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Co-exposure of heavy metals in rice and corn reveals a probabilistic health risk in Guizhou Province, China

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ABSTRACT

The adverse effects of heavy metals have arousing concern in the high geological background area, especially in southwestern Guizhou, China. However, the pollution status of heavy metals are still unclear when exposed to rice and corn in Guizhou province. Therefore, the concentration, pollution level, spatial distribution, and probabilistic health risks of Ni, Cr, Pb, Cu, and Zn are estimated in rice and corn. A total of 241 samples (117 for rice and 124 for corn) were collected from Guizhou province and measured by a method of inductively coupled plasma-mass spectrometry (ICP-MS). The results showed that rice and corn were contaminated with Ni and Cr. High concentrations of Ni were presented in the southeast of rice. It indicated that 22.0 % of rice samples were contaminated with Ni. HI values for children and adults exceeded 1.0 in rice and corn, suggesting that humans might be subject to probabilistic non-carcinogenic risks. FTCR demonstrated that rice and corn might cause probabilistic carcinogenic risks to children and adults, which were both greatly higher than 1.0×10^{-4}. Moreover, the contributions of Ni to the HI and FTCR were the highest for adults and children. Therefore, more attention should be paid to the exposure of heavy metals in rice and corn, especially in Ni. The results would provide a novel prospective for pollution control and be helpful for environmental regulation.

1. Introduction

Heavy metal pollution has pervaded many parts of the world, especially in developing countries such as China (Rasee et al., 2023). Several toxic heavy metals, such as lead (Pb), zinc (Zn), copper (Cu), chrome (Cr), and nickel (Ni), have been found potential health risks to local consumers (Sarwar et al., 2017; Awual, 2019). And, persistent exposure to them might cause organ damage, cerebrovascular diseases, central nervous system disorders, and cancer of the reproductive system (Cendrowska-Pinkosz et al., 2022; Kubra et al., 2021). Geogenic and anthropogenic causes are the two significant pathways that resulting in the high background of heavy metals in the environment, including volcanic activity, forest fires, erosion, and weathering (Sheikh et al., 2023; Salman et al., 2021). However, the reasons that how heavy metals induce diseases are complicated and multiple in those regions. Guizhou province as typical high geological area, it is therefore essential to make the contamination status of heavy metals in crops and their impacts on food security clear.

Rice and corn are one of the most significant foodstuffs around the world (Li et al., 2022a). In the recent years, the health risks posed by heavy metals had been reported in rice and corn from several countries. Guo et al. (2022) confirmed that the Ni, Cr, Pb, Cu, and Zn exposed to rice could threat serious health hazards to humans, which total non-carcinogenic risk were 3.558 for adults and 6.104 for children, respectively. According to the National food safety standard, the highest proportion among heavy metals concentrations, exceeding rice samples was found in Pb (32.2 %), Cr (12 %), As (7.3 %), and Hg (4.4 %) (CNMH., 2022). In addition, the results showed high values for Pb and cadmium from corn in all samples and might not be very safe for human consumption (Tagumira et al., 2022). More seriously, it is reported that over 600 million people are injured after eating food polluted by heavy metals each year (Qu et al., 2012). However, as two major cereals in

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Guizhou province, few study is systematically aware of the rice and corn pollution by heavy metals in the high geological background area.

To our knowledge, deterministic and probabilistic (Monte Carlo simulation) assessment are two methods that well conducted to evaluate the human health risks due to heavy metals. The deterministic risk regarding heavy metals has been applied in many studies (Huang et al., 2021; Zhang et al., 2020). However, previous studies proved that the dietary intake for body weight (BW), ingestion rate (IR), and exposure duration (EDs) varied for individuals in different nations, which to some degree may overestimate or underestimate the results of health risks for local population (Li et al., 2022b). Herein, the deterministic risk technique may exist some uncertainties during exposure assessment, leading to less persuasive risk results. In order to avoid the error, the probabilistic risk assessment with Monte Carlo simulation in this study is applied to estimate the probability of outcomes in a process that cannot easily be predicted due to the intervention of random variables (Liu et al., 2019). Also, the single factor pollution index and spatial distribution of heavy metals were measured as well, which could make the evaluation results more comprehensive and objective.

In light of these discussions, to better understand the pollution status and health risks posed by Ni, Cr, Pb, Cu, and Zn in Guizhou province, 241 samples (117 for rice and 124 for corn) were collected to (1) measure the contents, (2) estimate the pollution levels, (3) understand the spatial distribution, and (4) clarify the probabilistic non-carcinogenic risk and carcinogenic risk for adults and children. These findings will offer more convincing evidence and a scientific basis for local pollution control and ensure the health of the populace in Guizhou Province.

2. Material and methods

2.1. Study region and sample preparation

Guizhou province (103°36–109°35′E, 24°37–29°13′N) was distributed in Southwestern China. All of samples in our study were collected from Bijie, Guiyang, Zunyi, Kaili, Anshun, Duyun, and Xingyi of Guizhou province. The study area selected were all observed with the high geological background value. And, the mean annual rainfall and temperature are 1900 mm and 16.4 ℃, respectively. Total of land in Guizhou province is 1.76×10^5 km^2, in which arable land are almost 4.52×10^4 km^2 accounting for 25.67 % of the total region. In 2021, the output of rice and corn in Guizhou province were 4.16 million and 2.20 million tons, accounting for 39.32 % and 20.81 % of the grain output, respectively.

In 2021, 241 samples (117 for rice and 124 for corn; Fig. S1) were collected using the random sampling method at harvest season, and each sample was consisted with five sub-samples. The portable global positioning system (GPS) was used to precisely record the latitude and longitude for the spatial distribution. Furthermore, the corn and rice samples were cleaned in the laboratory and dried at 60 °C. Following hulling, samples of rice and corn were crushed, sieved through 0.15 mm mesh, and placed in polyethylene bags for storage.

2.2. Chemical analysis

The samples of rice and corn were digested using the microwave digestion method (Huang et al., 2021). About 0.2 g of powdered corn and rice samples were placed in a digestion tube and predigested with 2 ml of HNO_3 for 4 h, then 1 ml of H_2O_2 was added and digested with a microwave device. After the digestion, the digestion extract was brought to room temperature before being diluted with deionized water to make 50 ml. Lastly, inductively coupled plasma mass spectrometry was used to detect the concentrations of Cr, Cu, Zn, Ni, and Pb (ICP-MS, PerkinElmer, Waltham, MA, USA).

2.3. Quality control and assurance (QC/QA)

In order to ensure optimum condition in the concentration determination operation, three aspects should be noted as follows. 1)Pay attention to the cleanliness of the cone, atomiser and rectangular tube should be paid attention during testing, and many samples should be cleaned in time after feeding samples; 2) The purity of argon should be noted and the exhaust volume of ventilation system is of 8–10 m/s. 3) The instrument is first tuned using a tuning solution, and the points of the standard series are determined sequentially, followed by the determination of sample blanks and specimens. When analyzing the samples, 5 % of parallel double samples are made at least. The result of each measurement of parallel double samples is within the permissible relative deviation of 30 % or less, and the pass rate of parallel double samples measurement is above 95 %.

All chemicals of guaranteed reagent (GR) were used in the whole study. All reagents were manufactured from Tianjin Kemio Chemical Reagent Co., Ltd. All samples and reagents were prepared using deionized water. Each sample was analyzed in triplicate within a 5.0 % difference between replicated results. The accuracy of Ni, Cr, Pb, Cu, and Zn concentrations was verified using standard reference material for rice (GBW08502) and corn (GBW10012). The recovery ratios of heavy metals were within 88 % to 119.0 %.

2.4. Pollution assessment

To reflect the pollution status of Ni, Cr, Pb, Cu, and Zn, the single factor pollution index (SFPI) was used (Luo et al., 2020). Then, the composite levels of Ni, Cr, Pb, Cu, and Zn pollution were extensively estimated using the Nemero composite pollution index (NCPI) (Zhang et al., 2019). Eqs. (1)–(2) were used to calculate the SFPI and NCPI:

$$P_i = \frac{C_i}{S_i} \tag{1}$$

Where P_i represents the SFPI; C_i is the contents of heavy metal (mg/kg); S_i (mg/kg) is the standard limited value on the basis of the National Food Safety Standard (GB 2762–2017). The pollution levels are classified as follows: (1) $P_i \leq 1.0$, clean; (2) $1.0 < P_i \leq 2.0$, slight pollution; (3) $2.0 < P_i \leq 3.0$, moderate pollution; and (3) $P_i > 3.0$, strong pollution (Du et al., 2019).

$$P = \sqrt{\frac{P_{iavg}^2 + P_{imax}^2}{2}} \tag{2}$$

Where P represents the NFPI; P_{iavg} and P_{imax} is the mean value and maximum value of SFPI in rice and corn; The pollution status of Ni, Cr, Pb, Cu, and Zn could be classified as: (1) $P \leq 0.7$, clean; (2) $0.7 < P_i \leq 1.0$, precautionary; (3) $1.0 < Pi \leq 2.0$, light pollution; (4) $2.0 < P_i \leq 3.0$, moderate pollution; and (5) $Pi > 3.0$, strong pollution (Zang et al., 2020).

2.5. Health risk assessment

2.5.1. Probabilistic non-carcinogenic risk

The probabilistic non-carcinogenic risk was evaluated by the target hazard quotient (THQ), which was established by the United States Environmental Protection Agency (USEPA), in combination the average daily intake (ADI) and oral reference dose (RfD) (Doabi et al., 2018). The THQ represents individual heavy metal via single pathway of rice or corn consumption posed a probabilistic non-carcinogenic risk. The total THQ (TTHQ) is used to assess the total risk of heavy metals via rice or corn consumption. In order to calculate the overall probabilistic non-carcinogenic risk of various heavy metals, the hazard index (HI) is used. Eqs. (5)–(7) can be used to compute the ADI, THQ, TTHQ, and HI (Huang et al., 2018; Song et al., 2021):

$$ADI = \frac{C_i \times IR \times EF \times ED}{BW \times AT} \tag{3}$$

$$\text{THQ} = \frac{ADI}{RfD} \tag{4}$$

$$\text{TTHQ} = \sum_{i=1}^{n} THQ_i \tag{5}$$

$$\text{HI} = TTHQ_{rice} + TTHQ_{corn} \tag{6}$$

Where *ADI* refers to average dietary intake (mg/kg/d); *IR* stands for ingestion rate (kg/d); C_i is the contents of Ni, Cr, Pb, Cu and Zn in crops (mg/kg); *EF* represents the exposure frequency (d/a); *ED* is short for exposure duration (a); *BW* and *AT* stands for the body weight (kg) and the average time (d), respectively. The values of relevant parameters are shown in Table S1 (Duan, 2015). *RfD* is reference dose of Ni (0.02 mg/kg/d), Cr (1.5 mg/kg/d), Pb (0.0035 mg/kg/d), Cu (0.04 mg/kg/d) and Zn (0.3 mg/kg/d) in corn and rice (Lu et al., 2021); When THQ, TTHQ or HI are greater than 1.0, indicating that the population may suffer from a probabilistic non-carcinogenic risk (Du et al., 2019).

2.5.2. Probabilistic carcinogenic risk

The probabilistic carcinogenic risk (CR) was used to assess individual heavy metal through single pathway of rice or corn consumption. The index of TCR (Total Carcinogenic Risk) is applied to estimate the probabilistic carcinogenic risk of multiple heavy metal via single pathway of rice or corn consumption. The FTCR is employed to estimate the finally total probabilistic carcinogenic risk of heavy metals via both rice and corn consumption. The calculating equations of CR, TCR and FTCR are as follows (Lu et al., 2021):

$\text{CR} = ADI \times SF$ (7)

$$\text{TCR} = \sum_{i=1}^{n} CR_i \tag{8}$$

$$\text{FTCR} = TCR_{rice} + TCR_{corn} \tag{9}$$

Where *SF* is the carcinogenic slop factor of Cr (0.50), Ni (0.84) and Pb (0.0085) (Huang et al., 2021). When CR and TCR values are higher than 1.0×10^{-4} (acceptable risk), indicating that have a carcinogenic risk to population (Mao et al., 2019).

2.6. Statistical analysis

Analysis of the data discrepancy was computed by ANOVA with SPSS 25.0 software (IBM, USA) and the figure was represented using the Origin 2021Pro (Origin Lab, USA). The spatial distribution was analyzed by the inverse distance weight method by the ArcGis10.5 software (Esri, USA). The Monte Carlo simulation method was employed to estimate probabilistic carcinogenic and non-carcinogenic risks of human beings using Crystal Ball 11.24 (Oracle, USA), and the simulation was run for 10,000 iterations.

3. Results and discussion

3.1. The contents of heavy metals in rice and corn

The contents of Cr, Cu, Zn, Ni, and Pb in rice were 0.001–1.169, 0.037–4.442, 0.014–14.923, 0.019–7.772, and 0.001–0.193 mg/kg, and that in corn were 0.001–1.839, 1.305–5.226, 0.168–32.967, 0.042–8.103, and 0.002–0.163 mg/kg, respectively (Table. 1). Compared with the National Food Safety Standard in China (GB2762-2017), the Cr maximum concentrations in rice and corn were 0.169 times and 0.839 times higher than the MPC values, and Ni were 6.80 times and 3.40 times higher than the MPC values, respectively. Moreover, the exceeding ratios of Ni in rice and corn samples were up to 28.0 % and 15.4 %, respectively.

Table 1
The concentrations of HMs in rice and corn in the study area (mg/kg).

Crops		Cr	Cu	Zn	Ni	Pb
Rice	Average	0.215^b	1.388^b	3.161^b	1.310^a	0.013^b
	SD	0.221	0.993	4.89	1.936	0.024
	Min	0.0003	0.037	0.014	0.019	0.001
	Max	1.169	4.442	14.923	7.772	0.193
	MPC*	1.000	10.00	50.00	1.000	0.200
Corn	Average	0.471^a	1.868^a	19.776^a	0.618^b	0.031^a
	SD	0.423	0.556	4.475	0.664	0.034
	Min	0.003	1.035	0.168	0.042	0.002
	Max	1.839	5.266	32.967	4.42	0.163
	MPC*	1.00	10.00	50.00	1.000	0.200

* The value from National Food Safety Standard (GB2762-2017).
The different letters indicate significant differences at $p < 0.05$.

Our results demonstrated that Ni and Cr in rice and corn might exist in different pollution status. As previously described, Huang et al. (2021) found that the maximum content of Ni in rice was 2.01 mg/kg, which was lower than that in our results. The average concentration of Ni in rice was 2.05 and 3.83 times higher than that in the Yangtze River Delta and Hunan Province, respectively (Hu et al., 2019; Wang et al., 2017). In addition, the maximum content of Cr in corn was 6.21 times higher than that reported by Song et al. (2021). This observed that pollution differences of heavy metals were existed in different regions. It might be greatly contributed to the different geological background values, which could pose inconsistent concentrations for heavy metals via soil-crops system. In addition, Ni could be taken up by plants through the iron uptake system when plants were flooded by irrigation water, which could in turn result in iron spots and iron deficiency on the root surface of rice (Li et al., 2020). Moreover, it proved that more concerns should be paid to the Cr exposure in the high geological background area with an exception of Cadmium.

3.2. Spatial distribution of heavy metals

The spatial distributions of Ni, Zn, Pb, Cu, and Cr in rice and corn are further presented in Fig. 1. In rice, high concentrations of Ni and Zn were mainly presented in the southeastern regions. In corn, both Zn and Cu were distributed in the north. And, the same trends for Ni and Cr of high concentrations were observed and distributed in the northeast region.

Spatial distributions of Ni, Zn, Pb, Cu, and Cr in rice and corn depends on many factors, including geological background, soil characteristics, crop types, and anthropogenic causes (Cui et al., 2022; David et al., 2019). Guizhou had an anomalous background in terms of its geology, in which soil background values were higher than the average values of Chinese soils (Kong et al., 2018). For example, the maximum value of Ni in soil in southwestern Guizhou was 47.8 mg/kg (Zhang et al., 2018). In fact, the metal smelting process might discharge wastewater sludge with high concentrations of Ni and Cr, which could result in higher concentrations of these HMs in soil (Li et al., 2020; Wu et al., 2020). These results may be correlated with the occurrence of high contents of Ni and Cr in rice and corn in the west and northeast-27241517442180.

3.3. Pollution level of heavy metals in rice and corn

The pollution degrees for heavy metals are shown in Fig. 2. The SFPIs of Cr, Cu, Zn, Ni, and Pb in rice were ranged in 0.001–1.169, 0.004–0.4442, 0.001–0.299, 0.019–7.772 and 0.006–0.966, respectively, and that in corn were ranged in 0.003–1.839, 0.103–0.527, 0.003–0.660, 0.042–4.418 and 0.008–0.817, respectively. The maximum SFPI values for Ni and Cr were both more than 1.0, suggesting

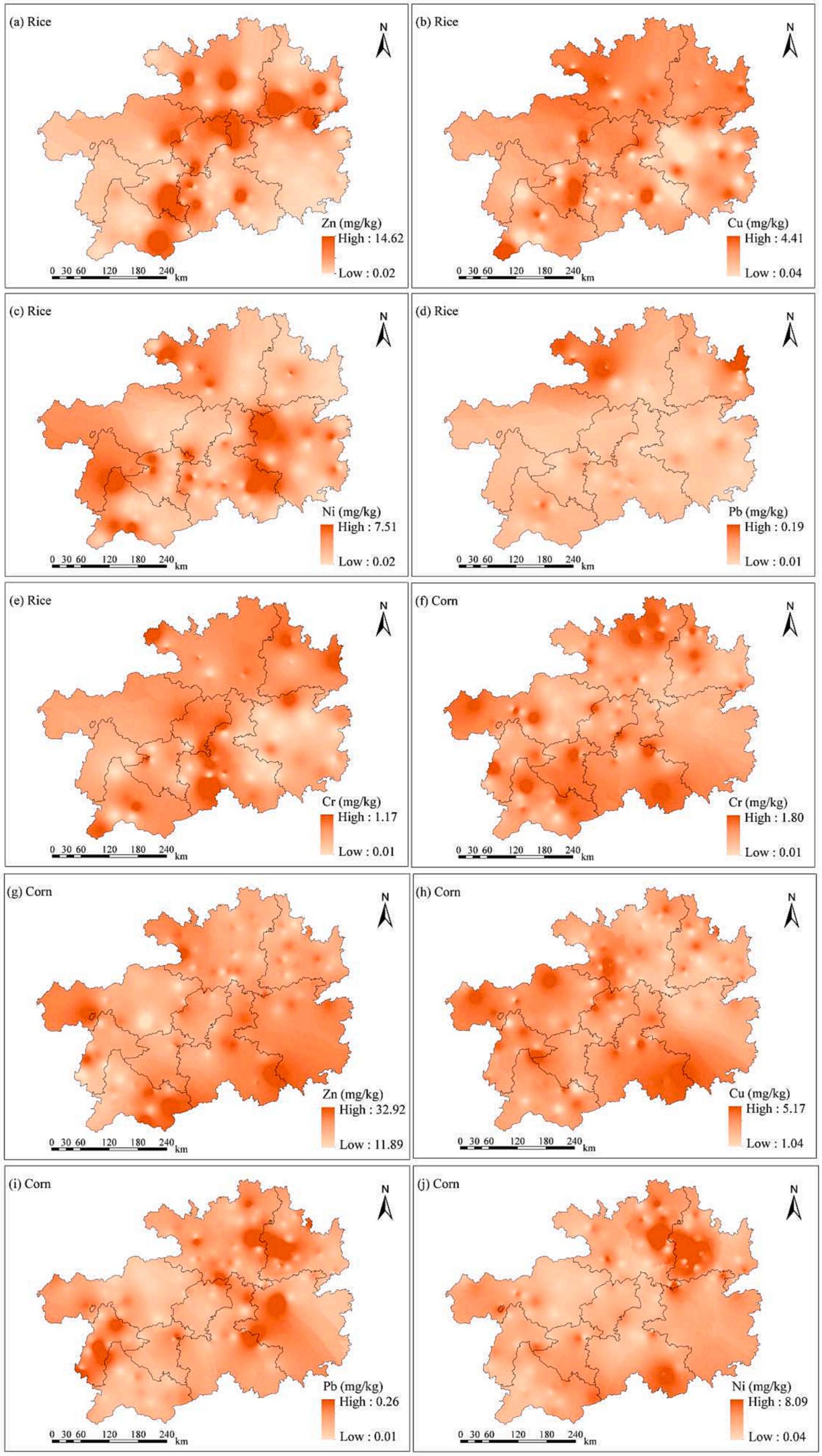

Fig. 1. Spatial distributions of Cu, Zn, Pb, Ni and Cr in rice and corn.

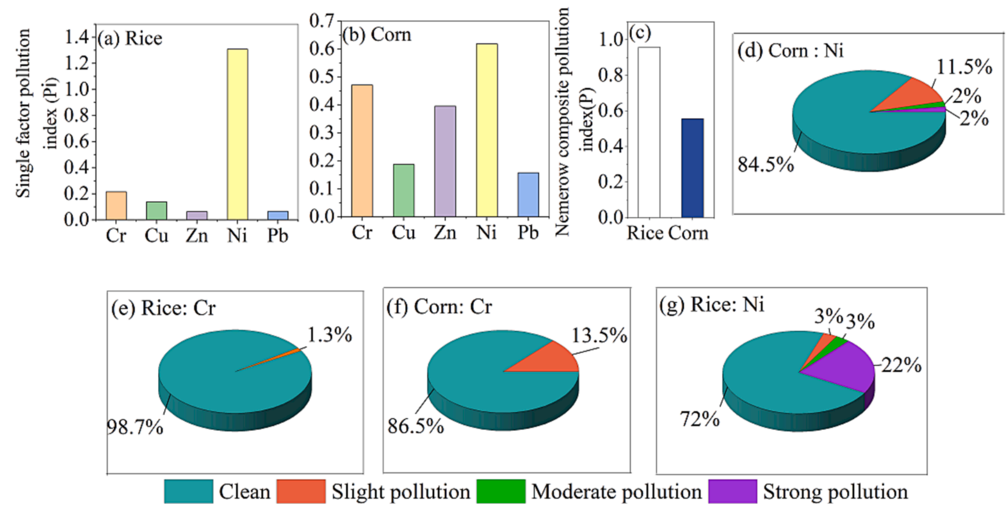

Fig. 2. The SFPI values of rice (a) and corn (b), NCPI values of rice and corn (c), and pollution levels of Ni (g) and Cr (e) in rice and Ni (d) and Cr (f) in corn.

that pollution in rice and corn might be observed by exposure of Ni and Cr.

From the discussions above, it might be highly associated with the high contents for Ni and Cr of soils in Guizhou Province (Kong et al., 2018), which increases the accumulation of Ni and Cr in rice and corn to different degrees. Furthermore, the soil pH could also favor the uptake of Ni and Cr in rice and corn (Li et al., 2022a). Therefore, the actual contamination of heavy metal could also be better analyzed if the correlation is conducted between concentration and pH values.

3.4. Probabilistic health risk assessment

3.4.1. Probabilistic non-carcinogenic risk

The target hazard quotient (THQ) with Monte Carlo simulation was applied to further estimate the probabilistic non-carcinogenic risk. The 95th percentile of THQ_{Ni} in rice was 1.940 for adults and 2.343 for children, suggesting that Ni might cause a probabilistic non-carcinogenic risk to the population via rice consumption. However, all of the THQ values in corn were all below 1.0, demonstrating that no probabilistic non-carcinogenic risk were observed exposed to investigated heavy metals.

Furthermore, the total probabilistic non-carcinogenic risks were presented as TTHQ via rice or corn intake. The mean value of TTHQ in children via rice ingestion was greater than 1.0 (Fig. 3a), which demonstrated that children might have a probabilistic non-carcinogenic risk. The values of TTHQ in corn indicated that no probabilistic non-carcinogenic risk was produced in investigated area (Fig. 3a). In addition, the HI values were 1.98 for children and 1.14 for adults, respectively (Fig. 3b), showing that rice and corn intake might lead to probabilistic non-carcinogenic risks of humans. Moreover, the contribution of Ni to HI was the highest, which were 48.2 % for adults and 39.7 % for children, respectively (Fig. 3c-d). It highlighted that a probabilistic non-carcinogenic risk might be mainly attributed to Ni exposure for local residents.

Long-term exposure to Ni, Cr, Pb, Cu, and Zn through crops will inevitably present a non-carcinogenic risk to human beings. According

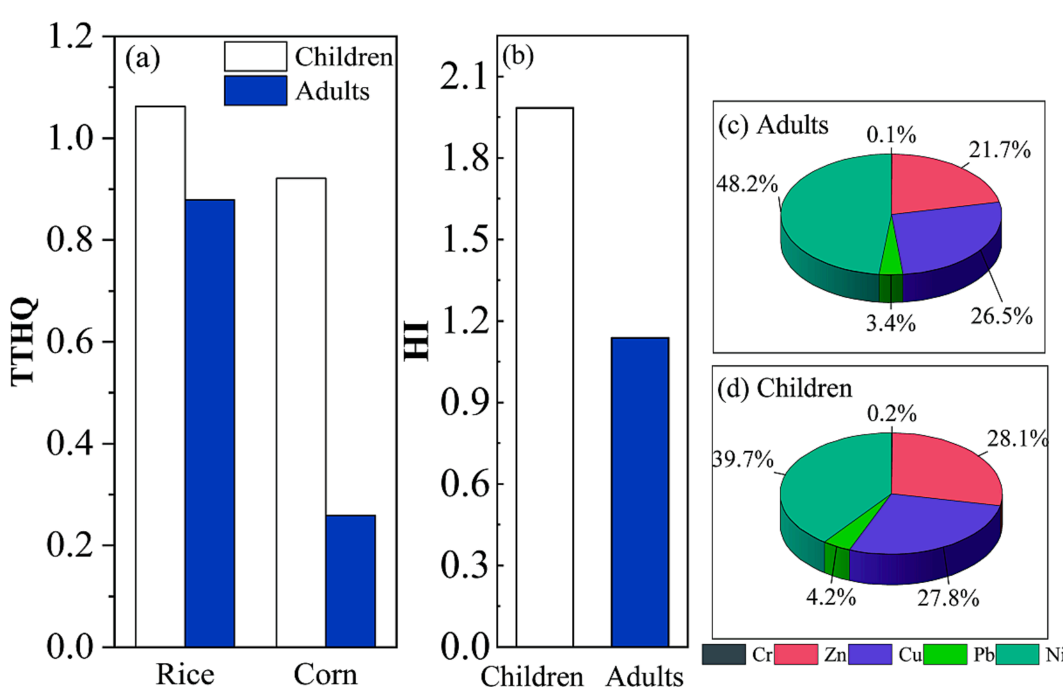

Fig. 3. TTHQ via rice (a) and corn (b) consumption, HI of children and adults (b), contribution ratio of HMs to HI in adults (c) and children (d).

to Li et al. (2017), Ni (THQ:1.81) and Zn (THQ:1.50) via rice consumption had a significant non-carcinogenic risk for children. The THQ values of Pb through rice were 115 times higher than our results in Daye City of Hubei Province (Cai et al., 2019). The THQ values of Ni, Cr, Pb, Cu, and Zn via rice ingestion in Bangladesh were higher than those in Guizhou Province (Proshad et al., 2019). However, previous studies in Guizhou Province showed that no concern has been given to Ni thus far (Kong et al., 2018). Therefore, attention should be given to the risks associated with Ni via rice consumption in local populations. In addition, our results suggested that strict measures should be taken to decrease the heavy metal pollution in rice such as low adsorption (Awual et al., 2019). Apart from this, the dietary intake for RfD, IR, ED, and BW are different for individuals, and there was varied contamination status in various areas. Therefore, the results would be more helpful for providing a scientific guidance if the practical data was obtained.

3.4.2. Probabilistic carcinogenic risk

The probabilistic carcinogenic risk was also assessed by CR values with Monte Carlo simulation (Fig. 4). The CR values for different heavy metals in rice and corn were ranked as Ni > Cr > Pb. The results of Ni and Cr in corn and rice were greater than the acceptable risk of 1.0×10^{-4}, implying that long-term exposure to them might pose probabilistic carcinogenic risks to local populace. Furthermore, the greatest CR values of Ni through corn were 3.15×10^{-3} for children and 8.86×10^{-4} for adults, respectively, indicating an unacceptable risk of cancer were observed in rice and corn. According to Fig. 5a-b, the results of TCR_{Rice} (children: 1.05×10^{-2}, adults: 8.73×10^{-3}), TCR_{Corn} (children: 4.67×10^{-3}, adults: 1.31×10^{-3}) and FTCR (children: 1.52×10^{-2}, adults: 1.00×10^{-2}) were all higher than 1.0×10^{-4}, showing that exposed to rice or corn might pose a probabilistic carcinogenic risk of the local humans. More importantly, the contribution of Ni to the FTCR value was largest, were at 89.5 % for adults and 85.1 % for children (Fig. 5c-d). It highlighted that the probabilistic carcinogenic risk via rice and corn was mainly attributed to Ni.

Previous studies had reported the carcinogenic risks mediated by Ni exposure via rice and corn (Cui et al., 2022). Song et al. (2021) reported that Ni had the greatest carcinogenic risk to corn, which was similar to our study. In Hunan Province, Cui et al. (2022) demonstrated that the CR value for Ni in rice was also greater than the acceptable risk, indicating that Ni exposure via rice ingestion might lead to a significant carcinogenic risk to humans. In total, it showed that exposed to Ni in crops had been a potential problem for human of health combined with our findings. To the best of our knowledge, many present studies mainly focused on the exposure of Cadmium and Fluorine in the high geological background area of Guizhou province (Li et al, 2021a; Li et al., 2023). Therefore, our results might be a little addition to the current pollution status of heavy metals in Guizhou, which might be helpful for protecting the health of local human beings.

Children have larger probabilistic health risks than adults on the present studies. It could be contributed to that children were more sensitive and higher absorption for heavy metals than adults since their underdeveloped organs (Rehan et al., 2023). In addition, to reduce the health risks associated with rice and corn consumption, some measures could be implemented from two perspectives. On the one hand, varieties with low absorption of heavy metals can be selected for planting since some studies have shown that there are differences in the absorption capacity of different varieties of rice for heavy metals, therefore choosing some materials with strong adsorption properties may also be an effective way to reduce the concentration of heavy metals (Hasan et al., 2023). On the other hand, rice could be finely processed, which could reduce the concentration of heavy metals to some degree (Lu et al., 2021; Kubra et al., 2021). It is suggested that we can reduce the exposure of heavy metals through sensible processing in daily life and thereby to reduce the health risks.

Conclusions

As two important agricultural products in Guizhou province, special attention to rice and corn are required to assure food safety. In the current study, the concentration, pollution level, and spatial distribution of Ni, Cr, Pb, Cu, and Zn were assessed and probabilistic health risks to local citizens had been investigated as well. The concentrations of Cr and Ni showed a higher risk in rice and corn. Different elements showed various spatial distribution, which might be associated with local geological background values. Furthermore, the pollution assessment indicated that 22.0 % of rice samples were seriously contaminated with Ni. Moreover, mean values of HI and FTCR via rice and corn exceeded 1.0 for both children and adults, among which the Ni was the greatest contributor. It highlighted that local populace might suffer probabilistic health risks and more attention should be paid to Ni exposure. Totally,

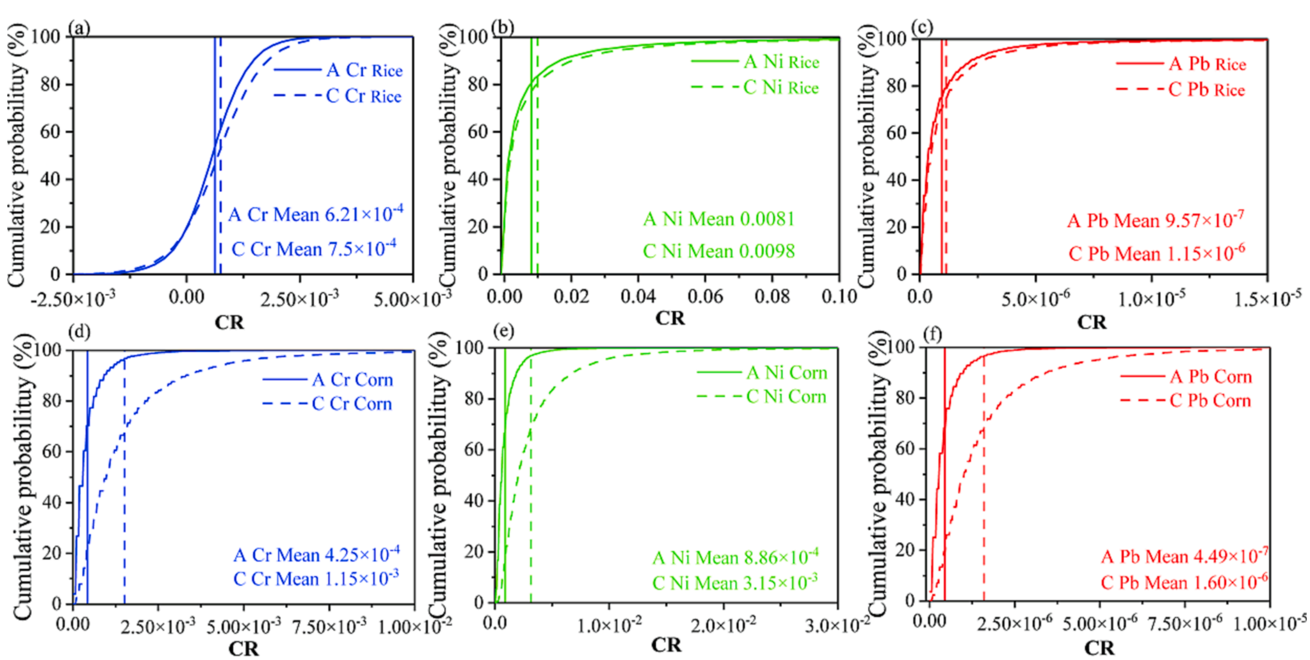

Fig. 4. The cumulative probabilities of CR of Cr (a), Ni (b) and Pb (c) via rice and Cr (d), Ni (e) and Pb (f) via corn consumption.

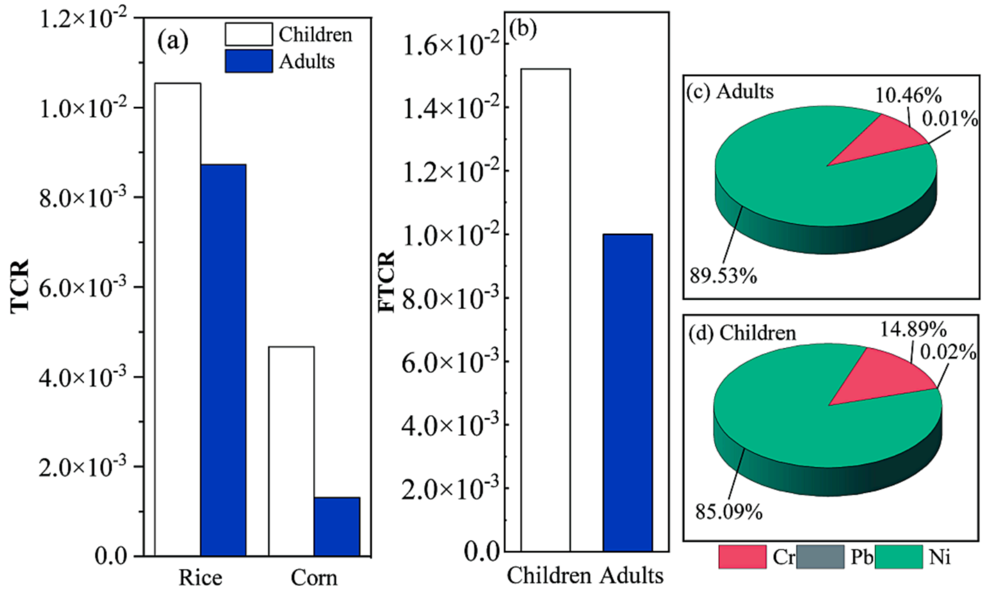

Fig. 5. The TCR via rice or corn consumption (a), contribution ratio of Ni, Pb and Cr via rice (c) or corn (d) consumption to the FTCR.

comprehensive analysis were applied to evaluate the contamination status of heavy metals in the present study, especially in probabilistic assessment with Monte Carlo simulation. Our results would be helpful for environmental regulation and provide a novel prospective for pollution control.

CRediT authorship contribution statement

Yifang Zhao: Formal analysis, Investigation, Software, Writing – original draft. **Dashuan Li:** Formal analysis, Investigation, Software, Writing – original draft. **Daofen Xiao:** Formal analysis, Investigation, Software, Writing – original draft. **Zhun Xiang:** Resources. **Xianping Yang:** Project administration. **Yuanji Xiao:** Project administration. **Xiangli Xiao:** Project administration. **Jianzhong Cheng:** Resources. **Qinhui Lu:** Funding acquisition, Supervision, Visualization. **Qinghai Zhang:** Funding acquisition, Supervision, Visualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2023.101043.

References

Awual, M. R. (2019). An efficient composite material for selective lead(II) monitoring and removal from wastewater. *Journal of Environmental Chemical Engineering*, Article 103087.

Awual, M. R., Hasan, M. M., Asiri, A. M., & Rahman, M. M. (2019). Novel optical composite material for efficient vanadium(III) capturing from wastewater. *Journal of Molecular Liquids, 283*, 704–712.

Cendrowska-Pinkosz, M., Ostrowska-Lesko, M., Ognik, K., Krauze, M., Juskiewicz, J., Dabrowska, A., Szponar, J., & Mandziuk, S. (2022). Dietary copper deficiency leads to changes in gene expression indicating an increased demand for NADH in the prefrontal cortex of the rat's brain. *International Journal of Molecular Sciences, 23*(12), 6706.

Cai, L. M., Wang, Q. S., Luo, J., Chen, L. G., Zhu, R. L., Wang, S., & Tang, C. H. (2019). Heavy metal contamination and health risk assessment for children near a large Cu-smelter in central China. *The Science of the Total Environment, 650*(Pt 1), 725–733.

CNMH (2022). Maximum Levels of Contaminants in Foods. National Health Commission of the People's Republic of China GB 2762-2022.

Cui, H., Wen, J., Yang, L., & Wang, Q. (2022). Spatial distribution of heavy metals in rice grains and human health risk assessment in Hunan Province, China. *Environmental Science and Pollution Research, 29*(55), 83126–83137.

David, E., Eleazu, C., Igweibor, N., Ugwu, C., Enwefa, G., & Nwigboji, N. (2019). Comparative study on the nutrients, heavy metals and pesticide composition of some locally produced and marketed rice varieties in Nigeria. *Food Chemistry, 278*, 617–624.

Doabi, S. A., Karami, M., Afyuni, M., & Yeganeh, M. (2018). Pollution and health risk assessment of heavy metals in agricultural soil, atmospheric dust and major food crops in Kermanshah province, Iran. *Ecotoxicology and Environmental Safety, 163*, 153–164.

Du, Y., Chen, L., Ding, P., Liu, L., He, Q., Chen, B., & Duan, Y. (2019). Different exposure profile of heavy metal and health risk between residents near a Pb-Zn mine and a Mn mine in Huayuan county, South China. *Chemosphere, 216*, 352–364.

Duan, X. (2015). *Highlights of the Chinese Exposure Factors Handbook*. Academic Press. in Chinese.

Guo, Y., Huang, M., You, W., Cai, L., Hong, Y., Xiao, Q., Zheng, X., & Lin, R. (2022). Spatial analysis and risk assessment of heavy metal pollution in rice in Fujian Province, China. *Frontiers in Environmental Science, 10*.

Hasan, M.M., Salman, M.S., Rehan, A.I., Awual, M.E., Rasee, A.I., Waliullah, R.M., Hossain, M.S., Kubra, K.T., Sheikh, M.C., Khaleque, M.A., Marwani, H.M., Islam, A., Awual, M.R. (2023). Facial conjugate adsorbent for sustainable Pb(II) ion monitoring and removal from contaminated water. Colloids and Surfaces A-Physicochemical and Engineering Aspects 131794.

Hu, B., Shao, S., Fu, Z., Li, Y., Ni, H., Chen, S., Zhou, Y., Jin, B., & Shi, Z. (2019). Identifying heavy metal pollution hot spots in soil-rice systems: A case study in South of Yangtze River Delta, China. *The Science of the Total Environment, 658*, 614–625.

Huang, T., Deng, Y., Zhang, X., Wu, D., Wang, X., & Huang, S. (2021). Distribution, source identification, and health risk assessment of heavy metals in the soil-rice system of a farmland protection area in Hubei Province, Central China. *Environmental Science and Pollution Research International, 28*(48), 68897–68908.

Huang, Y., Chen, Q., Deng, M., Japenga, J., Li, T., Yang, X., & He, Z. (2018). Heavy metal pollution and health risk assessment of agricultural soils in a typical peri-urban area in southeast China. *Journal of Environmental Management, 207*, 159–168.

Kubra, K. T., Salman, M. S., & Hasan, M. N. (2021). Enhanced toxic dye removal from wastewater using biodegradable polymeric natural adsorbent. *Journal of Molecular Liquids, 328*, Article 115468.

Kong, X., Liu, T., Yu, Z., Chen, Z., Lei, D., Wang, Z., Zhang, H., Li, Q., & Zhang, S. (2018). Heavy Metal Bioaccumulation in Rice from a High Geological Background Area in Guizhou Province, China. *International Journal of Environmental Research and Public Health, 15*(10).

Li, D. S., Zhang, Q. H., Sun, D. L., Yang, C. L., & Luo, G. F. (2022a). Accumulation and risk assessment of heavy metals in rice: A case study for five areas of Guizhou Province, China. *Environmental Science and Pollution Research, 29*(56), 84113–84124.

Li, D. S., Zhang, C., Li, X. X., Li, F. M., Liao, S. M., Zhao, Y. F., Wang, Z. L., Sun, D. L., & Zhang, Q. H. (2022b). Co-exposure of potentially toxic elements in wheat grains reveals a probabilistic health risk in Southwestern Guizhou, China. *Frontiers in Nutrition, 9*, Article 934919.

Li, F. M., Liao, S. M., Zhao, Y. F., Li, X. X., Wang, Z. L., Liao, C. X., Sun, D. L., Zhang, Q. H., & Lu, Q. H. (2023). Soil exposure is the major fluoride exposure pathways for residents from the high fluoride karst region in Southwest China. *Chemosphere, 310*, Article 136831.

Li, H. B., Wang, J. Y., Chen, X. Q., Li, Y. P., Fan, J., Ren, J. H., Luo, X. S., Juhasz, A. L., & Ma, L. Q. (2020). Geogenic nickel exposure from food consumption and soil ingestion: A bioavailability based assessment. *Environmental Pollution, 265*(Pt B), Article 114873.

Li, Y., Fang, F., Wu, M., Kuang, Y., & Wu, H. (2017). Heavy metal contamination and health risk assessment in soil-rice system near Xinqiao mine in Tongling city, Anhui province, China. *Human and Ecological Risk Assessment: An International Journal, 24*(3), 743–753.

Liu, Y., Lu, W., Wang, H., Gao, X., & Huang, Q. (2019). Improved impact assessment of odorous compounds from landfills using Monte Carlo simulation. *The Science of the Total Environment, 648*, 805–810.

Lu, Q., Xiao, Q., Wang, Y., Wen, H., Han, B., Zheng, X., & Lin, R. (2021). Risk assessment and hotspots identification of heavy metals in rice: A case study in Longyan of Fujian province, China. *Chemosphere, 270*, Article 128626.

Luo, X., Ren, B., Hursthouse, A. S., Jiang, F., & Deng, R. J. (2020). Potentially toxic elements (PTEs) in crops, soil, and water near Xiangtan manganese mine, China: Potential risk to health in the foodchain. *Environmental Geochemistry and Health, 42*(7), 1965–1976.

Mao, C., Song, Y., Chen, L., Ji, J., Li, J., Yuan, X., Yang, Z., Ayoko, G. A., Frost, R. L., & Theiss, F. (2019). Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. *Catena, 175*, 339–348.

Proshad, R., Kormoker, T., Islam, M. S., & Chandra, K. (2019). Potential health risk of heavy metals via consumption of rice and vegetables grown in the industrial areas of Bangladesh. *Human and Ecological Risk Assessment: An International Journal, 26*(4), 921–943.

Qu, C. S., Ma, Z. W., Yang, J., Liu, Y., Bi, J., & Huang, L. (2012). Human exposure pathways of heavy metals in a lead-zinc mining area, Jiangsu Province. *China Plos One, 7*(11), e46793.

Rasee, A. I., Awual, E., Rehan, A. I., Hossain, M. S., Waliullah, R. M., Kubra, K. T., … Awual, M. R. (2023). Efficient separation, adsorption, and recovery of Samarium (III) ions using novel ligand-based composite adsorbent. *Surfaces and Interfaces, 41*, Article 103276.

Salman, M. S., Hasan, M. N., Kubra, K. T., & Hasan, M. M. (2021). Optical detection and recovery of Yb(III) from waste sample using novel sensor ensemble nanomaterials. *Microchemical Journal, 162*, Article 105868.

Sarwar, N., Imran, M., Shaheen, M. R., Ishaque, W., Kamran, M. A., Matloob, A., Rehim, A., & Hussain, S. (2017). Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. *Chemosphere, 171*, 710–721.

Sheikh, C., Hasan, M., Hasan, N., Salman, S., Kubra, K. T., Awual, M. E., Waliullah, R. M., Rasee, A. I., Rehan, A. I., Hossain, M. S., Marwani, H. M., Islam, A., Khaleque, A., & Awual, R. (2023). Toxic cadmium(II) monitoring and removal from aqueous solution using ligand-based facial composite adsorbent. *Journal of Molecular Liquids, 389*, Article 122854.

Song, T., An, Y., Cui, G., Tong, S., & He, J. (2021). Bioconcentrations and health risk assessment of heavy metals in crops in the Naoli River Basin agricultural area, Sanjiang Plain, China. *Environmental Earth Sciences, 80*(12).

Tagumira, A. B., Saphina, A., & Emirant, B. (2022). Concentrations and human health risk assessment of selected heavy metals in soils and food crops around Osukuru phosphate mine, Tororo District, Uganda. *Toxicology Reports, 9*, 2042–2049.

Wang, L., Ma, L., & Yang, Z. (2017). Spatial variation and risk assessment of heavy metals in paddy rice from Hunan Province, Southern China. *International Journal of Environmental Science and Technology, 15*(7), 1561–1572.

Wu, Z., Zhang, L., Xia, T., Jia, X., & Wang, S. (2020). Heavy metal pollution and human health risk assessment at mercury smelting sites in Wanshan district of Guizhou Province, China. *RSC Advances, 10*(39), 23066–23079.

Zang, Z., Li, Y., Liu, S., Li, H., Hao, Z., & Xu, Y. (2020). Assessment of the heavy metal pollution and health risks of rice cultivated in Hainan Island, China. *Environmental Forensics, 22*(1–2), 63–74.

Zhang, J., Yang, R., Chen, R., Peng, Y., Wen, X., & Gao, L. (2018). Accumulation of heavy metals in tea leaves and potential health risk assessment: A case study from Puan County, Guizhou Province, China. *International Journal of Environmental Research and Public Health, 15*(1).

Zhang, T., Xu, W., Lin, X., Yan, H., Ma, M., & He, Z. (2019). Assessment of heavy metals pollution of soybean grains in North Anhui of China. *The Science of the Total Environment, 646*, 914–922.

Zhang, Z., Wu, X., Wu, Q., Huang, X., Zhang, J., & Fang, H. (2020). Speciation and accumulation pattern of heavy metals from soil to rice at different growth stages in farmland of southwestern China. *Environmental Science and Pollution Research International, 27*(28), 35675–35691.