

Ecological and Human Health Risks of Potentially Toxic Elements in the Soil–Lotus Root System Adjacent to Highways

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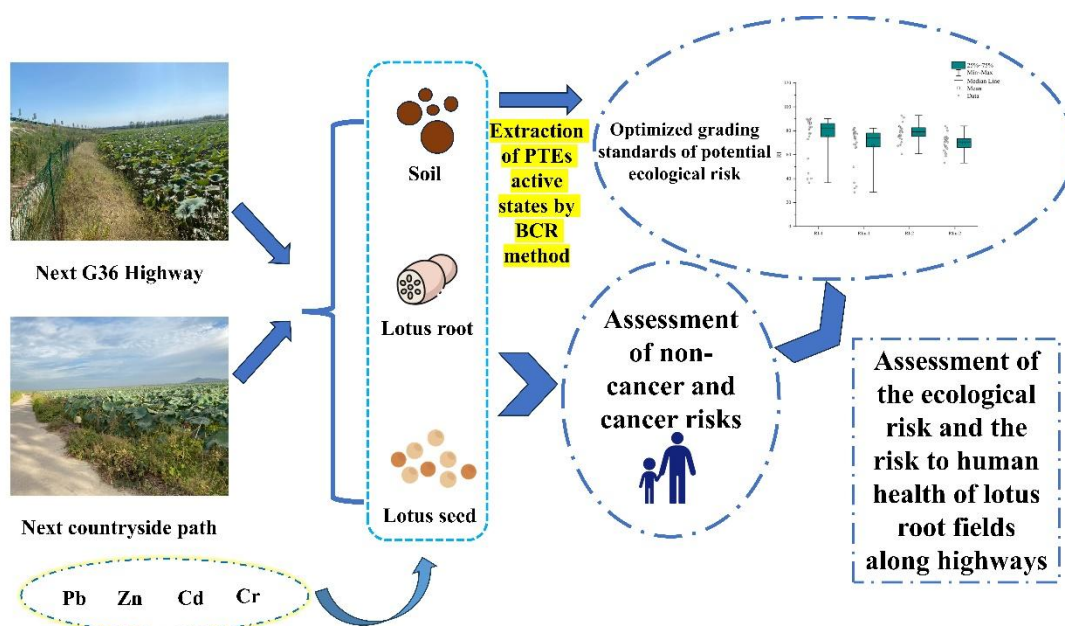
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Ecological and Human Health Risks of Potentially Toxic Elements in the Soil – Lotus Root System Adjacent to Highways

Abstract

Potentially toxic elements (PTEs) from road traffic accumulate in agricultural soils, enter crops, and threaten human health through the food chain. This study investigated PTEs contamination in soil, lotus root, and lotus seed from fields along a highway. Ecological risk assessment based on total PTE contents revealed that Cd posed a high ecological risk, while Zn, Pb, and Cr remained at low or negligible risk levels across both plots. When considering bioavailable fractions through the risk assessment code (RAC), Cd consistently represented the dominant secondary environmental threat due to its elevated acid-soluble proportions. Concurrently, Pb, Zn, and Cr were verified to pose localized low risks owing to their heavy immobilization within stable residual matrices. Non-carcinogenic health risk assessments indicated that children constitute a highly sensitive cohort prone to cumulative exposure via the soil–plant pathway, with lotus seeds identified as the primary contributor to potential carcinogenic risks. These findings provide a scientific basis for controlling PTEs pollution in aquatic crops near highways.



Key words: Roadside agricultural paddy; Ecological risk assessment; Aquatic crops;
Soil management

Environmental implication

This study highlights the environmental implications of PTEs contamination in soils and aquatic crops near highways, emphasizing the risks to ecosystems and human health. The findings demonstrate the need for targeted pollution prevention strategies, particularly for high-risk elements like Cd. The identification of lotus seeds as a significant carcinogenic risk source underscores the importance of monitoring and controlling PTEs uptake in crops. These insights provide a scientific basis for implementing soil remediation measures, promoting sustainable agricultural practices, and establishing stricter regulatory guidelines to mitigate PTEs pollution and their far-reaching effect on environmental and public health.

1. Introduction

The development of roads as a major mode of transportation has progressed rapidly across the country. By the end of 2023, the total mileage of roads in China had reached 5.35 million kilometers (Zheng et al., 2023) . While road construction has facilitated regional economic growth, it has also posed a significant environmental threats to agricultural soils adjacent to these roads . The soil spots on both sides of trunk highways exceed the standard by 20.3 percent and are predominantly contaminated with potentially toxic elements(PTEs), including cadmium (Cd), chromium (Cr), lead (Pb), copper (Cu), and zinc (Zn) (Zeng et al., 2019). Sources of toxic elements in the soil are mainly affected by anthropogenic influences. In traffic activities, exhaust emissions release Pb, Zn and Cr,while brake wear generates Cd and Cr, tyre and road surface wear contribute to the presence of Pb Zn, Cd (Nduka et al. 2023; An et al. 2022; Zhu et al. 2020; Singh et al. 2024). These PTEs are carried by rainfall and subsequently form road runoff, which can contaminate agricultural soils (Adewmi et al. 2022).

Furthermore, organic fertilizers, pesticides, and irrigation water often contain Pb, Zn, Cu, Cd. The excessive application of these elements in agricultural practices and irrigation leads to their accumulation in the soil (Salam et al., 2024; Najmi et al., 2025). In addition, the soil may naturally contain Cd, Zn, and other elements due to the influence of the soil-forming parent material (Aihemaiti et al., 2018). These PTEs accumulate in roadside agricultural soils through runoff and atmospheric deposition, adversely affecting soil quality and crop safety. The contamination of the soil-crop system compromises agricultural product quality and poses risks to human health through transfer along the food chain (Wang et al., 2022; Qin et al., 2021; Cao et al., 2024).

As a major agricultural country, China accounts for a vast production and structural diversity of cultivated crops (Wang et al., 2023). Aquatic vegetables-characterized by their edible organs-constitute a cornerstone of regional agricultural planting structures and local food economies (Jiang et al., 2008). Crucially, the total cultivation area of aquatic vegetables in China has expanded significantly in recent years, exhibiting rapid structural growth (Cui et al., 2022). Due to their highly developed aerenchyma and vascular bundles, aquatic plants are highly efficient in intercepting, absorbing, and translocating potentially toxic elements (PTEs) from pore water, silt deposits, and atmospheric deposition, frequently demonstrating higher bioaccumulation potentials than terrestrial vegetable crops (Xiong et al., 2013; Ghuge et al., 2023).

However, despite the escalating risks associated with road traffic emissions along expanding highway corridors, existing environmental research has predominantly focused on terrestrial staples such as wheat, corn, and dryland rice, leaving a critical knowledge gap regarding roadside aquatic ecosystems (Shammi et al., 2021; Singh et al., 2024). In particular, lotus root (*Nelumbo nucifera*), which commands the largest cultivation footprint among all aquatic vegetables in China, remains poorly understood under the synergistic regulation of agricultural inputs and traffic-derived pollution (Xiong et al., 2013; Luo et al., 2017). This study aims to bridge this research gap by systematically evaluating the total concentrations and bioavailable fractions of Pb, Cd, Zn and Cr in the soil-lotus root system adjacent to a high-traffic expressway network and a control rural road. By

integrating modified BCR sequential extraction with refined human health risk assessment models for both lotus roots and seeds, these findings establish a rigorous theoretical foundation for food safety monitoring and risk mitigation along transportation corridors (Jayarathne et al., 2018).

2 Study method

2.1 Study area

The study focused on two lotus root fields: one located on the side of the road at the intersection of G36 Ningluo Expressway and S15 Xu-Meng Expressway in Huai Shang District, Bengbu City (Sample Plot 1) and the other situated on the side of a countryside path in Finding Township, Huai Yuan County (Sample Plot 2). The G36 Ningluo Expressway in Sample Plot 1 is one of the primary transportation routes in China, with an average daily traffic volume of 35553 Passenger Car Unit each day (pcu/d), a roadway width of 21 to 26 meters(m), a design speed of 120 km/h, and a relatively flat terrain that is situated at a distance from densely populated areas and industrial pollutants. The expressway is approximately 2 m above the surrounding farmland. In contrast, Sample Plot 2 is a sparsely populated rural area with a lower traffic volume.

2.2 Material and sample analysis

2.2.1 Sampling Point Layout

Upon completing the field survey along the study route, several key factors were considered in selecting the study area, including topographic relief, traffic flow, farmland distribution patterns along the route, and other locational characteristics. Sample Plot 1 is characterized by an embankment and a fence located approximately 5 m from the roadside. Five sampling sections were established parallel to the road's direction of travel, with the fence serving as the boundary. These sections were positioned at distances of 0 m, 10 m, 20 m, 80 m, and 100 m from the fence. In Sample Plot 2, the lotus root field lies directly adjacent to the road. To ensure a representative sample, five sections were similarly established parallel to the road's direction, using the roadside as the boundary. These sections were also situated at distances of 0 m, 10 m, 20 m, 80 m, and 100 m from the road. For each section in both plots, five sample points were collected, spaced 50 meters apart, to enhance the representativeness of the data. The exact locations of all sampling points are depicted in Figure 1. In total, 50 soil samples from paddy fields and 50 plant samples from lotus roots and seeds were collected for analysis.

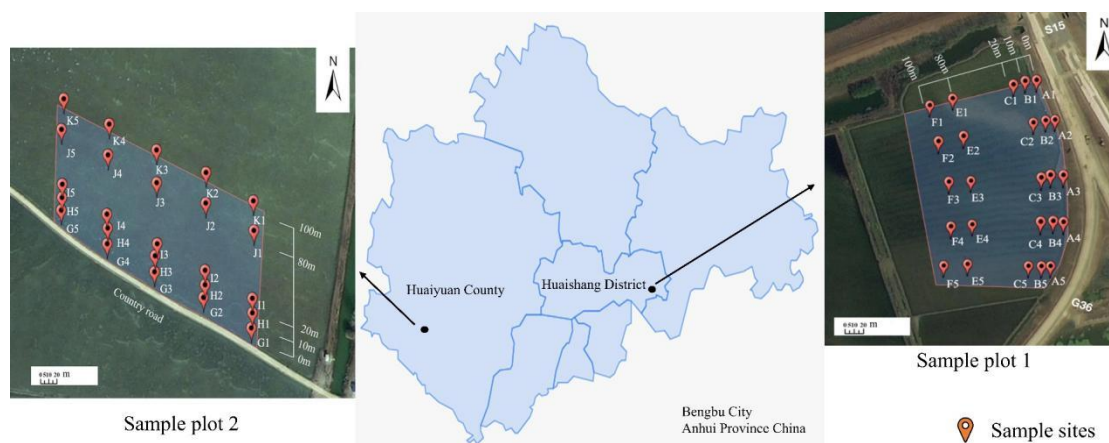


Fig.1 Sample plot sampling map

2.2.2 Sample collection and pre-processing

(1) Soil sampling

In accordance with the established sampling points, each point was designated a 2m×2m sampling unit. A grab sampler was utilized in each unit to determine the sampling depth, and five sub-samples were collected from the surface layer of the submerged soil (0~20 cm), with each sub-sample weighing 100 g. These samples were thoroughly mixed and placed into a polyethylene bag, thus forming a soil sample. The soil samples collected from the root field were transferred to a dust-free laboratory for natural air-drying. Once air-dried and any impurities had been removed, they were ground with an onyx mortar, passed through a 100~mesh nylon sieve, and then sampled using the tetrad method. They were then placed in polyethylene bags for preservation prior to testing.

(2) Crop sampling

Each unit was designated as a 2 m×2 m sampling area. The lotus root and lotus seeds were collected from each unit, with five sub-samples taken from each. These sub-samples were then thoroughly mixed and placed into a polyethylene bag, representing the crop samples. The crop samples were then rinsed with tap water to remove soil particles and subsequently with deionised water. They were then chopped with a porcelain knife, air-dried, placed in Petri dishes or envelopes, and heated in an oven set to 110~115°C for 30 minutes. This was followed by a second heating cycle at 70~75°C to achieve constant weight. The lotus seeds were then crushed using a stainless steel high-speed universal pulveriser and passed through a 100~mesh nylon sieve. The material was then placed in a paper bag for subsequent measurement.

2.2.2 Experimental analysis

The principal focus of the study is the digestion of plant samples, the refinement of the BCR method for the extraction of bioavailable PTEs, and the digestion of soil samples in both whole and residue states. Steps of plant ablation refer to Zhu's method (Zhu et al., 2024) : Weighed 0.2 g of pre-treated crop samples and poured into a polytetrafluoroethylene ablation jar; 6 ml HNO₃ (70%) and 2 ml H₂O₂ (30%) were placed. The jar was placed in a CEM Mars one microwave digestion instrument for digestion. After digestion, the instrument was cooled down to below 80°C, and the jar was removed. Acid was driven, fixed volume, fixed volume with a disposable water washing filter 10 ml solution into a centrifuge tube, well labeled, and stored for measurement. Steps for the extraction of PTEs active states by BCR method (Jayarathne et al., 2018), as Table 1 shows.

Table1

Modified BCR sequential extraction procedures

Step	Morphological	Extraction conditions	Extraction reagents (0.5g soil sample)
I	Weak Acid	25 °C, oscillation 16 h	20 ml 0.11 mol·L ⁻¹
	Extractable State		CH ₃ COOH
II	Reducible State	25 °C, oscillation 16	20 ml 0.5 mol·L ⁻¹
	(chemistry)	h,pH=1.5	NH ₂ OH·HCl
III	Oxidizable State	85 °C, Intermittent	(1) 5 ml 8.8 mol·L ⁻¹ H ₂ O ₂
		oscillation 1h,pH=2-3	
		85 °C, Intermittent	(2) 5 ml 8.8 mol·L ⁻¹ H ₂ O ₂
		oscillation 1h,pH=2-3	(3) 25 ml 1.0 mol·L ⁻¹
IV	Residual State	25 °C, oscillation 16	CH ₃ COONH ₄
		h,pH=2.0	HF + HCL + HClO ₄ +
		Digestion	HNO ₃

Method for the total determination of PTEs in soil refer to Yu's (Yu et al., 2024) method: The pre-treated crop samples were weighed at 0.1 g and transferred to a polytetrafluoroethylene ablation tank. Subsequently, 6 ml HNO₃ (70%), 2 ml H₂O₂ (30%), and 2 ml HF (40%) were added. The remaining steps were followed as per the instructions for the plant samples.

Once processed, the concentrations of PTEs in the lotus root, lotus seed, and soil in its entirety and active state were determined using ICP-OES. To ensure accuracy and precision, one blank and parallel sample were included in each batch of 15 samples. Each sample was then analyzed three times, mean recoveries for metal elements in soil samples were within 100±5% of the standard material recoveries. The mean value of percentage recovery for sequential extraction was 95±5%. The test quality parameters all met the standard requirements.

2.3 Evaluation method

The potential ecological risk index (RI) was employed to assess the ecological risk associated with soil PTEs contamination. Additionally, the non-carcinogenic and carcinogenic risk assessments were conducted to determine the health risks to the exposed lotus root and lotus seed population.

Potential Ecological Risk Index

The Potential Ecological Risk Index method takes into account the nature of PTEs, environmental fate characteristics, concentration levels, biotoxicity, ecological effects, etc (Xiang et al., 2021). In this study, in addition to the selection of the traditional (RI), an ecological risk index approach based on improved bioavailability (RI_m) was also used (Jayarathne et al., 2018). The corresponding formulas are presented in Equations (1), (2), (3):

$$C_f^i = C_s^i / B_n^i \quad (1)$$

$$E_r^i = T_f^i / C_f^i \quad (2)$$

$$RI = \sum_{i=1}^n E_r^i \quad (3)$$

where C_f^i is individual PTE contamination factor; C_s^i is the amount of PTE i with the unit of mg·kg⁻¹. B_n^i is the background value for PTE i with the unit of mg·kg⁻¹. T_f^i is the toxicity response factor for PTE i . In this study, the optimized scoring criteria of the potential

ecological risk index method were used, and the criteria for soil potential ecological risk index contamination are given in Table 2 and Table 3.

Table 2

Pollution standard of soil potential ecological risk index

E_i^f	Risk degree of E_i^f	RI	Risk degree of RI
$E_i^f < 40$	Low	$RI < 150$	Low
$40 \leq E_i^f < 80$	Moderate	$150 \leq RI < 300$	Moderate
$80 \leq E_i^f < 160$	Considerable	$300 \leq RI < 600$	Considerable
$160 \leq E_i^f < 320$	High	$RI \geq 600$	Very high
$320 \leq E_i^f$	Very high		

Table 3

Optimized grading standards of potential ecological risk

Index	Elements	Risk degree				
		Low	Medium	High	Very High	Extremely High
E_i^f	Cd	<30	30~60	60~120	120~240	≥ 240
	Cr	<2	2~4	4~8	8~16	≥ 16
	Pb	<5	5~10	10~20	20~40	≥ 40
	Zn	<1	1~2	2~4	4~8	≥ 8
RI		<50	50~100	100~200	200~400	≥ 400

Assessment of non-cancer and cancer risks

Using the United States Environmental Protection Agency's (USEPA) human health risk assessment methodology, which is divided into non-carcinogenic risk assessment and carcinogenic risk assessment, the results of the mathematical model reflect the health risk of direct consumption of lotus root and seeds by adults and children.

The non-carcinogenic risk was evaluated using the Average Daily Dose (ADD) model, as represented by the formula (4)(5)(6).

$$ADD=(EF \times ED \times IR \times C)/(BW \times AT) \quad (4)$$

$$THQ = ADD/RfD \quad (5)$$

$$HI=THQ_{Pb}+THQ_{Cd}+THQ_{Cr}+THQ_{Zn} \quad (6)$$

Which ADD is average daily dose with $mg \cdot (kg \cdot d)^{-1}$. The parameters used in the formula include exposure frequency (EF), exposure duration (ED), ingestion rate (IR), contaminant concentration (C), body weight (BW), and averaging time (AT). THQ shows the target hazard quotient for individual PTE. RfD is the Reference exposure dose for PTEs with a unit of $mg \cdot (kg \cdot d)^{-1}$. HI is the sum of THQ of multiple PTEs. When the HI is less than or equal to 1, the risk level is considered slight or negligible. However, when HI exceeds 1, it indicates that multiple heavy metals may pose potential health risks to humans. The higher the HI value, the greater the risk level (Yang et al., 2019). The meanings and reference values for these parameters were shown in Table 4.

Table 4

Non-carcinogenic evaluation Parameter meaning and value

Parameter	Name	Unit	Parameter Values
EF	Exposure Frequency	day ⁻¹	365
ED	Exposure Duration	year	10 for children; 30 for adults
IR	Ingestion Rate of Vegetables	kg·day ⁻¹	0.2 for children; 0.3 for adults
C	Concentration in Vegetables	mg·kg ⁻¹	Measured value
BW	Body Weight	kg	15.9 for children; 56.8 for adults
AT	Averaging Time	day	3650 for children; 10950 for adults

Carcinogenic risk evaluation models are shown in (7) and (8):

$$ILCR = ADD \times SF \quad (7)$$

$$ILCR_n = \sum ILCR \quad (8)$$

where ILCR is the cancer risk of single PTE. SF is the carcinogenicity slope factor in $\text{kg} \cdot (\text{d} \cdot \text{mg})^{-1}$; $ILCR_n$ is the integrated carcinogenicity risk. The evaluation criteria for carcinogenic risk assessment is shown in Table 5.

Table 5

Carcinogenic evaluation criteria

Index value	Risk level	Index value	Risk level
$ILCR < 10^{-6}$	No risk	$ILCR_n < 10^{-6}$	No risk
$10^{-6} < ILCR \leq 10^{-4}$	Acceptable	$10^{-6} < ILCR_n \leq 10^{-4}$	Acceptable
$ILCR > 10^{-4}$	Unacceptable	$ILCR_n > 10^{-4}$	Unacceptable

3 Results

3.1 Potential ecological risk assessment of rooted field soils along highways

The soil background values for PTEs in Anhui Province were selected as reference values for the study (Teng et al., 2014), Analysis E_r^i , E_{rm}^i , RI, RI_m of Zn, Pb, Cd and Cr (Wan et al., 2021; Zheng et al., 2020), (See table 6,7). The percentage of the total number of sample points with different levels of contamination is shown in Table 8.

Table6

Potential ecological risk and risk levels of the total amount of PTEs in soil

Plot	Fractions	Range	Risk range	Mean	Risk degree
1	E_r^{Zn}	0.33~1.61	Low-Moderate	0.86	Low
	E_r^{Pb}	6.42~10.53	Moderate-High	8.80	Moderate
	E_r^{Cd}	25.52~77.29	Low-Moderate-High	62.12	High
	E_r^{Cr}	3.00~4.10	Moderate-High	3.66	Moderate
	RI	36.49~90.21	Low-Moderate	75.43	Moderate
2	E_r^{Zn}	0.58~1.14	Low-Moderate	0.94	Low

E_r^{Pb}	8.44~10.92	Moderate-High	9.70	Moderate
E_r^{Cd}	47.55~78.85	Moderate-High	63.95	High
E_r^{Cr}	3.54~3.94	Moderate	3.79	Moderate
RI	60.74~92.88	Moderate	78.38	Moderate

Table 7

Potential ecological risk and risk levels based on available PTEs in soil in plots

Plot	Fractions	Range	Level range	Mean	Risk degree
1	E_{rm}^{Zn}	0.21~0.82	Low	0.40	Low
	E_{rm}^{Pb}	2.41~6.14	Low-Medium	4.45	Low
	E_{rm}^{Cd}	25.52~77.29	Low-Medium-High	62.12	High
	E_{rm}^{Cr}	0.30~0.43	Low	0.36	Low
	RI _m	28.59~82.26	Low-Medium	67.33	Medium
2	E_{rm}^{Zn}	0.25~0.45	Low	0.32	Low
	E_{rm}^{Pb}	4.45~5.49	Low-Medium	5.07	Medium
	E_{rm}^{Cd}	47.55~78.85	Medium -High	63.95	High
	E_{rm}^{Cr}	0.28~0.38	Low	0.34	Low
	RI _m	53.15~83.98	Low-Medium	69.68	Medium

Table 8

The percentage of RI and RI_m sample points of different grades in two plots

Project	Plot	Account (%)		
		Low	Medium	High
RI	1	16	84	0
	2	0	100	0
RI _m	1	20	80	0
	2	0	100	0

As shown in Table 6, significant differences in the mean E_r^i values were observed between the two sample plots. In Sample Plot 1, Zn, Pb, and Cr exhibited low or negligible ecological risk, whereas Cd posed a distinct high ecological risk (E_r^{Cd} range: 25.52–77.29). The stable geochemical nature of Pb (E_r^{Pb} : 6.42 – 10.53) and Cr (E_r^{Cr} : 3.00 – 4.10) restricted their environmental mobility, keeping them strictly within low-risk limits, whereas Zn (E_r^{Zn} : 0.33 – 1.61) fluctuated between low and medium risk. In Sample Plot 2, the mean E_r^i values followed the order Cd (63.95) > Pb (9.70) > Cr (3.79) > Zn (0.94), with risk levels similar to Sample Plot 1. E_r^{Cd} (47.55 – 78.85) and E_r^{Pb} (8.44 – 10.92) encompassed medium to high risks, while E_r^{Zn} (0.58 – 1.14) and E_r^{Cr} (3.54 – 3.94) remained within the low to medium risk range.

Table 7 indicates significant differences in E_{rm}^i values between the two plots, with results aligning with E_r^i due to the active state detection of Cd. In Sample Plot 1, the mean E_{rm}^i values ranked as Cd (62.12) > Pb (4.45) > Zn (0.40) > Cr (0.36), with Cd in the high-risk category and all other elements in the low-risk range. The risk levels of Zn (E_{rm}^{Zn} : 0.21 – 0.82) and Cr (E_{rm}^{Cr} : 0.30 – 0.43) remained low, while Pb (E_{rm}^{Pb} : 2.41 – 6.14) fluctuated between low and medium risk. In Sample Plot 2, the ranking was Cd (63.95) > Pb (5.07) > Cr (0.34) > Zn (0.33), maintaining similar risk classifications. The ecological risk of Zn (E_{rm}^{Zn} : 0.21 – 0.82) and Cr (E_{rm}^{Cr} : 0.30 – 0.43) remained low, while Pb (E_{rm}^{Pb} : 4.45 – 5.49) spanned low to medium risk levels.

As shown in Table 8, the proportion of RI sites in Sample Plot 1 was 16% low risk and 84% medium risk, which was similar to the proportion of RI_m sites (20% low risk and 80% medium risk sites). The proportion of RI and RI_m sites in Sample Plot 2 was consistent and all sites were medium risk. The RI and RI_m in the two sample plots are shown in Figure 2.

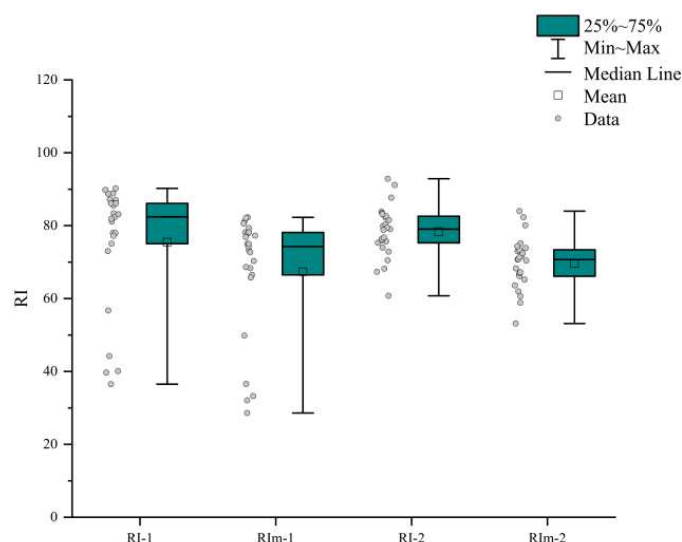


Fig. 2 RI、RI_m of soil PTEs in twp plots

Combining the data from Tables 6 to 8 and Figure 2, it was evident that the combined potential ecological risk (RI and RI_m) of PTEs in the two sample plots showed significant differences.. The mean RI value for Sample Plot 1 was 75.43, indicating a medium risk level, with the RI ranging from 36.49 to 90.21. This reflected a fluctuation in ecological risk, varying from low to medium risk.

The ecological risk assessment indicated that Sample Plot 2 had a mean RI of 78.38 (range: 60.74 – 92.88), consistently falling within the medium risk level. In Sample Plot 1, the mean RI was 67.33 (range: 28.59 – 82.26), with 80% of sites classified as medium risk and 20% as low risk (RI < 50). The RI_m values in Sample Plot 2 ranged from 53.15 to 83.98, with all sites categorized as medium risk. Zn posed a negligible ecological risk at both sites, while Pb and Cr exhibited low to medium risk with minimal fluctuation. In contrast, Cd was the primary pollutant of concern, displaying a broader risk range from low to high, with a predominant high-risk classification.

3.2 Health risk assessment of lotus roots and seeds along highways

3.2.1 Evaluation of non-carcinogenic risks

In this study, the measured concentrations of Zn, Pb, Cd, and Cr in lotus root and lotus seed were used to evaluate non-carcinogenic risks. These values were substituted into the non-carcinogenic risk assessment model to calculate the target hazard quotients for children (THQ_c) and adults (THQ_a). Additionally, the overall hazard indices for children (HI_c) and adults (HI_a) were derived to assess the cumulative non-carcinogenic risk posed by the intake of these pollutants from lotus root and lotus seed.

The results of the risk assessment for THQ_c and THQ_a in lotus root and lotus seed from the two sample plots are summarized in Figure 3 to 6. Furthermore, the cumulative risk assessment results for Hlc and Hla in lotus root and lotus seed across the two sample plots are detailed in Figure 7.

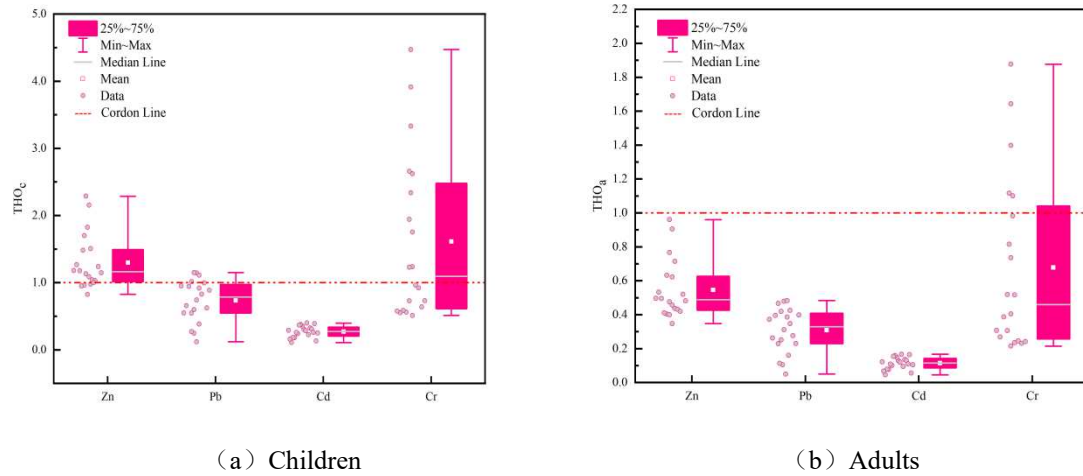
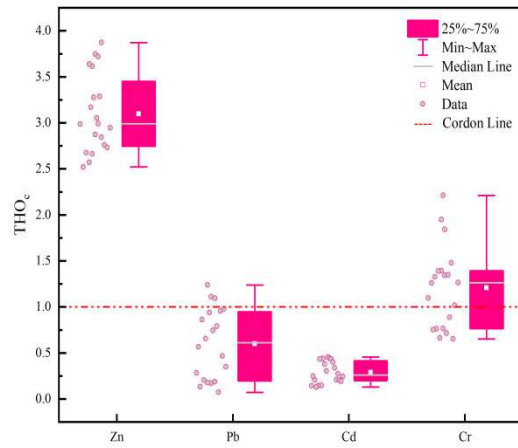


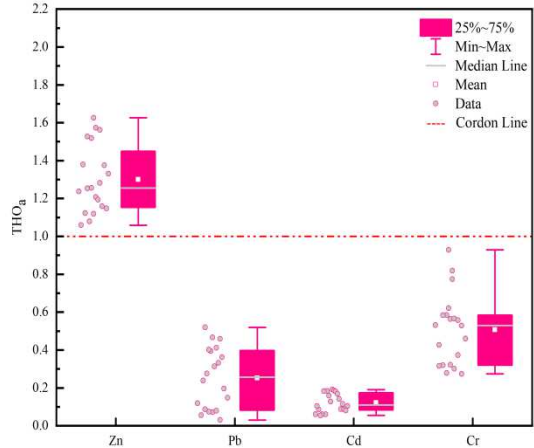
Fig. 3 THQ_c 、 THQ_a of PTEs in lotus root in Sample Plot 1

The THQ_c in lotus root at Sample Plot 1 ranked as follows based on mean values: Cr (1.61) > Zn (1.30) > Pb (0.73) > Cd (0.27). The THQ_c values for Pb and Cd were less than Plot 1, indicating negligible effects on humans, with non-carcinogenic risks that could be disregarded. However, Zn and Cr presented potential non-carcinogenic risks as their THQ_c values exceeded Plot 1.

For adults, the THQ_a of lotus root ranked as Cr (0.68) > Zn (0.55) > Pb (0.31) > Cd (0.11) based on mean values. The non-carcinogenic risks for all four PTEs were negligible for adults, as their THQ_a values were less than or equal to Sample Plot 1



(a) Children



(b) Adults

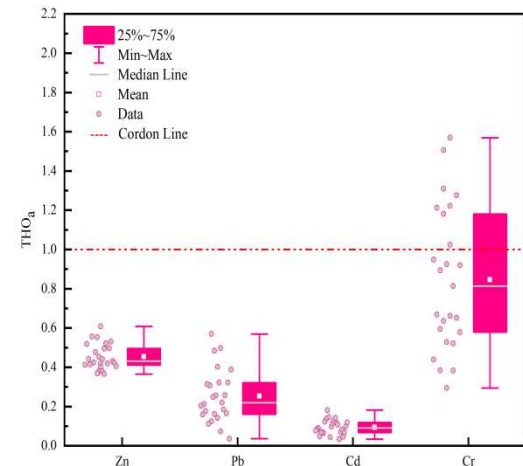
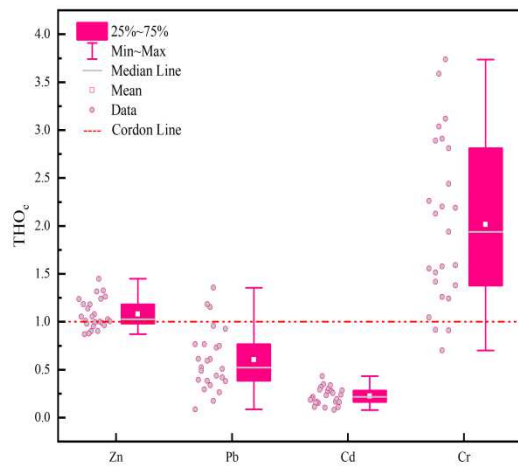
Fig. 4 THQ_c、THQ_a of PTEs in lotus seed in Sample Plot 1

265

266 Based on Figure 4, the THQ_c for lotus seeds in Sample Plot 1 was ranked by mean
 267 value as follows: Zn (3.10) > Cr (1.21) > Pb (0.60) > Cd (0.29). The THQ_c values for Pb and
 268 Cd were less than or equal to Plot 1, indicating negligible non-carcinogenic risks. In
 269 contrast, Zn and Cr posed potential non-carcinogenic risks, with THQ_c values exceeding
 270 Plot 1.

271 For adults, the THQ_a of lotus seeds ranked by mean value as Zn (1.30) > Cr (0.51) > Pb
 272 (0.25) > Cd (0.12). The non-carcinogenic risks for Cr, Pb, and Cd were negligible (THQ_a ≤
 273 1). However, Zn presented a potential non-carcinogenic risk, with a THQ_a value greater than
 274 Sample Plot 1.

275



(a) Children

(b) Adults

Fig. 5 THQ_c、THQ_a of PTEs in lotus root in Sample Plot 2

Combining Figure 5, the THQ_c of lotus root at Sample Plot 2, ranked by mean value, was Cr (2.01) > Zn (1.08) > Pb (0.60) > Cd (0.22), consistent with the ranking in Sample Plot 1. The non-carcinogenic risks of Pb and Cd were negligible, while Zn and Cr posed potential non-carcinogenic risks (THQ_c > 1). The THQ_a of lotus root, ranked by mean value, was Cr (0.85) > Zn (0.45) > Pb (0.25) > Cd (0.09). The risk assessment results for all four elements were negligible.

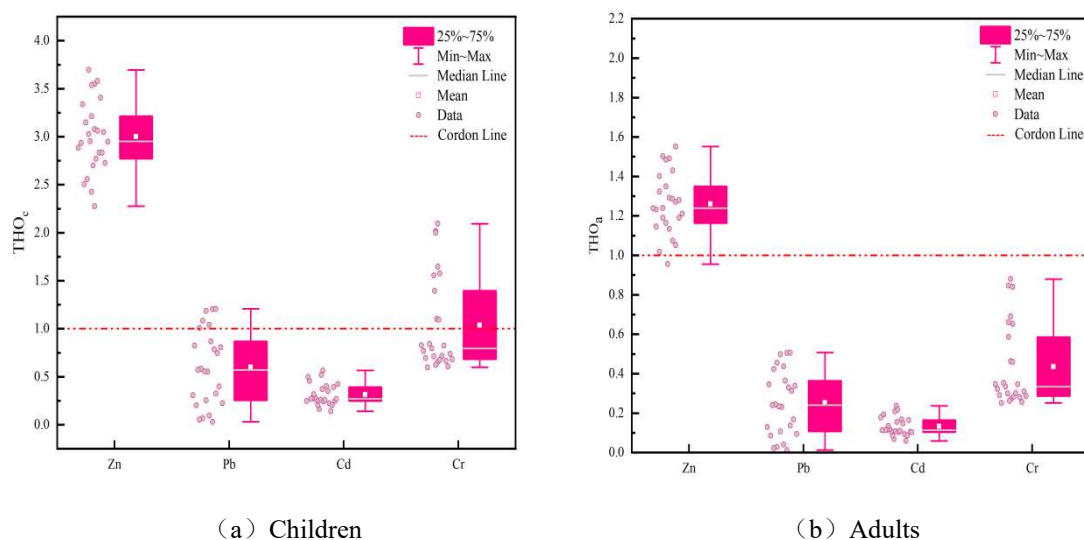


Fig. 6 THQ_c、THQ_a of PTEs in lotus seed in Sample Plot 2

Combining the data from Figure 6, the THQ_c for lotus seed in Sample Plot 2 ranked by mean value as Zn (3.00) > Cr (1.04) > Pb (0.60) > Cd (0.31). The THQ_a followed a similar ranking: Zn (1.26) > Cr (0.44) > Pb (0.25) > Cd (0.13). The THQ_a results for lotus seed in Sample Plot 2 were consistent with those in Sample Plot 1.

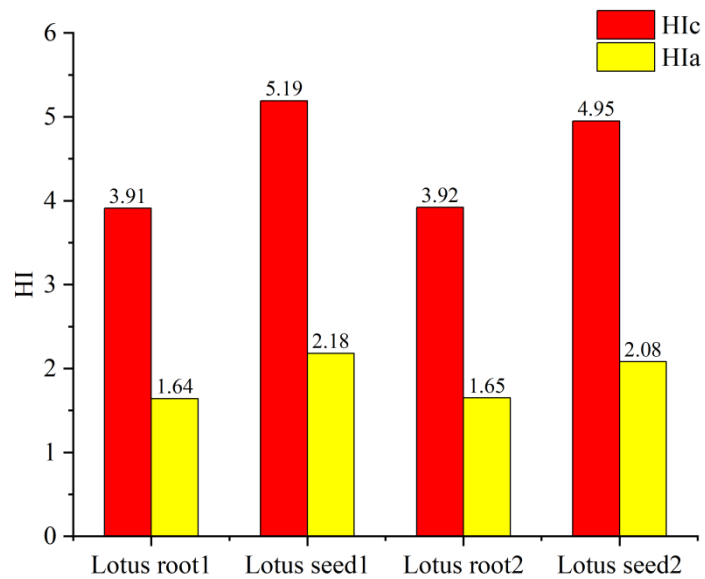


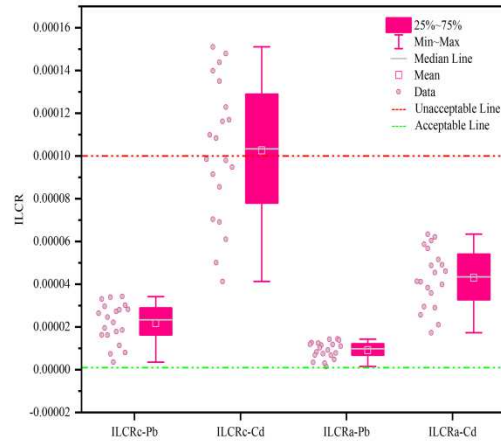
Fig .7 HI of lotus root and lotus seed in two plots

As shown in Figure 7, the mean values of HI_c for lotus root and lotus seed in Sample Plot 1 were ranked as lotus seed > lotus root. Similarly, in Sample Plot 2, the mean values of HI_c followed the same order: lotus seed > lotus root. The mean values of HI_a in both sample plots also exhibited this trend.

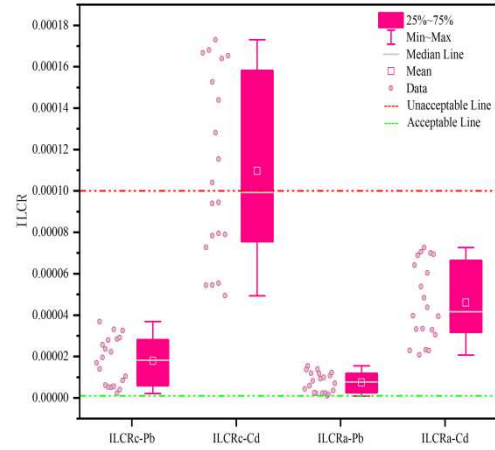
The HI_c and HI_a values for lotus root and lotus seed in the study area ranged from 1 to 10, indicating potential combined non-carcinogenic risks from multiple PTEs, with lotus seed posing the highest combined risk. However, neither the THQ_c and THQ_a for children nor the HI_c and HI_a for adults showed a significant difference in magnitude between the two sample plots, as the values were very similar across both locations.

3.2.2 Evaluation of carcinogenic risks

The International Association for Research on Cancer (IARC) classifies Cd and Pb as carcinogens, so in this study, the measured values of Pb and Cd in lotus root and lotus seed in the two sample plots were substituted into the cancer risk assessment model to obtain the single PTE carcinogenic risk ($ILCR_c$, $ILCR_a$) and the combined carcinogenic risk $ILCR_{cn}$, $ILCR_{an}$) for children and adults. The results of the $ILCR_c$, $ILCR_a$ in lotus root and lotus seed are show in Figure 8 and Figure 9.

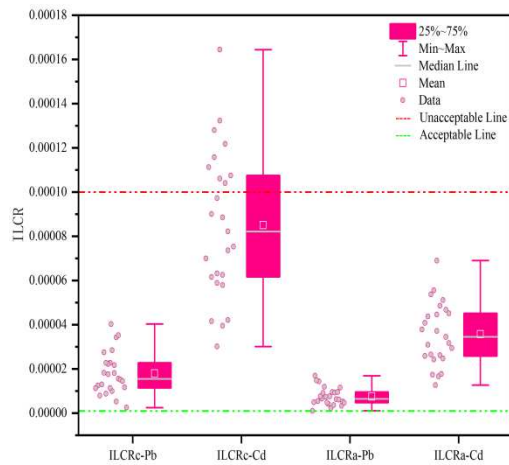


(a) lotus root

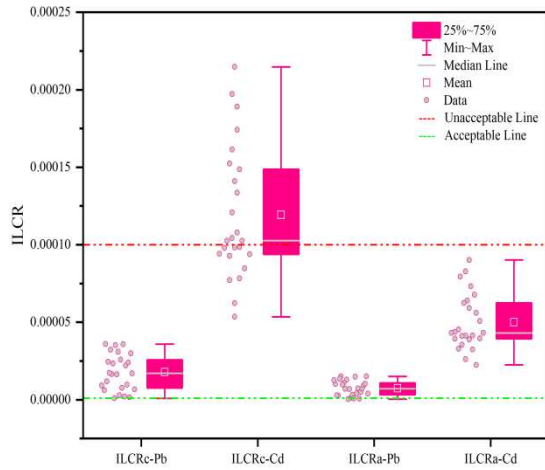


(b) lotus seed

Fig. 8 $ILCR_c$ 、 $ILCR_a$ of Pb and Cd in lotus root and lotus seed in Sample Plot 1



(a) lotus root



(b) lotus seed

Fig. 9 $ILCR_c$ 、 $ILCR_a$ of Pb and Cd in lotus root and lotus seed in Sample Plot 2

As shown in Figures 7 and 8, the carcinogenic risks of Pb and Cd in lotus root and lotus seed in the two Sample Plots were significantly higher than those based on adults. The mean and maximum values of the carcinogenic risk of Cd in lotus seed were higher than those of lotus root. The mean value of the cancer risk based on children for Cd was higher than the cancer risk based on adults, the mean value of the cancer risk based on children for Pb was higher than the cancer risk based on adults for Pb, and the mean value of the cancer risk based on children for Cd was higher than the cancer risk based on adults for lotus root and lotus seed in the two sample plots.

The results of the percentages of different risk levels of $ILCR_{cn}$ in lotus root and lotus seed in the two sample plots are given in Figure 10.

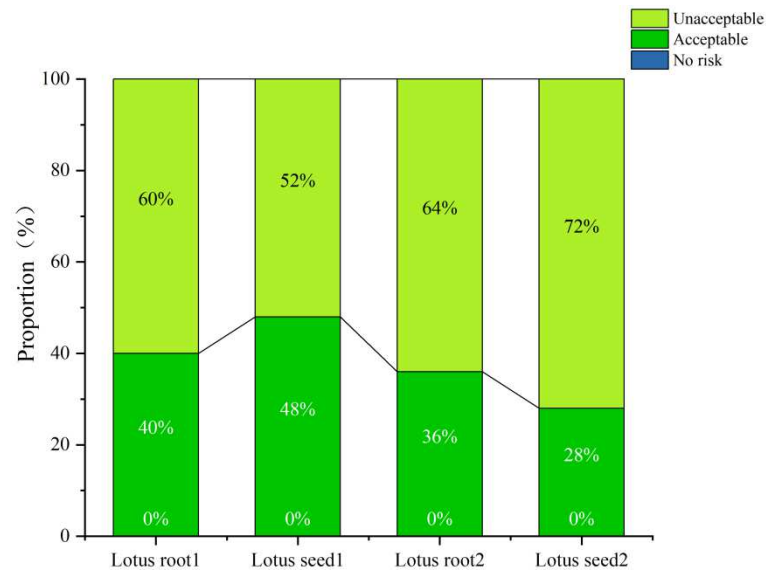


Fig .10 Different risk levels of $ILCR_{cn}$ in lotus root and lotus seed in two plots

As shown in Figure 10, the proportion of samples with unacceptable risk in Sample Plot 2 was higher in Sample Plot 1, suggesting higher carcinogenic risk from PTEs in these crops.

4 Discussion

4.1 Soil ecological risk assessment

For Zn, Pb, Cd and Cr, the mean values, whether based on the total amount of E_r^i and RI or on the effective state content E_{rm}^i and RI_m , showed a trend of Sample Plot2 > Sample Plot 1, indicating that the potential ecological risk was higher in Plot 2, although Zn, Pb, and Cr primarily represented low or negligible risks. The reason for these phenomena could be that the isolation barriers, The presence of elevated levels of fast-acting potassium is indicative of the potential application of greater quantities of organic fertiliser within the designated sample plot 2. (Zhang et al., 2015; Yao et al., 2021; Jeong et al., 2022). These factors lead to the PTEs content in Sample Plot 1 having obvious high-value area and low-value area, so the phenomenon that the ecological grade fluctuation range of sample Plot 1 was larger and the mean value was smaller. At the same time, because there was no obvious shelter on the roadside of Sample Plot 2, the PTE particles generated by traffic activities were very susceptible to the influence of wind speed and wind direction, and the soil measured downwind of the road tended to show a higher concentration of PTEs (Shajib et al., 2019). The study area was situated in a subtropical

monsoon climate with prevailing northerly winds in winter, and Sample Plot 2 was located directly north of the road, thus presenting a greater potential ecological risk in Sample Plot 2. The results of E_r^i and E_{rm}^i showed that, except for Cd, the E_{rm}^i of the other three elements were smaller than E_r^i , especially in Cr which was more obvious, this was because of the residual state which was not easy to utilise in Zn, Pb and Cr occupy a certain proportion. In the two Sample Plots, the proportion of Cr in the residual state was 90.13% and 91.07% respectively, so the E_{rm}^i of Cr was much smaller than that of E_r^i . This size trend was also reflected in the two sample plots RI and RI_m , indicating that traditional potential ecological risk assessment tend to overestimate the localized toxicological hazards of highly immobilized elements, whereas the bioavailability-based approaches provide a more robust reflection of the actual environmental risks (Williams et al., 2020, Ahmad et al., 2022). The improved bioavailability-based ecological risk index method can more accurately assess the environmental hazards of PTEs and increase the applicability and flexibility of the potential ecological risk index method (Liu et al., 2021; Son et al., 2021; Kowalska et al., 2018). Based on the above results, it is recommended to monitor the soil at different locations on both sides of the road in zones, especially in downwind areas (e.g. Sample Plot 2) and in areas with weak barrier effects, with a focus on PTEs (e.g. Cd, Pb) that are easily diffused. Based on the monitoring results, risk assessment and land management strategies will be dynamically adjusted. In addition, improved ecological risk assessment methods based on bioavailability will be used as much as possible to improve the scientific validity and accuracy of the assessment results and to avoid misinterpretation of the ecological risk level.

4.2 Crop health risk assessment

4.2.1 Evaluation of non-carcinogenic risk of crops

The risk assessment results for THQ_c , THQ_a , HI_c and HI_a of lotus root and lotus seed in the two sample plots demonstrated that the probability of non-carcinogenic risk for children was markedly higher than that for adults. With regard to the non-carcinogenic risk of a PTE and the composite non-carcinogenic risk of multiple PTEs, it is evident that children constitute a sensitive group, exhibiting a greater propensity to be exposed to hazards associated with the ingestion of PTEs. This finding is in alignment with the results of the study of Rinklebe (Rinklebe et al., 2019), Mamat (Mamat et al., 2020) and Heidari (Heidari et al., 2021). Overall, lotus seeds pose a higher potential non-carcinogenic risk to children and adults than lotus roots. For lotus roots, although Zn, Pb, Cd, and

Cr have small and negligible negative effects on adults, Zn, Cr both pose a potential non-carcinogenic risk to children, and also lotus roots exhibit a potential composite carcinogenic risk to humans. The present study area needs to focus on the non-carcinogenic health risks of Zn and Cr in lotus root to human beings. The main sources of traffic of Zn, Cr in roadside paddy field soils are tyre and road wear and tear, shedding of materials from automobile parts, etc (Gorka et al., 2022; Hao et al., 2023; Peng et al., 2024). In the future, the use of improved materials for car tyres and body components could effectively reduce the deposition of PTEs particles on the roadside, thereby reducing the risk to human health. Zn, a micronutrient essential for plant growth, is required for photosynthesis and protein metabolism; consequently, it is often added to fertilizers. Excessive fertilizer application in lotus root fields may also contribute to the elevated health risk associated with Zn (Soudek et al., 2014; Wan et al., 2021; Fu et al., 2022).

The data revealed no significant correlation between the two sample plots for either the THQ_c and THQ_a based on children or the HI_c and HI_a based on adults. Furthermore, the majority of the values were found to be extremely close to each other. This suggests that the risk threat level of the two sample plots is not significantly correlated with PTEs from road traffic sources. Despite the proximity of Sample Plot 1 to a motorway, which renders it more susceptible to pollution from traffic sources, the presence of fences and vegetation barriers adjacent to the highway impedes the diffusion of PTEs from traffic sources. Conversely, although the traffic volume of Sample Plot 2 is low, its proximity to a road allows for the diffusion of PTEs in road sediment along with runoff directly to the root field (Islam et al., 2024; Ahmed et al., 2016; Kaur et al., 2022). It is therefore recommended that priority be given to the design and construction of reasonable vegetation barriers alongside motorways or heavily trafficked roads. This may entail the installation of green belts of appropriate widths and the planting of vegetation with high adsorption capacity. The objective of such measures would be to reduce the impacts of traffic pollutants on the surrounding environment. It is imperative that the frequency of sediment cleaning be increased in road management, particularly during the rainy season or in areas where runoff is likely to occur. This is to prevent the spread of PTEs pollution to surrounding land use types that are sensitive to such contamination.

4.2.2 Evaluation of carcinogenic risk of crops

The carcinogenic risk of Pb and Cd in lotus root and lotus seed in the two plots was markedly elevated in comparison to that observed in adults, a finding that was consistent with the

non-carcinogenic risk. Meanwhile, the carcinogenic risk level of Cd was higher than that of adults, which may be attributed to the fact that Cd possesses the largest carcinogenicity slope factor, and lotus roots and lotus seeds are more capable of accumulating Cd (Chinnannan et al., 2024). The mean and maximum values of the carcinogenic risk of Cd in lotus seeds were higher than those of lotus roots, and the number of points that reached the unacceptable carcinogenic risk level was also higher. This indicates that lotus seeds in the two sample plots posed a greater risk to human beings than lotus roots. Consequently, the elevated risk of Cd in soil, when considered alongside the assessment of the carcinogenicity risk of crops, indicates that Cd in the sample plots has reached an unacceptable risk level. This suggests that the elevated risk of PTEs in the soil is likely to be absorbed and enriched by aquatic plants, which represents a significant health threat to the human body following consumption (Uddin et al., 2021). Therefore, it is recommended that the cultivation of edible crops such as lotus root and lotus seed in highly contaminated areas (e.g. Sample Plot 2) be stopped immediately. Priority should be given to soil remediation to reduce PTE content by adding amendments, planting remediation plants or other effective measures. Resume cultivation of edible crops after the soil has been remediated to meet the standards in order to ensure the safety of agricultural products and reduce the risk to human health.

4.3 Comparison of risk evaluation methods

The combination of several risk evaluation methods reveals that the potential ecological index method and the potential ecological risk method based on effective state content indicate that Cd is at a high risk in both sample plots. Furthermore, the evaluation of carcinogenicity suggests that Cd may pose a greater threat to human health. These findings demonstrate a correlation between the results of the evaluation of different risk evaluation methods (Li et al., 2022; Arisekar et al., 2022). Concurrently, the ecological risk posed by Zn and Cr was found to be minimal in the single and effective state. However, the potential for non-carcinogenic risk was identified in the samples of lotus root and lotus seed. This finding underscores the necessity for a more comprehensive approach to PTEs pollution evaluation, as a single method may not fully capture the complexity of the contamination (Zhang et al., 2023). It is thus evident that in the study of regional pollution, the utilization of a plurality of risk evaluation methodologies and sample analysis is imperative to compensate for the inherent limitations of a singular evaluation method, thereby facilitating a more comprehensive reflection of the PTEs pollution situation. Furthermore, a dynamic assessment of spatial and temporal dimensions should be

incorporated to analyze the extent of pollution diffusion and identify change trends. Techniques for identifying the source of pollution, such as isotope analysis or principal component analysis, can be employed to ascertain the precise source of pollution and to optimize treatment strategies, the integration of ecological effect and health risk linkage analysis can elucidate the comprehensive impacts of pollution in a more comprehensive manner. Promoting new assessment models, such as machine learning prediction tools, can further enhance the precision and scientific rigor of pollution risk assessment.

4.4 Recommendations for roadside aquatic crop planting

Food safety is now a major concern in all countries and regions (Qin et al., 2021; Rifat et al., 2022). It is of paramount importance to exercise rigorous control over the quality and safety of crops at the outset of the food processing stage. This is particularly relevant in the case of certain aquatic vegetables, such as lotus root and wild rice, which are directly consumed by humans. The potential for PTE enrichment in these crops to be directly ingested into the human body through the mouth must also be considered (Zhou et al., 2024). The findings of this study indicate that the two roadside aquatic crop sample plots were contaminated with elevated levels of PTEs, predominantly Cd and Cr. This contamination presents both ecological and health risks. It is therefore recommended that, in the future, any planting of roadside aquatic crops should be preceded by an assessment of the PTE pollution status of the soil and water in the area. It would be prudent to avoid planting in areas with a high pollution level, as this would not only reduce the threat to human health but also ensure a viable yield of agricultural crops. It is advisable to refrain from cultivating crops intended for human consumption, such as lotus root, wild rice, watercress, rhododendron, etc. Instead, it would be prudent to select commercial ornamental aquatic crops, including water lilies, water hibiscus, goldfish algae, and so on. Furthermore, it would be prudent to consider planting water bodies that have been subjected to remediation in order to circumvent the potential for PTE contamination. Furthermore, the planting of a mixture of PTE contaminated aquatic crops, such as *Eichhornia crassipes*, *Pistia stratiotes*, *Lemna minor*, *Phragmites communis* (Rezania et al., 2016; Rezania et al., 2015; Ghuge et al., 2023). It is recommended that roadside buffer zones, such as shelterbelts and barriers, be considered when planting roadside reservoirs with high traffic flow. This is to block the spread of PTE particles generated by road traffic, thereby reducing the risk to human health (Altaf et al., 2021). Concurrently, in order to guarantee food safety, soil and water quality monitoring of roadside aquatic crop cultivation regions

should be reinforced (Chen et al., 2024), and a dynamic risk warning apparatus should be constituted to promptly identify contaminated areas (Nie et al., 2024). It is recommended that public education and technology promotion be employed to enhance farmers' awareness of PTE pollution and to facilitate the implementation of safe cultivation techniques. Through interdisciplinary collaboration, standards and regulations should be established to facilitate the advancement of eco-agriculture and guarantee the quality of agricultural products and the sustainability of the ecological environment.

5 Conclusion

The ecological risk assessment based on total PTE concentrations revealed similar risk levels in both sample plots, with Cd posing the highest risk, followed by Pb, Cr, and Zn. However, considering effective states showed distinct differences, with Cd remaining a high-risk element across plots, while other PTEs exhibited variable risk levels. Human health risk assessment indicated that lotus seeds present higher composite non-carcinogenic risks than lotus roots, particularly for children exposed to Zn and Cr. Although adult carcinogenic risks were within acceptable limits, Cd in lotus seeds posed elevated carcinogenic risks to children. These findings suggest that traffic-derived PTEs are not the dominant source of contamination in roadside aquatic crops. Nevertheless, the study underscores the importance of assessing both total and bioavailable PTEs to accurately evaluate ecological and human health risks, with special attention required for child exposure pathways.

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Ethics declarations

Competing interests

The authors declare no competing interests.

Data availability

All data generated during this study are included in this published article.