02–0.392	9.54–26.5	2.11E-03–0.351	16.0–48.6	4.63–6.28
Standard deviation	1.00	0.114	4.67	0.121	9.43	0.64
Coefficient of variation (CV), %	29.4	66.2	28.9	133	33.7	10.1
Yichun city						
Mean (n = 11)	7.65	0.299	26.7	0.0392	21.4	6.33
Range	2.93–13.1	3.59E-02–0.719	20.2–32.1	2.13E-03–0.120	15.8–27.1	5.17–6.87
Standard deviation	2.95	0.220	3.82	4.73E-02	3.71	0.58
Coefficient of variation (CV), %	38.7	73.2	14.3	120	17.4	9.10
Ganzhou city						
Mean (n = 9)	4.07	0.178	12.8	0.116	27.2	6.33
Range	3.00–6.45	8.17E-02–0.282	8.10–22.7	3.17E-03–0.276	20.3–37.7	4.75–6.62
Standard deviation	1.32	8.67E-02	5.55	0.114	6.45	0.72
Coefficient of variation (CV), %	32.4	48.6	43.2	97.6	24.5	11.4
Jiangxi province						
Mean	5.99	0.373	17.8	5.94E-02	28.9	6.33
Range	2.10–14.6	3.63E-02–1.73	7.93–32.1	6.28E-03–0.276	12.4–160	4.30–7.27
Standard deviation	2.88	0.254	6.64	7.33E-02	22.2	0.762
Coefficient of variation (CV), %	47.9	98.7	37.1	130	77.0	12.0
Limit level	30	0.3	150	0.25	50	
Background values	10.4	0.1	48.0	0.08	32.1	

Data analysis

Nerome index evaluation

Evaluation of the soil was carried out according to the evaluation parameters and calculation methods of the Chinese environmental standard (HJ 333-2006) (China National Environmental Protection Agency [CNEPA], 2006). The pollution index of the soil was calculated using Equations 1 and 2:

$$P_i = \frac{C_s}{C_m}, \quad (1)$$

$$P_c = \sqrt{\frac{\overline{P_i}^2 + P_{max}^2}{2}}, \quad (2)$$

where P_i is the single factor index, Cs is the measured value of HM, and Cm is the maximum limit of HJ 333-2006; P_c is the comprehensive pollution index, $\overline{P_i}$ is the average of the single factor index, and P_{max} is the maximum of single factor index. According to HJ 333-2006, both P_i and P_c are classified into three levels: $P_c \leq 0.7$ as safe; $0.7 < P_c \leq 1.0$ as clean; $1.0 < P_c \leq 2.0$ as slightly polluted; $2.0 < P_c \leq 3.0$ as moderately polluted; and $P_c > 3.0$ as heavily polluted (Li *et al.*, 2018).

Table 2. Analysis results of heavy metal contents in various vegetables (mg kg^{-1}).

Vegetable type		As	Cd	Cr	Hg	Pb
Leafy vegetables	Mean (n = 39)	2.74E-02	4.73E-02	0.177	1.46E-03	0.122
	Range	2.08E-03–0.126	4.06E-03–0.186	2.02E-02–1.36	3.05E-06–0.004	0.018–0.431
	Mean of Jiujiang	3.72E-02	4.84E-02	0.216	1.41E-02	6.68E-02
	Mean of Shangrao	2.49E-02	3.32E-02	0.264	1.37E-03	8.83E-02
	Mean of Fuzhou	1.01E-02	3.43E-02	4.69E-02	1.28E-03	4.41E-02
	Mean of Yichun	1.63E-02	5.10E-02	7.86E-02	5.63E-04	0.156
	Mean of Ganzhou	9.22E-02	0.147	0.227	4.38E-03	0.296
Fruit vegetables	Mean (n = 33)	4.87E-03	8.61 E-03	4.77E-02	1.04E-04	5.11E-02
	Range	3.01 E-05–1.65E-02	6.85 E-04–3.88E-02	9.26 E-03–0.391	3.03 E-06–8.02 E-04	9.22 E-03–0.152
	Mean of Jiujiang	5.27E-03	6.47E-03	1.33E-02	6.23E-02	0.115
	Mean of Shangrao	4.36E-03	6.18E-03	7.64E-02	1.03E-04	4.87E-02
	Mean of Fuzhou	5.11E-03	4.25E-03	2.09E-02	1.21E-04	2.91E-02
	Mean of Yichun	7.04E-03	2.87E-02	5.01E-02	3.05E-06	0.101
	Mean of Ganzhou	6.25E-03	1.61E-02	6.48E-02	1.52E-04	7.73E-02
Solanaceo-us vegetables	Mean (n = 22)	6.64 E-03	2.53E-02	7.41E-02	9.05E-05	0.183
	Range	8.93 E-04–3.79E-02	4.65 E-03–6.73E-02	8.94 E-03–0.286	3.02 E-06–2.94 E-04	7.48 E-03–2.45
	Mean of Jiujiang	8.17E-03	3.33E-02	2.80E-02	2.03E-04	3.66E-02
	Mean of Shangrao	4.46E-03	2.01E-02	0.132	8.26E-05	8.48E-02
	Mean of Fuzhou	2.25E-03	1.32E-02	2.41E-02	3.65E-5	2.21E-02
	Mean of Yichun	1.32E-02	3.07E-02	8.84E-02	6.71E-5	0.106
	Mean of Ganzhou	9.05E-03	3.61E-02	5.03E-02	6.34E-5	0.425
Root vegetables	Mean (n = 5)	1.61E-02	3.94E-02	0.133	1.32E-03	0.204
	Range	1.80 E-03–5.70E-02	3.85 E-03–9.65E-02	2.51 E-02–0.340	3.04 E-05–6.10 E-03	2.91 E-02–0.330
	Mean of Jiujiang	-	-	-	-	-
	Mean of Shangrao	3.06E-03	8.05E-03	0.183	1.12E-04	5.85E-02
	Mean of Fuzhou	-	-	-	-	-
	Mean of Yichun	3.24E-02	8.32E-02	0.119	3.05E-03	0.287
	Mean of Ganzhou	1.19E-02	1.44E-02	6.17E-02	1.22E-04	0.330
Limit levels		0.5	0.05 (leafy vegetables 0.2; root vegetable 0.1)	0.5	0.01	0.1 (leafy vegetables 0.3)

Potential ecological risk index

The potential ecological RI of the soil can reflect the content, sensitivity and toxicity of HMs in the soil environment according to the nature and behavioral characteristics of HMs in the soil. The RI of the soil was calculated as follows:

$$E_i = T_i \times \frac{C_s}{C_n}, \tag{3}$$

$$RI = E_{As} + E_{Cd} + E_{Cr} + E_{Hg} + E_{Pb}, \tag{4}$$

where T_i is the standard HM toxicity coefficient (Hakanson, 1980), As = 10, Cd = 30, Cr = 2, Hg = 40 and Pb = 5; C_s is the measured value of a HM; C_n is the background value of HM. Referring to Hakanson's (1980) division criteria for HMs, E_i is the potential ecological RI of a single HM, $E_i \leq 40$ indicates a slight ecological risk, $40 < E_i \leq 80$ indicates a moderate ecological risk, $80 < E_i \leq 160$ indicates a strong ecological risk, $160 < E_i \leq 320$ indicates a very strong ecological risk, and $E_i > 320$ indicates an extremely strong ecological risk. The RI is the sum of the potential ecological risk indices of various HMs, and RI ≤ 150 represents a slight ecological risk, 150 < RI ≤ 300 indicates a moderate ecological risk, 300 < RI ≤ 600 indicates a strong ecological risk, and RI > 600 indicates an extremely strong ecological risk (Gong *et al.*, 2016; Wei *et al.*, 2023).

Bioconcentration factor

The BCF is used to describe the transfer or mobility of metals from the soil to vegetables (Tariq, 2021; Zunaidi *et al.*, 2023) and was calculated as shown in Equation 5,

$$BCF = \frac{R_v}{R'_s} \quad (5)$$

where BCF is the bioconcentration factor, R_V is the concentration of HMs in the edible part of vegetable, and R_S is the concentration of HMs in the soil.

Health risk assessment

Health risks are measured by calculating chronic daily intake (CDI), THQ and TTHQ for HMs. Equations 6–8 were used to calculate THQ and TTHQ values:

$$CDI = \frac{EF \times ED \times FIR \times C}{BW \times TA}, \quad (6)$$

$$THQ = \frac{CDI}{RfD \text{ or } TDI}, \quad (7)$$

$$TTHQ = THQ_{As} + THQ_{Cd} + THQ_{Cr} + THQ_{Hg} + THQ_{Pb}, \quad (8)$$

where FIR is the daily vegetable consumption, which is assumed to be 0.345 kg d^{-1} $person^{-1}$; EF is the rate of exposure (365 d $year^{-1}$); and ED is the period of exposure (74.68 years); BW is the mean body weight of an adult (60 kg); TA is the average duration of exposure to HMs, which is assumed to be 365 days $year^{-1}$×74.68 years (CNEPA, 2013); *C* is the content of HMs in vegetables; RfD is the reference daily allowed dose of HMs, and the RfDs of As, Cd, Cr, and Hg are 0.0003, 0.001, 1.5, 0.0003 mg kg^{-1} d^{-1}, respectively (Chen *et al.*, 2021; Sawut *et al.*, 2018). Tolerable daily intake (TDI) is only applied in the THQ formula for Pb (0.0036 mg kg^{-1} d^{-1}) (Mohammadpour *et al.*, 2022a). TTHQ is the sum of THQs of various HMs. THQ <1 or TTHQ < 1 indicate no severe health risk from HM exposure, while values greater than or equal to 1 suggest adverse health effects of HMs (Chen *et al.*, 2021; Machate, 2023).

Statistical analysis

SPSS 17.0 was used to process raw data and perform statistical analyses of survey results, such as minimum, maximum, mean, standard deviation, analysis of variance and correlation. Pearson correlation analysis was used to evaluate the relationship. A two-tailed $P \leq 0.05$ was considered statistically significant. Oracle Crystal Ball V11 was used to process the Monte Carlo simulation (Mohammadpour *et al.*, 2022a, 2022b). Part of the figure was drawn by OriginPro 8.

Results and Discussion

Concentrations and distributions of HMs in soils

The plastic-covered shed soil properties and HM concentrations are shown in Table 1. The respective mean contents of As, Cd, Cr, Hg and Pb in different cities were as follows: Jiujiang city—7.03, 0.502, 17.0, 0.03.1 and 45.3 mg kg^{-1}; Shangrao city—6.56, 0.221, 15.0, 0.0480 and 24.7 mg kg^{-1}; Fuzhou city—3.43, 0.173, 15.9, 0.0912 and 27.9 mg kg^{-1}; Yichun city—7.65, 0.299, 26.7, 0.0392 and 21.4 mg kg^{-1}; and Ganzhou city—4.07, 0.178, 12.8, 0.116 and 27.2 mg kg^{-1}. Based on the data for each of the mentioned cities, the mean contents of As, Cd, Cr, Hg and Pb in Jiangxi Province were 5.99, 0.373, 17.8, 0.0594 and 28.9 mg kg^{-1}, respectively. The average pH of the soil in the five cities was 6.33, which was acidic, and only a few soil samples in Shangrao city were alkaline. The mean concentration of As in the soil of Yichun city was highest, but it was lower than both background value (10.4 mg kg^{-1}) for Jiangxi Province and maximum limit (30 mg kg^{-1}) in the environmental criteria for Chinese greenhouse soil (CNEPA, 2006). The mean Cd concentration in the soil of Jiujiang city was highest, and the mean Cd concentration of all soil samples exceeded both background value (0.1 mg kg^{-1}) and maximum limit (0.3 mg kg^{-1}). This means that Cd pollution is serious. The mean Cr concentration in the soil of Yichun city was highest, but it was lower than both background value and maximum limit. The Hg mean concentration in the soil of Ganzhou city was highest, and it was higher than the background value but lower than the maximum limit. The Pb mean concentration in the soil of Jiujiang city was highest, exceeded the background value but lower than the maximum limit. Among the mean contents of HMs in Jiangxi Province, only Cd and Hg exceeded the background value but only Cd exceeded the maximum limit; other HMs were lower than the background value and maximum limit. The factors influencing accumulation of HM are mainly human activity (such as excessive application of chemical fertilizers, manures and fungicides) and soil properties (Meng *et al.*, 2021; Wang *et al.*, 2022). The mean contents of Cd, As, Hg and Cr were lower than those reported by Liu *et al.* (2021), while the mean Pb content remained the same. The mean Cd content was higher than that in northwestern China (Chen *et al.*, 2021) and northern China (Meng *et al.*, 2021). Studies conducted by Ji *et al.* (2018) and Su *et al.* (2023) reported that Cd was a ubiquitous and predominant pollutant in the soils of southern China, which agreed with the results of this study.

Evaluation of pollution degree and potential ecological risk hazards of soil

The pollution degree of the soil was evaluated by Equations 1 and 2, as shown in Figures 2 and 3. The respective mean single factor index of As, Cd, Cr, Hg,

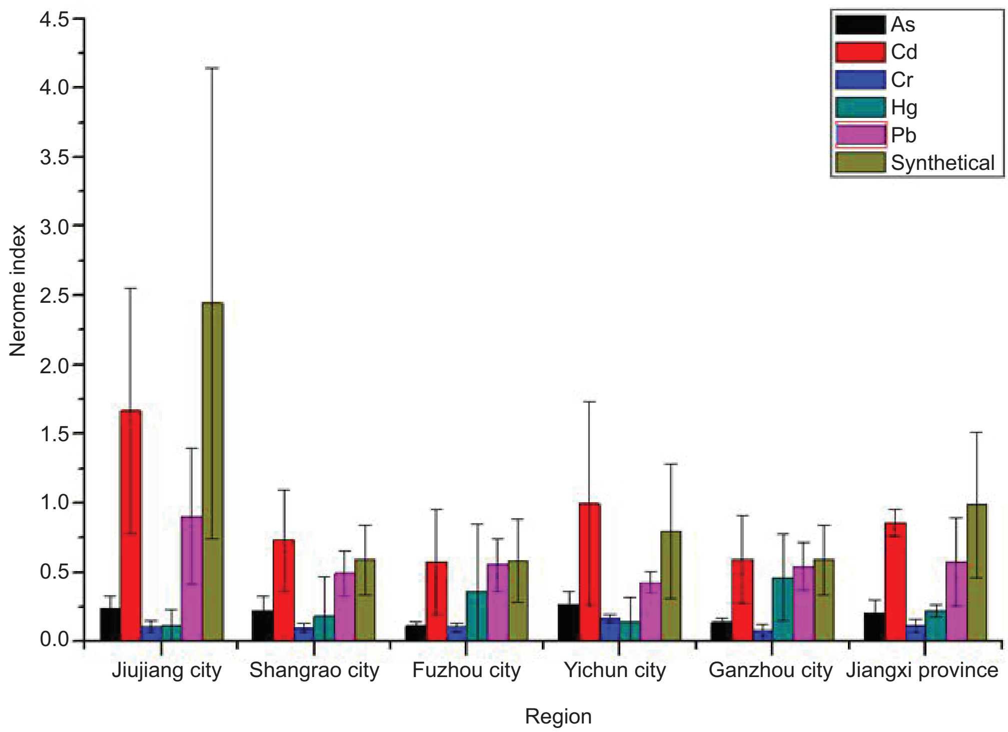

Figure 2. Evaluation results of HMs in the soils in different regions based on the Nerome index.

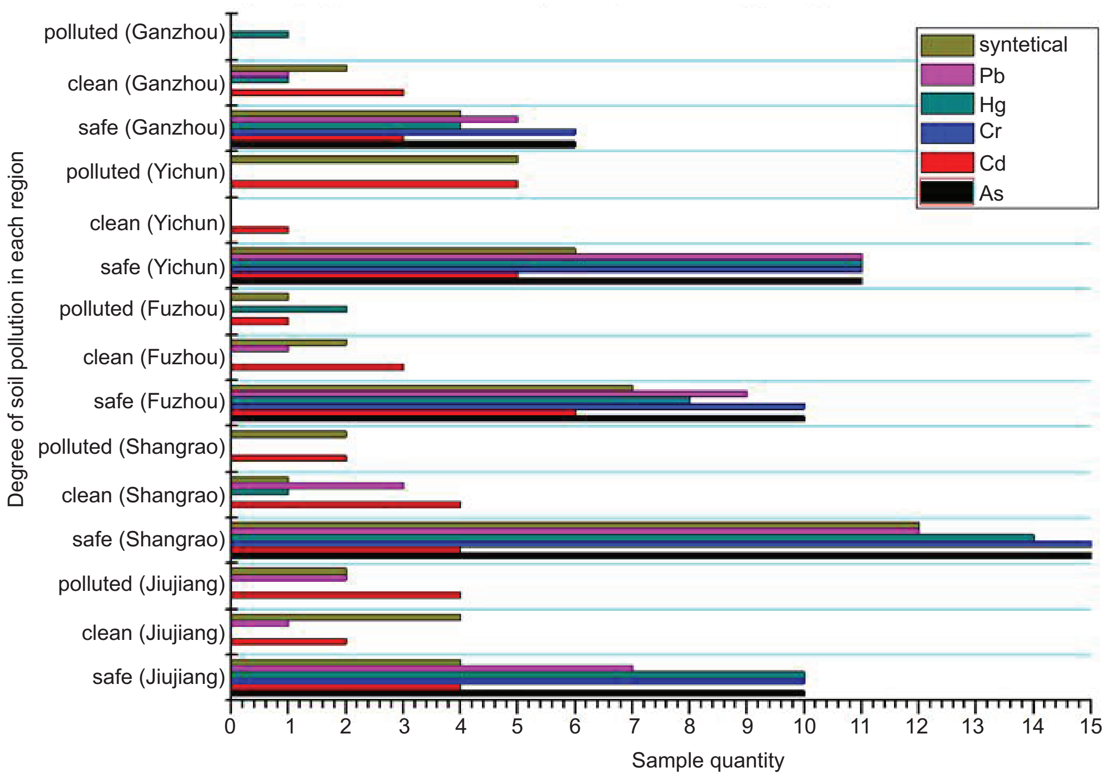

Figure 3. Diagram showing the proportion in the soil sample compared to the regional pollution.

Pb and synthetic factor index in different cities were as follows: Jiujiang city—0.243, 1.667, 0.109, 0.119, 0.906 and 2.443; Shangrao city—0.224, 0.735, 0.096, 0.185, 0.494 and 0.59; Fuzhou city—0.114, 0.576, 0.106, 0.365, 0.558 and 0.585; Yichun city—0.267, 0.998, 0.166, 0.144, 0.428 and 0.796; and Ganzhou city—0.139, 0.594, 0.083, 0.465, 0.545 and 0.593. Based on the data for each city, the mean single factor index of As Cd Cr Hg Pb and the synthetic factor index in Jiangxi Province were 0.206, 0.859, 0.114, 0.223, 0.578 and 0.988, respectively. The soil single factor indexes of As, Cr, and Hg were less than 0.7 in all cities, which indicated that they were in safe levels. The single factor index of Cd in Jiujiang city was more than 1 but less than 2, which indicated that the soil was slightly polluted. The single factor index of Cd in Yichun and Shangrao cities was more than 0.7 but less than 1, which indicated that the soil was clean, and Cd was in safe levels in Fuzhou and Ganzhou. The single factor index of Pb in Jiujiang city was more than 0.7 but less than 1, which indicated that the soil was clean. The synthetic factor index of the soils in all cities was ranked in the following decreasing order: Jiujiang > Yichun > Ganzhou > Shangrao > Fuzhou. The synthetic factor index of Jiujiang was more than 2 but less than 3, which indicated that the soil in Jiujiang was moderately polluted. The synthetic factor index of soil in Jiangxi Province was more than 0.7 but less than 1, which indicated that the soil was clean. The single factor index of HMs in Jiangxi Province was ranked as Cd > Pb > Hg > As > Cr, and the single factor index of Cd was more than 0.7, which indicated that the soil was clean but polluted with Cd to a certain extent.

The RI of the soil is presented in Figures 4 and 5. The order of the potential ecological RI for a single HM was Cd > Hg > As > Pb > Cr. The single potential ecological hazardous RI of Hg, As, Cr and Pb was less than 40, which indicated that these HMs were a slight ecological risk. The single potential ecological hazardous RI of Cd was maximum in the soils across all the cities, and a strong ecological risk occurred in Jiujiang and Yichun, and a moderate ecological risk occurred in other cities. We must consider Cd pollution in local soils to ensure that vegetables and fruits are not polluted by it. Figure 5 shows that 75% of the soil samples had a potential ecological RI of less than 150, indicating a slight ecological risk, 21.9% of the soil samples had a potential ecological RI between 150 and 300, indicating a medium ecological risk, and only one soil sample had an extremely strong ecological risk.

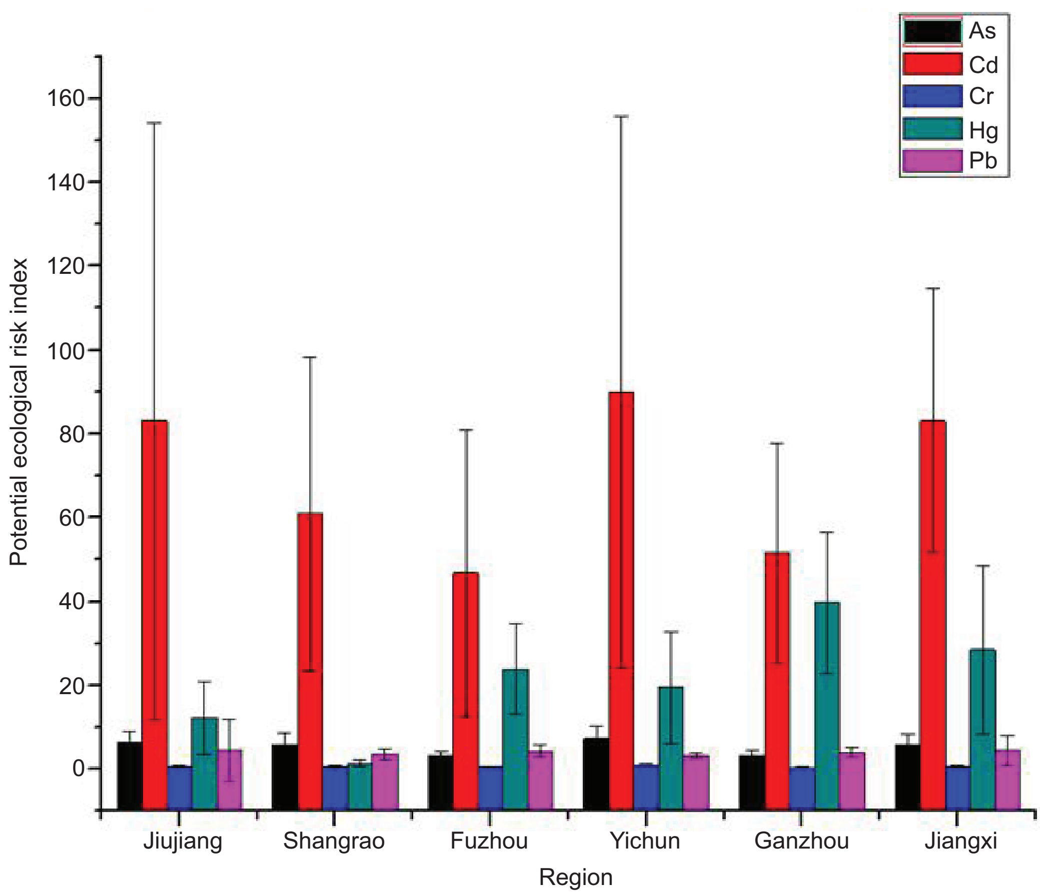

Figure 4. Mean of single potential ecological hazard index values for the soil in each region.

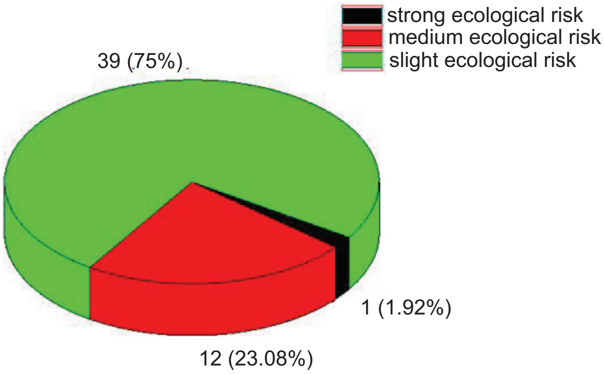

Figure 5. Number distribution map of soil samples with different potential risk intensities.

Results of vegetable analysis

Many studies have confirmed that the contents of As, Cd, Cr and Pb in leafy vegetables are significant higher than those in other vegetables (Liu, 2021; Wang *et al.*, 2022). The HM contents in vegetables are shown in Table 2. The respective mean contents of As, Cd, Cr, Hg and Pb in different types of vegetables are as follows: leafy vegetables—2.74E-02, 4.73E-02, 0.177, 1.46E-03 and 0.122 mg kg^{-1}; fruit vegetables—4.87E-03, 8.61E-03, 4.77E-02, 1.04E-04 and 5.11E-02 mg kg^{-1}; solanaceous vegetables—6.64E-03, 2.53E-02, 7.41E-02, 9.05E-05 and 0.183 mg kg^{-1}; and root vegetables—1.61E-02, 3.94E-02, 0.133, 1.32E-03 and 0.204 mg kg^{-1}. The contents of As Cd and Cr in vegetables followed the following decreasing sequence: leafy vegetables > root vegetables > solanaceous vegetables > fruit vegetables. The content of Hg followed the following decreasing sequence: root vegetables > leafy vegetables > fruit vegetables > solanaceous vegetables, and Pb followed the following decreasing sequence: root vegetables > solanaceous vegetables > leafy vegetables > fruit vegetables. The mean content of As (9.22E-02 mg kg^{-1}) and Cd (0.147 mg kg^{-1}) in Ganzhou leafy vegetables was maximum but less than the maximum limit assigned by the China National Food Safety Standards (Chinese Ministry of Health [CMH], 2017). The mean concentration of Cr in leafy vegetables in Shangrao, Ganzhou and Jiujiang was higher than in other cities and other vegetables but less than the maximum limits of China National Food Safety Standards. The mean concentration of Hg in fruit vegetables (6.23E-02 mg kg^{-1}) and leafy vegetables (1.41E-02 mg kg^{-1}) in Jiujiang was highest, exceeding the maximum limit of China standards. The respective mean concentration of Pb in solanaceous vegetables and root vegetables exceeded by 1.8- and 2.0-fold than the maximum limits of China standards. The mean concentration of Pb (0.425 mg kg^{-1}) in solanaceous vegetables in Ganzhou was highest, with a 4-fold increase than the maximum limit of China.

Liu *et al.* (2021) reported on the accumulation of HMs in root vegetables, leafy vegetables, and fruit vegetables produced in China plastic greenhouses. Their study showed that the Pb content in root vegetables was higher than that reported by Liu *et al.* (2021), while the HM content in other vegetables was lower than that reported by Liu *et al.* (2021). The As content in vegetables was significantly correlated in a positive manner with Cd, Cr and Hg contents (r = 0.411, 0.302, 0.413, respectively; $P \leq 0.01$). The higher the accumulation of As in vegetables, the higher the corresponding content of Cd, Cr and Hg, and vice versa. The Cd content in vegetables was significantly correlated in a positive manner with the Hg content (r = 0.584, $P \leq 0.01$), that is, the higher the accumulation of Cd, the higher the accumulation of Hg in vegetables. This result demonstrated that HMs had synergistic effects.

BCF and TTHQ of vegetables

The BCF values of HMs in vegetables are shown in Figure 6. The BCF of HMs in different vegetables followed the following decreasing sequences:

> Leafy vegetables: Cd (0.166) > Hg (0.1401) > Pb (0.0049) > As (0.0048) > Cr (0.0100); fruit vegetables: Cd (0.0689) > Hg (0.0246) > Cr (0.0035) > Pb (0.0023) > As (0.0011); solanaceous vegetables: Cd (0.1646) > Hg (0.0298) > Pb (0.0078) > Cr (0.0054) > As (0.0013); and root vegetables: Cd (0.2873) > Hg (0.0719) > Pb (0.0075) > Cr (0.0059) > As (0.0016).

The BCF of different HMs in vegetables followed the following decreasing sequences:

> As: leafy vegetables > root vegetables > solanaceous vegetables > fruit vegetables; Cd: root vegetables > leafy vegetables > solanaceous vegetables > fruit vegetables; Cr: root vegetables > solanaceous

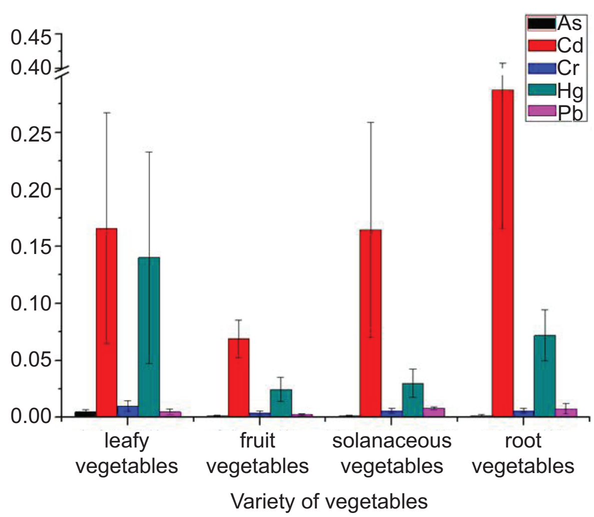

Figure 6. BCFs of HMs in variety vegetables.

vegetables > fruit vegetables > leafy vegetables; Hg: leafy vegetables > root vegetables > solanaceous vegetables > fruit vegetables; and Pb: solanaceous vegetables > root vegetables > leafy vegetables > fruit vegetables.

The migration ability of Cd from the soil to vegetables was strongest, which corroborated the previous research (Chen *et al.*, 2021; Meng *et al.*, 2021) whereas Hg, As and Cr showed weak migration ability. The migration ability of Cd in root vegetables was 1.7-fold of leafy vegetables and solanaceous vegetables. Research conducted by Chen *et al.* (2021) and Jalali and Meyari (2022) reported that the migration ability of Cd in leafy vegetables was highest, which was different from the results of the present study.

The difference in HM accumulation in different types of vegetables was attributed to the ability of plants in the uptake and transport of HM (Zunaidi *et al.*, 2023). Transpiration and roots play significant roles in HM accumulation in vegetables. Available HMs in the soil are absorbed by the roots; some HMs are retained in the roots, which leads to more accumulation of HMs in root vegetables than in other vegetables. The remaining HMs are transported and accumulated in the aboveground parts of vegetables by transpiration. The strong vegetable enrichment capability leads to accumulation of more HMs and stronger transpiration. Leafy vegetables can accumulate more HMs than other vegetables because of higher translocation and transpiration rates (Chen *et al.*, 2021; Gupta *et al.*, 2021). BCF was negatively correlated with pH ($P \leq 0.05$), which indicated that the accumulation capacity of vegetables for HMs did not change significantly with change in pH. This is different from the common belief that with decrease in soil pH, the availability of HMs in the soil can be improved (Liu *et al.*, 2021), leading to an increase in the accumulation of HMs in vegetables.

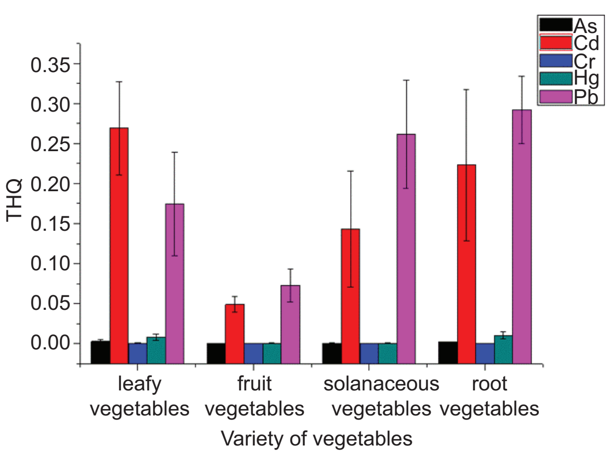

Figure 7. THQ and its proportion of different heavy metal in various vegetables.

The THQ and TTHQ values of HMs in vegetables are shown in Figure 7. The THQ of HMs in different vegetables followed the following decreasing sequences:

Leafy vegetables—Cd (0.2689) > Pb (0.1745) > Hg (0.0082) > As (0.0031) > Cr (0.0007); fruit vegetables—Pb (0.0730) > Cd (0.0493) > Hg (0.0008) > As (0.0006) > Cr (0.0002); solanaceous vegetables—Pb (0.2618) > Cd (0.1430) > As (0.0008) > Hg (0.0007) > Cr (0.0003); and root vegetables—Pb (0.2918) > Cd (0.2231) > Hg (0.0106) > As (0.0018) > Cr (0.0005).

The respective THQ of different HMs in leafy vegetables, fruit vegetables, solanaceous vegetables and root vegetables accounted for the following values: Cd: 59.06%, 39.80%, 35.18%, 42.27%; Pb: 38.32%, 58.94%, 64.38%, 55.28%. The THQ of Pb in root vegetables was highest, followed by Cd in leafy vegetables, and Cr in all vegetables was lowest. Cd and Pb are major factors for THQs, and local residents should focus on the risks of Pb and Cd when consuming vegetables.

The TTHQ of HMs in vegetables followed the following decreasing sequence: root vegetables > leafy vegetables > solanaceous vegetables > fruit vegetables. The TTHQ of HM in root vegetables was highest, reaching 0.53, and the intake of root vegetables should be controlled in moderation. The TTHQ of all vegetables was less than 1.0, which indicated that there was no significant noncarcinogenic risk to adults.

Monte Carlo Simulation

The 5%, 95% confidence level and mean of THQs are shown in Figure 8 (A, C, E and G) , sensitivity of adults are shown in Figure 8 (B, D, F and H). As shown in Figure 8 (A, C, E and G), the probability estimation proved that TTHQ levels in adults followed the following sequence: root vegetables (mean = 0.53) > leafy vegetables (mean = 0.46) > solanaceous vegetables (mean = 0.41) > fruit vegetables (mean = 0.12). The values of 0.47–0.59, 0.40–0.51, 0.36–0.46 and 0.11–0.14 were observed for the 5th and 95th percentiles in vegetables, respectively. The results proved that TTHQ < 1 for all vegetables, which intends that the probability of noncarcinogenic risks was not enhanced. Figure 8 (B, D, F and H) presents the sensitivity analysis of effective factors in TTHQ. The mean body weight (BW), the average duration of exposure to HMs (TA) and the tolerable daily intake (TDI) had a negative value in sensitivity analysis for adults. It demonstrated that BW, TA and TDI were inversely related to health risks. The period of exposure (ED), the rate of exposure (EF),

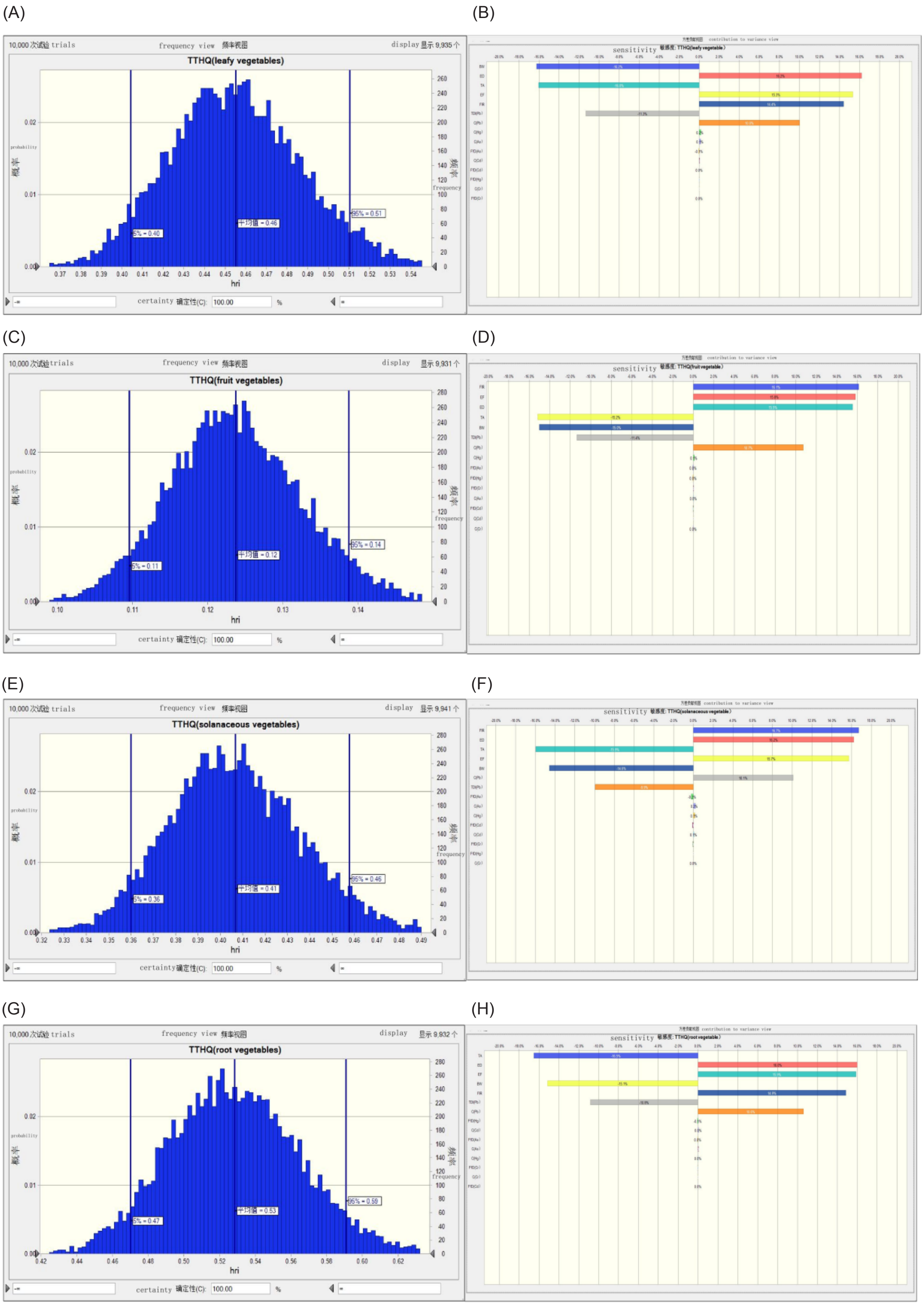

Figure 8. (A) Probability analysis of leafy vegetables TTHQ in adults; (B) sensitivity analysis of leafy vegetables TTHQ in adults; (C) probability analysis of fruit vegetables TTHQ in adults; (D) sensitivity analysis of fruit vegetables TTHQ in adults; (E) probability analysis of solanaceous vegetables TTHQ in adults; (F) sensitivity analysis of solanaceous vegetables TTHQ in adults; (G) probability analysis of root vegetables TTHQ in adults; and (H) sensitivity analysis of root vegetables TTHQ in adults.

the daily vegetable consumption (FIR) and concentration of Pb had significant influence (above 10%) on the TTHQ of adults, with other parameters having the lowest (<1%) influence. However, ED, EF and FIR values are fixed, with concentration of Pb being prominent. Therefore, Pb was identified as the priority control metal in Jiangxi plastic-covered sheds. This result was consistent with the results of the China plastic-shed vegetable production area (Meng *et al.*, 2021).

Conclusions

The soil and four different vegetables of plastic-covered sheds were collected from the study area, and the degree of HM pollution and the human health risk assessment were analyzed. Cd and Hg in the soil exceeded the local background value, and Cd also exceeded the maximum limit levels of China. Evaluation of the Nerome index showed that the soil of the plastic-covered shed in Jiangxi Province was clean, but some of the soil in the area was moderately polluted by Cd. Evaluation of the potential ecological RI showed that most soils had no extremely strong ecological risk except the soils of Jiujiang and Yichun cities. As the contents of As Cd and Cr were highest in leafy vegetables, and that of Pb and Hg were highest in root vegetables, fruit and solanaceous vegetables could be more suitable for planting in plastic-covered shed than root and leafy vegetables. The results of the health risk assessment and the Monte Carlo simulation showed that Cd and Pb were major factors affecting THQ. The TTHQ of root vegetables was highest, so the intake of root vegetables should be controlled. The contribution of Cd and Pb to THQ was highest among the noncarcinogenic risk contributions of all HMs; therefore, Cd and Pb were identified as the priority control metals in the Jiangxi plastic-covered sheds.

Author Contributions

Conceptualization, methodology, investigation, editing, writing and original drafting were done by Genxin Nie. Resources, supervision, writing, reviewing and editing were done by Yaomin Zhou. Analysis and data collection were done by Tianhua Tu. Lifang Hu was responsible for sample collection. Ling Wu did methodology, reviewing and editing. All authors read and agreed to the published version of the manuscript.

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Declaration of Competing Interest

The authors declared that they had no known competing financial interests or personal relationship that could influence the research conducted in this paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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