Differences in enrichment and soil safety thresholds of five vegetables grown in Cd-polluted soil of Chengdu Plain China

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Abstract

By analyzing the differences in the enrichment capacity of Cd in several vegetables, the health risks posed by the edible parts of vegetables to human beings under different levels of soil Cd contamination in Chengdu pain were assessed, and the corresponding vegetable-soil Cd safety thresholds were established. We compared and analyzed the enrichment capacity of various vegetable varieties for Cd under various soil Cd contamination levels (0.13, 0.20, 0.32, 0.73, and 1.02 mg kg^{-1}) using five commonly grown vegetable varieties (*Lactuca sativa* var *longifoliaf*. Lam(Romaine lettuce), *Lactuca sativa* var. *ramosa* Hort. (Cos lettuce), *Brassica campestrisL.ssp.chinensis Makino* var.*communis* Tsen et Lee(pakchoi), Raphanus sativus L. (oleander), and *Lactuca sativa var. angustata*(lettuce)) as research targets. We also assessed potential issues with food safety and health risks associated with Cd in vegetables using the Hazard Quotient (*HQi*) criterion for human health risk assessment. The possible hazards to food safety and health from lead (Cd) in vegetables were assessed using the *HQi* criteria, and the Cd safety levels for vegetable soil were definited. Results of the assessment of the health risk of food intake indicated that lettuce was more likely to pose a risk than the other four vegetables and that children were more likely to pose a risk than adults with the same intake of vegetables. The enrichment capacity of soil Cd in lettuce was found to be significantly higher than that of Romaine lettuce, Cos lettuce, pakchoi, and oleander($n = 5$, $P < 0.05$). For the Chengdu Plain, the soil Cd safety thresholds were 0.32 mg kg^{-1} for Romaine lettuce, Cos lettuce, pakchoi and oleander, and 0.20 mg kg^{-1} for lettuce. These findings offer a scientific foundation for ensuring the quality and safety of vegetables, improving the environmental quality standards of Cd in farmland soils, and attaining the safe utilization of contaminated farmland.

1. Introduction

A nationwide survey on soil pollution was conducted during 2005–2012 in China. According to the bulletin of the survey, 16.1% of the investigated sites did not meet the standard for one or more indices and 82.8% of the above sites were caused by inorganic pollutants, mainly heavy metals (Sun et al., 2018). The accumulation of Cd in soil within plants can interfere with plant growth metabolism, affecting the quality and yield of crops to a certain extent (Madhu et al., 2020). When crops are consumed by humans, the Cd enriched in them enters the kidneys and liver of humans, potentially causing hypertension, cardiovascular diseases, hemorrhagic gastroenteritis, necrosis of the liver and kidneys, cancer, and even Itai-itai disease (Genchi G et al., 2020; Aoshima et al.,2019), endangering human health and food safety.

During the growth of plants, cadmium (Cd) in the soil is absorbed by the root system and translocated to the edible parts of vegetables, which can then enter the human body through the food chain (Moulis et al., 2010; Ju et al., 2012). There is significant variation in the ability of different vegetable species to accumulate the same heavy metal, they discovered that the Cd content of commercially available vegetables in Shandong Province revealed root vegetables > leafy vegetables > melons and fruits (Zhang et al., 2021). The concentrations of heavy metals decreased in the sequence as leafy vegetables > stalk vegetables/root vegetables/solanaceous vegetables > legume vegetables/melon vegetables (Zhou H et al., 2016). For Cd accumulation, the order of vegetable species was: leafy vegetables > solanaceous vegetables > kale vegetables > root vegetables > allimus > melon vegetables > legumes (Yang et al., 2010). Several researchers have developed related soil heavy metal safety criteria and risk assessments for various crop cropping systems in recent years to protect agricultural productivity better. The potential risk of heavy metal (Cd, Cr, Pb, Hg, and As) contamination of soils and crops in the urban agglomerations of the Pearl River Delta, China, was systematically assessed for the first time (Zhang et al., 2020). A health risk assessment of a wide range of vegetables from three economically developed districts in Zhejiang Province, China, by Liu Xingmei et al. showed that cadmium caused the greatest cancer risk (Liu et al., 2013). Health risk index (HRI) have revealed the possible potential risk of heavy metal contaminated plant species in the order of spinach (6.4) > wheat (6.4) > brinjal (5.9) > tomato (4.7) > red corn (4.5) > apple gourd (4.3) > white corn (3.8) > cabbage (3.1) > luffa (2.9) (Atta et al., 2023).

In order to ensure the safe production of vegetables, it is imperative that the differences in Cd enrichment between different vegetables be studied, that Cd safety thresholds be established for the soil in vegetable production areas, and that a health risk assessment of Cd in vegetables be developed.

Accordingly, by simulating soil Cd pollution, the authors explored the Cd enrichment and migration patterns of five mainstream vegetables (Romaine lettuce, Cos lettuce, pakchoi, oleander, and lettuce) in Southwest China, and clarified the differences in Cd enrichment among different vegetable varieties, they also assessed the exposure level of these five mainstream vegetables and the potential risk of harm to the population's health due to dietary Cd exposure, so as to provide the basis for the evaluation of the risk of dietary health in China. On this basis, based on the Cd content limits for vegetables in the GB2762-2022 National Standard for Food Safety Limits of Pollutants in Foods (National Standardization Management Committee of the People's Republic of China. 2022), a comprehensive health risk evaluation was conducted to clarify the soil Cd thresholds for the safe production of five mainstream vegetables in the Chengdu Plain, and to provide a basis for their safe production and for the refinement of the environmental quality standards for Cd in farmland soils.

2. Materials and Methods

2.1 Overview of the study area

The study area is located in the western part of Sichuan Province, between 103°-104°E longitude and 29°-31°N latitude, and is the largest plain in the three southwestern provinces of China. The plain has four distinct seasons, with no summer heat, little snow and ice in winter, mild climate, long summer, and short winter, long frost-free period, average annual temperature of 16°C, and average yearly precipitation of 1000 mm, belonging to the warm and humid subtropical Pacific southeastern monsoon climate zone. Surrounded by mountains, the plain is fertile, with soil types dominated by rice soil and purple soil, forming both zonal yellow and yellow-brown loam, non-zonal tidal soil and rice soil, and rocky soil such as limestone soil and purple soil. Cultivated land within the plains has deep, moderately textured soils, making it an important area for agricultural cultivation.

2.2 Experimental methods

2.2.1 Configuration of contaminated soil

Pot experiment soil was collected from the neutral purple soil (5–20 cm) of Chengdu University experimental base. After air drying and crushing, plant residues, stones and other impurities were removed, screened through 4 mm sieve and stored for standby. The pH value of the soil was 7.2, the organic matter content (OMC) was 24.8 mg·kg^{-1}, CEC20.43 cmol·kg^{-1}, and the available N, P and K were 31.82, 24.54 and 94.61 mg·kg^{-1}, respectively. The content of heavy metal Cd was 0.01 mg·kg^{-1}. With reference to the background value of soil Cd in Chengdu Plain, the environmental quality evaluation standard for the origin of edible agricultural products (National Environmental Protection Agency. 2006), the soil restriction value (National Environmental Protection Agency. 1995) and the risk screening value for agricultural land (Humic acid. 2018), five soil Cd contamination levels were set up within the range of 0.3–2.1 mg·kg^{-1}, and the $CdCl_2$ solution required for the corresponding concentration was calculated and formulated. The $CdCl_2$ solution was uniformly sprayed into the soil by spraying, stirred well, and then the soil pile was covered with cling film with fine holes, and aged at room temperature for 30 d. During this period, equal mass of water was supplemented every day, and the soil pile was stirred uniformly, and a small amount of samples were taken for determination after the aging equilibrium to obtain the final soil Cd concentrations of C1 (0.13 mg·kg^{-1}), C2 (0.20 mg·kg^{-1}), C3 (0.32 mg·kg^{-1}), C4 (0.73 mg·kg^{-1}), and C5 (1.02 mg·kg^{-1}).

2.2.2 Planting methods

The experiment was conducted at the Chengdu University Experimental Base over a period of 90 days (April to June 2023). The pots used for the pot experiment were PVC flowerpots with an inner diameter of 20 cm and a height of 16 cm. In this study, the lettuce seeds used were provided by Sichuan Liangming Agriculture Co., Ltd., with the variety being “Italian Bolting-Tolerant Lettuce”, a type of lettuce that is heat-tolerant, cold-resistant, and bolting-tolerant, allowing for cultivation throughout the year. The leaf mustard seeds were sourced from Chongqing Yu Agricultural Development Co., Ltd., with the variety identified as “Seasonless Spotless Leaf Mustard”. This variety has elongated lanceolate leaves with pointed tips and a light green color; the leaves are relatively upright, making it suitable for cultivation in all seasons. The bok choy seeds were also produced by Sichuan Liangming Agriculture Co., Ltd., under the variety name "Yellow Seedling Bok Choy", characterized by its tender yellow-green leaves, rapid plant growth, and delicate texture with a good taste. The radish seeds came from Chongqing Yu'ao Agricultural Development Co., Ltd., with the variety named "Seasonless Full Red Radish". This variety presents green loquat leaf shapes, with red petioles and leaf veins, short cylindrical fleshy roots, deep red skin, white flesh, a delicate texture, sweet taste, and high moisture content.For the experiment, seeds of leaf mustard, lettuce, bok choy, and radish were selected based on their fullness and uniform size.

These seeds were then rinsed thoroughly with H_2O_2 (w = 15%). Two layers of filter paper were placed in numbered Petri dishes, and 50 vegetable seeds were evenly distributed on top. The seeds were sprayed with water to keep them moist for 3 days until they germinated and were ready for use. Four kilograms of simulated Cd-contaminated soil were weighed into pots, marked with the corresponding concentration and group, and robust, uniformly sized vegetable seedlings were selected for transplanting. The lettuce seedlings were purchased from local farmers who had cultivated them for 15 days; they were uniform in size and undamaged. For each level of pollution, five pots were planted with three seedlings each. The temperature was within the range from 12.1 to 25.3°C while the humidity varied between 38 and 89%. The vegetables were regularly watered and fertilized until they completed their respective growth periods—60 days for leaf mustard and bok choy, 75 days for lettuce and radish, and 90 days for lettuce—after which they were harvested.

2.3 Sample collection

Soil and vegetable samples were collected separately. The soil samples were air-dried, ground to a fine texture, sieved through a 100-mesh screen, and then stored for subsequent testing. The vegetable samples were rinsed with clean water to remove any foreign objects and soil, then air-dried naturally. Approximately 500 grams of the edible portion of each sample was taken, ground into a homogenous mixture or puree, and stored for later analysis.

2.3.2 Measurement items and methods

The pH of the soil was measured by leaching with an aqueous solution containing 0.01 $mol{\cdot}L^{-1} CaCl_2$ and a pH meter, the organic matter in the soil was measured using a high-temperature exothermic potassium dichromate oxidation-volumetric method (National Standardization Management Committee of the People's Republic of China. 2022). After sieving the soil through a 100-mesh screen, weigh 0.1g (accurate to 0.0001g) and transfer it to a polytetrafluoroethylene (PTFE) vessel. Add 3 ml of nitric acid, 1 ml of hydrochloric acid, and 1 ml of hydrofluoric acid. Seal the vessel and place it into a matching steel tube, digesting it on a hot plate at 180°C for 20 hours. Then, add 1 ml of perchloric acid as a driving acid. After digestion, transfer the solution to a 50 ml volumetric flask and dilute it to the mark with ultrapure water. Finally, collect 10 ml of the supernatant of the digested solution and measure the concentration of Cd using inductively coupled plasma mass spectrometry (ICP-MS). The basic operating conditions were as follows: sample introduction rate: 0.8 ml/min; nebuliser gas flow rate: 0.92 ml/min; auxiliary gas flow rate: 0.7 ml/min; cooling gas flow rate: 13 L/min; instrument detection limit below 1 ppb.

Mature vegetables were collected, rinsed sequentially three times with tap water and purified water to remove surface soil particles. After air-drying naturally, approximately 500g of the edible portion was homogenised or blended, and stored for analysis. Weigh 0.2g (accurate to 0.0001g) of the edible plant sample into a PTFE vessel, then add 5 ml of nitric acid and 2–3 drops of hydrofluoric acid. Leave it for 12 hours for pre-digestion. Heat the initial digest solution to 160°C and digest for 8 hours to remove organic matter. After cooling, maintain a constant volume of 50 ml. The method for determining Cd in plants is the same as for soil. For quality control, all acidic reagents used were of high purity. The glassware and PTFE vessels used for digestion were soaked in 25% nitric acid solution for 12 hours prior to use. Soil reference material GSS-5 and plant reference material GBW10021 were used for quality control.

2.4 Data processing and analysis

2.4.1 Calculation of enrichment factor

Bioaccumulation factor (BAF) is the ratio of heavy metal content in edible parts of vegetables to that in soil, reflecting the effective coefficient of heavy metal transfer from soil to vegetables, which can be used to evaluate the ability of vegetables to absorb heavy metals from soil (Liu et al., 2021).

$$BAF\text{veg} = \frac{C\text{veg}}{C\text{soil}}$$

1

In Eq. (1), BAF_{veg} denotes the enrichment coefficient of the full amount of heavy metals in each vegetable. C_{veg} is the content of heavy metals in above-ground plants (mg·kg^{-1}), and C_{soil} is the content of metal elements in the soil (mg·kg^{-1}).

2.4.3 Health risk evaluation method

The human health risk evaluation used in this study was based on the US EPA (RAGS,2001), combined with the derived experimental data to calculate the Hazard quotients (HQi) of Cd in vegetables, which is used to comprehensively evaluate the health risk of the target element to humans (USEPA, 2011), and to combine the daily intake of Cd by the local population, and calculate the (%ADI) and (%RfD) respectively for chronic dietary intake risk assessment and acute dietary intake risk assessment (Zheng N et al., 2007; Chen C et al., 2011).

$$HQi = \frac{ADI}{RfD} \times\ 1000$$

2

$$ADI = \frac{W\text{Cd} \times\ I\text{R} \times\ E\text{F} \times\ F\text{I} \times\ E\text{D}}{B\text{W} \times\ A\text{T}}$$

3

In Eqs. (2) and (3), HQ_i is the hazard index of compound contamination by multiple target elements; ADI is the average daily intake of target elements via fruit and vegetable intake [mg/(kg-d)]; W_{Cd} is the mass fraction of the monitored element, Cd, in the vegetables (mg/kg); RfD is the average daily intake reference dose of the monitored target element, Cd, [μg/(kg-d)]; E_F is the exposure frequency (d/a); F_I is the fraction of intake, indicating the ratio of consumption of the study vegetables to the total amount of vegetables consumed, which was defaulted to 1 in this study, i.e., all the vegetables consumed were experimental vegetables; E_D is the duration of continuous exposure (a); I_R is the average daily vegetable intake (kg/d); B_W is the average body weight (kg); and A_T is the average exposure time (d). The parameters related to the risk coefficients of children and adults for contaminant intake are shown in Table 2. If the value of HQ_i is < 1, it is generally presumed to be safe for the risk of noncarcinogenic effects and if it is > 1, it is supposed that there is a chance of noncarcinogenic effects with an increasing probability as the value upsurges.

Evaluation Parameter	Reference Value	Literature Source
Frequency of exposure E_F/(d/a)	180	(Ali U et al., 2020)
Duration of exposure E_D/a	30(adults), 10(children)	(Ali U et al., 2020)
Vegetable intake I_R/(kg/d)	0.5	(Ding et al.,2021)
Target element in vegetables W_{Cd}/(mg/kg)	Measured in this study	
Measured in this study RfD/[μg/(kg·d)	Cd: 1.0	(GB 2762 – 2022)
Mean body weight B_W/kg	60(adults), 32.75(children)	(Chen et al., 2022)
Mean exposure time A_T/d	A_T=365×E_D	(Ali U et al., 2020)

Calculated by fitting a linear equation between the heavy metal content y (mg·kg^{-1}, FW) in the edible part of different vegetables and the soil heavy metal content x (mg·kg^{-1}) (Table 2). The limits for leafy vegetables (Cd 0.2 mg·kg^{-1}) and root vegetables (Cd 0.1 mg·kg^{-1}) in the Limits of Contaminants in Foods (GB2762-2022) were substituted into the corresponding fitting equations to calculate the safety threshold x. The safety threshold x was calculated by substituting the limits for leafy vegetables (Cd 0.2 mg·kg^{-1}) and root vegetables (Cd 0.1 mg·kg^{-1}) into the corresponding equations.

2.4.4 Checking statistical data

Our experimental data were checked several times to make sure and then processed by Excel 2010, analyzed for correlation, significance of difference with SPSS 17.0 and finally plotted with Origin 2022.

2.4.5 Quality Control (QC) and Quality Assurance (QA)

In our study, we meticulously implemented rigorous quality control (QC) and quality assurance (QA) measures to ensure the accuracy and reliability of the analysis. Throughout the process, our analytical instruments, such as the inductively coupled plasma mass spectrometer (ICP-MS), were carefully calibrated to maintain precision in measuring the concentrations of heavy metals in soil and vegetable samples. Additionally, the methods used for heavy metal analysis were thoroughly vali

Moreover, we adhered to standardised procedures during sample preparation to minimise variability and potential sources of error. This involved meticulously washing vegetable samples to remove any surface contaminants and ensuring they were completely dried for accurate measurement of metal concentrations. We also analysed three samples from each vegetable type to assess the precision and repeatability of our results, carefully examining any differences between

To further control for potential contamination during sample handling and processing, we included blank samples in the analysis. Simultaneously, we analysed standard reference materials with known metal concentrations alongside the vegetable samples to validate the accuracy of our analytical methods. Quality assurance checks were routinely conducted throughout the analysis to verify the reliability of the data. This included continuous monitoring of laboratory conditions, instrument performance, and data consistency. By adhering to these stringent QC and QA measures, we ensured that the heavy metal analysis was performed to the highest standards of precision, reliability, and repeatability. This meticulous approach enhances the credibility of our findings, instilling confidence in the validity of the results obtained.

3. Results and analyses

3.1 Interspecific differences in cadmium content of vegetables under different soil Cd pollution levels

Figure 2 depicts the amount of Cd present in several crops at varying soil Cd contamination levels. Overall, the amount of Cd accumulated in the same vegetables increased as the level of soil Cd pollution increased. The amounts of Cd in Romaine lettuce, Cos lettuce, pakchoi, oleander, and lettuce, 0.018–0.222, 0.029–0.318, 0.022–0.467, 0.030–0.365, and 0.050–0.606 $mg \cdot kg^{-1}$, respectively, varied. At the same pollution level, the amount of Cd accumulated in lettuce was significantly higher than that of the other four vegetables ($n = 5$, $P < 0.05$), and Cos lettuce had higher levels of Cd enrichment than Romaine lettuce rape and pakchoi in the soil Cd at C1-C4 pollution levels.As per the "National Standard for Food Safety, Limit of Contaminants in Food" GB2762-2022, the maximum amount of Cd allowed in vegetables is 0.2 $mg \cdot kg^{-1}$ for leafy vegetables and 0.1 $mg \cdot kg^{-1}$ for root vegetables. In this case, the Cd enrichment of Romaine lettuce and pakchoi under the contamination level of C1-C4 pollution did not surpass the standard. While lettuce alone did not surpass the Cd enrichment at C1 to C2 pollution contamination levels, Cos lettuce and oleander did not surpass these levels of pollution contamination.

3.2 Interspecific differences in Cd enrichment and transport in vegetables under different soil Cd pollution levels

Figure 3 shows that the Cd enrichment by the vegetable-soil system varies significantly not only between different vegetables but also between the same vegetables at different levels of soil Cd pollution. This is evident from comparing the enrichment capacity of these five common vegetables for soil Cd in the

Chengdu Plain. Under the same soil Cd pollution level, various vegetable species had varying enrichment coefficients. In general, Romaine lettuce had lower enrichment coefficients than the other four vegetables. Cos lettuce, pakchoi and oleander had similar enrichment coefficients that varied irregularly from C1 to C5, and lettuce had higher enrichment coefficients than the other four vegetables. While the average variation was in a range, the enrichment coefficients of the same vegetable species under varying soil Cd pollution levels varied (0.13–0.23 for Romaine lettuce, 0.30–0.43 for Cos lettuce, 0.19–0.32 for pakchoi, 0.22–0.36 for oleander, and 0.37–0.61 for lettuce). From C1 to C5, Romaine lettuce's enrichment coefficients varied the least, fluctuating at a smaller rate; in contrast, the enrichment coefficients of Cos lettuce, pakchoi, and oleander varied more, fluctuating at a larger rate; and in contrast, the enrichment coefficients of lettuce were significantly higher than those of the other four vegetables, fluctuating at a smaller rate.

3.3 Risk evaluation of vegetable intake under different soil Cd contamination levels

Through the root system, edible portions of vegetables can absorb elemental Cd from the soil, which can then build up and potentially affect the health of humans who eat the vegetables if the amount of Cd in the edible sections is excessive.The Hazard Quotient (HQ_i) values of five vegetables cultivated with varying soil Cd contamination levels were analyzed for adults and children, respectively, using the prior assessment approach. The findings are displayed in Figs. 4 and 5. It can be seen that when ingesting the same dose of vegetables, the hazard quotient (HQ_i) of different soil Cd contamination levels and different types of vegetables to different age groups of ingesting people are different: different vegetables grown under the same soil Cd contamination level, the HQ_i of lettuce (0.0366–0.1037) was the highest, followed by pakchoi (0.0245–0.0321), and Romaine lettuce was the lowest (0.0003 to 0.0008), with $HQ_{lettuce} > HQ_{pakchoi} > HQ_{oleander} > HQ_{Cos\ lettuce} > HQ_{Romaine\ lettuce}$, all five vegetables grown under the same level of soil Cd contamination produced higher HQ_i in children than in adults ($n = 5$, $P < 0.05$).

Figure 4 shows that among the vegetable hazard quotients for adults ingesting vegetables with different soil Cd contamination levels, Romaine lettuce has $HQ_i < 1$ at five soil Cd contamination levels, which is not potentially hazardous to adults and can be consumed without fear; Cos lettuce has $HQ_i < 1$ at C1 ~ C4 contamination levels and can be consumed without fear; pakchoi, oleander, and lettuce have $HQ_i < 1$ at C1 ~ C3 contamination levels and can be consumed without fear, and have $HQ_i > 1$ at C4, C5 contamination levels, which is potentially hazardous to the adults' health.

Figure 5 shows that among the hazard quotient of vegetables ingested by children at different soil Cd contamination levels, Romaine lettuce, Cos lettuce, oleander and pakchoi had $HQ_i < 1$ at C1 ~ C3 contamination levels, which did not pose any potential hazard to children and could be consumed without any worry, while at C4 and C5 contamination levels, all five vegetables had $HQ_i > 1$, which posed a higher potential health risk to children.

3.4 Soil-vegetable system Cd safety thresholds

The results of related analyses showed that the Cd content of vegetables was correlated with the content of Cd in soils with different levels of contamination, so regression analyses were used to establish a linear regression model between these vegetables and their total soil Cd, to determine the optimal equation for goodness-of-fit, and to derive the safety thresholds for the five vegetables in the Chengdu Plain (Table 2). It can be seen that among leafy vegetables, the safety threshold of total soil Cd for Romaine lettuce is 0.9283 $mg\cdot kg^{-1}$, that for Cos lettuce is 0.6765 $mg\cdot kg^{-1}$, and that for oleander is 0.5846 $mg\cdot kg^{-1}$. This threshold is based on the Cd content limit for leafy vegetables in the National Standard for Food Safety Limits for Pollutants in Food (0.2 $mg\cdot kg^{-1}$), pakchoi and lettuce are root vegetables, whose root and leaf parts are edible, and the limit for Cd content in root vegetables is 0.1 $mg\cdot kg^{-1}$, however, pakchoi, compared with lettuce, has a lower Cd content, lower bioconcentration coefficients, and lower potential health risk evaluations under the same contamination level. Therefore, the total soil Cd safety threshold for pakchoi was higher at 0.3498 $mg\cdot kg^{-1}$, while that for lettuce was 0.2020 $mg\cdot kg^{-1}$.

vegetable species	Safety thresholds for total Cd in vegetables $mg\cdot kg^{-1}$	linear regression equation	goodness of fit	Safety thresholds for total Cd in soil $mg\cdot kg^{-1}$
Romaine lettuce	0.2	y = 0.223x-0.07	0.994	0.9283
Cos lettuce	0.2	y = 0.34x-0.03	0.954	0.6765
pakchoi	0.2	y = 0.467x-0.073	0.896	0.5846
oleander	0.1	y = 0.406x-0.042	0.983	0.3498
lettuce	0.1	y = 0.594x-0.02	0.961	0.2020

4. Discussion

4.1 Differences in enrichment factors for different types of vegetables

The present study showed that the enriched Cd contents of the five studied vegetables were significantly different under the same pollution level, indicating that the heavy metal enrichment coefficients of vegetables were species-specific (De et al., 2010). In general, the enrichment coefficient of Romaine lettuce was the lowest, and the coefficient of variation was small, which belonged to the stable low-enrichment vegetable species; the enrichment coefficient of lettuce was the highest, which was significantly higher than the other four vegetables under the five soil Cd contamination levels, and belonged to the stable high-enrichment vegetable species; the enrichment coefficients of Cos lettuce, oleander and pakchoi were more variable, and fluctuated within an interval under different contamination levels, which belonged to the more unstable medium-enrichment vegetable species.

The differences in the enrichment of heavy metal Cd in different varieties of vegetables are due to the biological mechanisms among vegetable varieties and the physiological and genetic characteristics of vegetables themselves (Cui et al., 2023). They found that the enrichment capacity of Cd in the Chengdu Plain was Chinese cabbage(*Brassica rapa* var. *Glabra* Regel) > lettuce > oleander, which was basically the same as the conclusion of this study, indicating that there was no difference in the enrichment capacity of lettuce and radish in terms of years. In this experiment, celery, lettuce, and spinach belong to the same genus (Asteraceae Lactuca), theoretically exhibiting similar enrichment capabilities for Cd. However, the results show that celery > lettuce > spinach. This difference may be due to variations in the root, stem, and leaf structures, nutritional composition, and maturity periods of these three related vegetables. Lettuce, which is rich in vitamin K, vitamin B6, and potassium (Das, R. et al., 2020), has well-developed roots and stems, with an elongated stem and the longest maturity period (90 days), thus exhibiting the strongest Cd enrichment capability. Cos Lettuce, rich in vitamin A, vitamin C, and calcium, has a shorter stem structure and well-developed leaves, with a maturity period (75 days) longer than that of spinach, resulting in a weaker Cd enrichment capability compared to celery but stronger than spinach. Romaine lettuce, rich in vitamin E, folic acid, and iron, has narrow and elongated leaves and the shortest maturity period (60 days), thus exhibiting the weakest Cd enrichment capability.

By applying oleander, Chinese cabbage, and lettuce as examples (Zhao et al., 2010). Cui Dongxia et al. demonstrated that the Cd enrichment capacity was as follows: lettuce leaf part > lettuce stem part > Chinese cabbage > oleander (Cui et al., 2012). This is different from Zhao Xiaorong's study, and it may be because Chinese cabbage displayed a marginally stronger enrichment capacity than radish as a result of climatic and soil factors; Mi Baobin et al. showed that the accumulation of heavy metal Cd by vegetables was lettuce > cruciferous (pakchoi, oleander) through pool planting experiments, which was in line with the results of this experimental study (Mi et al., 2019). Overall, it seems that lettuce, a vegetable with higher enrichment of heavy metal Cd than Cos lettuce, pakchoi, oleander and Romaine lettuce at all pollution levels, has a significantly higher enrichment capacity than the other vegetables, breaking the generalisation of leafy vegetables > rootstalks in related studies.

4.2 Evaluation of Health Risks of Intake of Different Types of Vegetables

Elemental Cd studied in this experiment is a heavy metal that seriously endangers human health and safety, and it enters the human body through the food chain causing many health risks, so it has been the focus of researchers to evaluate health risks. In this study, it was found that the five vegetables did not pose any health risk to adults at low levels of soil Cd pollution (0.13, 0.20, and 0.32 $mg \cdot kg^{-1}$), while lettuce posed a health risk to children at the 0.32 $mg \cdot kg^{-1}$ level. Hu, W. et al. studied high levels of the heavy metal Cd in leafy vegetables grown in greenhouses with a target hazard factor greater than one(Hu et al., 2014). Wan Jiayue et al studied the edible parts of four types of vegetables (86 varieties) by using potting experiments showed that leafy vegetables and root vegetables have higher health risks, followed by lycopene and legumes, and pods are at a safe level of health risk(Wan et al., 2019). Li Yang et al studied a soil -Vegetable system showed that leafy vegetables > root and tuber > lycopene (chilli), Cd in vegetables in the study area did not pose a health risk to adults and children, and the risk of Cd exposure in children was higher than that in adults(Li et al., 2020). All these studies strongly suggest that leafy vegetables and root vegetables are more likely to enrich soil Cd and have a higher health risk for human consumption, and that children have a higher exposure risk than adults, which is consistent with the findings of this experiment.

4.3 Different types of vegetables - differences in soil safety thresholds

For the establishment of vegetable-soil safety thresholds, Meng Yuan et al investigated the soil Cd safety thresholds for spinach (*Spinacia oleracea*), oilseed rape (*Brassica napus*), lettuce, oilseed rape, amaranth, airseed rape (*Ipomoea aquatica* Forssk.), and Chrysanthemum coronarium (*Glebionis coronaria Cass.* ex Spach) in Xi'an area as 0.33, 0.38, 0.46, 1.15, 0.59 to 1.79, 1.49 to 8.16, and 8.98 to 17.11 $mg·kg^{-1}$, respectively (Meng et al., 2019). The soil Cd thresholds for lettuce and oilseed rape were different from those of the present experiment, which may be due to the differences in soil physicochemical properties and geoclimate, as well as the differences in vegetable varieties. Xiao W.D. et al. established an evaluation model for Cd availability in leafy vegetables based on soil properties, showing that the total amount of Cd in amaranth, celery, and Chinese cabbage was 0.26, 0.34, and 0.83 $mg·kg^{-1}$, respectively, while the bioavailable thresholds were 0.13, 0.24, and 0.23 $mg·kg^{-1}$, respectively(Xiao et al., 2018). LI, F. R. et al. conducted potting tests by collecting soils with various heavy metal concentrations from vegetable production areas in the Pearl River Delta region, and fitted the equations based on the limit values of food hygiene standards to derive the full limit value of heavy metal Cd suitable for cabbage planting soils to be 1.94 $mg·kg^{-1}$, which is at variance with the threshold value of Cd for cabbage soils in the present experiments, probably due to the fact that the fitted equations of the data analyses were in the natural ideal state under which there is a big difference with the reality (Li et al., 2019). Vegetable-soil safety thresholds are strongly related to soil physicochemical properties, natural climatic conditions, and specific types of vegetables. The reason may be related to the biological mechanisms among different regional vegetable varieties, the physiological and genetic characteristics of the vegetables themselves, as well as the differences in soil physical and chemical properties and climatic conditions. The experiment selected five types of vegetables that are widely cultivated in the Chengdu Plain area, which differ from the vegetable varieties and research regions chosen by other scholars. In terms of soil physical and chemical properties, Liu, N. et al.(2023) have shown that pH is one of the important factors affecting the adsorption and desorption of cadmium by soil components, thereby influencing the enrichment of cadmium in vegetables from the soil. Kuang, X.,et al.(2024) research indicates that the redox potential (Eh) can affect the bioavailability of cadmium in the soil, with the form, chemical state, and ion concentration of cadmium in the soil all changing with the alteration of the soil's redox conditions. Zou, C. et al.(2023) have demonstrated that soil organic matter can reduce the activity of cadmium ions while also forming complexes and chelates through reactions with cadmium, altering the speciation of cadmium and thereby affecting its accumulation in the soil and enrichment by vegetables; additionally, the content of N, P, K, and the concentration of ions in the soil can also cause differences in the vegetable-soil Cd threshold. In this study, based on the comprehensive consideration of health risk evaluation, the soil Cd threshold for lettuce in the Chengdu Plain (0.20 $mg \cdot kg^{-1}$) was lower than the existing national standard limit value (Cd 0.3–0.6 $mg \cdot kg^{-1}$), and the soil thresholds for oleaginous vegetables The soil Cd thresholds of lettuce, lettuce, cabbage and radish (0.32 $mg \cdot kg^{-1}$) were within the national standard limit values.

5. Conclusions

(1) This study showed that, under the same level of soil Cd pollution, the Cd enrichment capacity of lettuce was higher than that of the other four vegetables (Romaine lettuce, Cos lettuce, oleander and pakchoi), and its planting conditions were more stringent. Therefore, lettuce should be planted with caution or not planted in the fields with high Cd content in Chengdu Plain, and it is recommended that Romaine lettuce, which has a weaker Cd enrichment capacity and a stable variability, be planted, and that the Cd contamination from other agricultural products (fertilizers and pesticides) be strictly controlled.

(2) According to the health risk evaluation, at low levels of soil Cd contamination (0.13, 0.20, 0.32 $mg \cdot kg^{-1}$), the five vegetables did not pose any health risk to adults, while lettuce posed a health risk to children at the level of 0.32 $mg \cdot kg^{-1}$. It is recommended that residents in the Chengdu Plain region should try to choose Romaine lettuce, Cos lettuce, oleander and pakchoi, which have a low health risk, in their consumption of vegetables, with particular attention to the intake of lettuce by children. Particular attention should be paid to children's intake of lettuce.

(3) The establishment of vegetable-soil Cd safety thresholds requires more specific condition constraints, such as soil physicochemical properties, vegetable species, and region, etc. In the case of the Chengdu Plain area, the soil Cd safety thresholds for Romaine lettuce, Cos lettuce, oleander and pakchoi were 0.32 $mg \cdot kg^{-1}$, and for lettuce, the Cd safety soil threshold was 0.20 $mg \cdot kg^{-1}$.

Declarations

The authors declare that they have no conflicts of interest relevant to this study in accordance with the guidelines of the Society of Process Safety and Environmental Protection. This research was supported by the Sichuan Rural Development Research Center under project CR2001 and the Research Project of Chengdu Water Ecological Civilisation Construction Research Key Base under project 2018SST015.

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Author Contributions Statement:

The specific contributions of each author to this study are outlined as follows:

Xin Sun: Responsible for the design of the pot experiment, data collection, and analysis. Contributed to drafting and revising the manuscript.

Yang Gao: Participated in the execution of the pot experiment, contributed to data analysis, and interpretation of results.

Shengwang Pan: Involved in literature search and background research, as well as reviewing and editing the manuscript content.

Each author has reviewed and approved the final submitted version and agrees to the public statement of their individual contributions.

This author contributions statement provides a clear overview of the roles and contributions of each author in the study, aiding readers and reviewers in understanding their involvement and expertise in the research project.

Author Contribution

The specific contributions of each author to this study are outlined as follows:Xin Sun: Responsible for the design of the pot experiment, data collection, and analysis. Contributed to drafting and revising the manuscript.Yang Gao: Participated in the execution of the pot experiment, contributed to data analysis, and interpretation of results.Shengwang Pan: Involved in literature search and background research, as well as reviewing and editing the manuscript content.Each author has reviewed and approved the final submitted version and agrees to the public statement of their individual contributions.This author contributions statement provides a clear overview of the roles and contributions of each author in the study, aiding readers and reviewers in understanding their involvement and expertise in the research project.

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Data Availability Statement

The experimental data supporting this study are available upon request. The data were processed using SPSS (Statistical Package for the Social Sciences) and OriginPro software. Experimental figures and charts can be accessed and edited from the supplementary files provided.

References

1. Ali U, Zhong M, Shar T, et al. (2020). The influence of pH on cadmium accumulation in seedlings of rice (Oryzasativa L.)[J]. Journal of Plant Growth Regulation,39(2): 19–29
2. Aoshima, K., Horiguchi, H. (2019). Historical Lessons on Cadmium Environmental Pollution Problems in Japan and Current Cadmium Exposure Situation. In: Himeno, S., Aoshima, K. (eds) Cadmium Toxicity. Current Topics in Environmental Health and Preventive Medicine. Springer, Singapore.
3. Atta, M. I., Zehra, S. S., Dai, D. Q., Ali, H., Naveed, K., Ali, I., … Abdel-Hameed, U. K. (2023). Amassing of heavy metals in soils, vegetables and crop plants irrigated with wastewater: Health risk assessment of heavy metals in Dera Ghazi Khan, Punjab, Pakistan. Frontiers in plant science, 13, 1080635.
4. Chen C, Qian Y, Chen Q, Li C. (2011). Assessment of daily intake of toxic elements due to consumption of vegetables, fruits, meat, and seafood by inhabitants of Xiamen, China. J. Food Sci. 76:T181–T188.
5. Chen Y T, Li J Y, He Q, et al. (2022). Pollution characteristics and health risk assessment of heavy metals from maize in the surrounding farmland of Guobei Coal Mine[J]. Environmental Chemistry, 41(2): 526–535.
6. Cui, D. X., Liu, Y. P., Zeng, Y. J., et al. (2012). Analysis of the correlation between Cd accumulation in vegetables and soil environment. Southwest University Journal (Natural Science Edition), 34(6), 133–137. (in Chinese)
7. Cui, S., Wang, Z., Li, X., Wang, H., Wang, H., & Chen, W. (2023). A comprehensive assessment of heavy metal (loid) contamination in leafy vegetables grown in two mining areas in Yunnan, China—A focus on bioaccumulation of cadmium in Malabar spinach. Environmental Science and Pollution Research, 30(6), 14959–14974.
8. Das, R., & Bhattacharjee, C. (2020). Lettuce. In Nutritional composition and antioxidant properties of fruits and vegetables (pp. 143–157). Academic Press.
9. De, T.K., De, M., Das, S. et al. (2010). Level of Heavy Metals in Some Edible Marine Fishes of Mangrove Dominated Tropical Estuarine Areas of Hooghly River, North East Coast of Bay of Bengal,

India. Bull Environ Contam Toxicol 85, 385–390.

10. Ding, G. Q., Ma, A. G., Sun, C. Y., et al. (2021). China residents' dietary guide scientific research report (2021) [R]. Beijing: Chinese Nutrition Society.
11. Genchi G, Sinicropi MS, Lauria G, Carocci A, Catalano A. The Effects of Cadmium Toxicity. International Journal of Environmental Research and Public Health. 2020; 17(11):3782.
12. Hu, W., Chen, Y., Huang, B., & Niedermann, S. (2014). Health Risk Assessment of Heavy Metals in Soils and Vegetables from a Typical Greenhouse Vegetable Production System in China. Human and Ecological Risk Assessment: An International Journal, 20(5), 1264–1280.
13. Humic acid. (2018, April). Standards for risk management and control of soil pollution in agricultural land (Excerpt). Humic acid, 58–61.
14. Ju, Y.R., Chen, W.Y., Liao, C.M., 2012. Assessing human exposure risk to cadmium through inhalation and seafood consumption. J. Hazard. Mater. (227–228), 353–361.
15. Kuang, X., Wang, Z., Peng, L., Wang, Y., Song, H., Li, C., … Hu, Y. (2024). Microcystis-dominated paddy crusts enhancing the cadmium accumulation in rice plant (Oryza sativa L.). International Biodeterioration & Biodegradation, 190, 105774.
16. Li, F. R., Dian, W. E. N., WANG, F. H., SUN, F. F., Xu, W. A. N. G., DU, Y. Q., … Kai, W. A. N. (2019). Derivation of soil Pb/Cd/As thresholds for safety of vegetable planting: A case study for pakchoi in Guangdong Province, China. Journal of integrative agriculture, 18(1), 179–189.
17. Li, Y., Zhang, N. M., Wei, F. S. (2020). Health risk assessment and benchmarks for cadmium in vegetable soils in the high cadmium background area of Eastern Yunnan [J]. Environmental Science in China, 40(10), 4522–4530.
18. Liu, N., Zhang, S. B., Guo, X. Y., & Ning, R. Y. (2023). Influencing factors of cadmium content in wheat grain: a meta-analysis and decision tree analysis. Huan **g ke Xue = Huan**g Kexue, 44(4), 2265–2274.
19. Liu, X., Gu, S., Yang, S., Deng, J., & Xu, J. (2021). Heavy metals in soil-vegetable system around E-waste site and the health risk assessment. Science of The Total Environment, 779, 146438.
20. Liu, X., Song, Q., Tang, Y., Li, W., Xu, J., Wu, J., … Brookes, P. C. (2013). Human health risk assessment of heavy metals in soil–vegetable system: a multi-medium analysis. Science of the total environment, 463, 530–540.
21. Madhu, P., & Sadagopan, R. (2020). Effect of Heavy Metals on Growth and Development of Cultivated Plants with Reference to Cadmium, Chromium and Lead- A Review. Journal of Stress Physiology & Biochemistry, 16 (3), 84–102.
22. Meng, Y., Zhang, L., Wang, L. Q., et al. (2019). Enrichment effects of several leafy vegetables on Cd and As in compound contaminated soils [J]. Plant Nutrition and Fertilizer Science, 25(6), 972–981. (in Chinese)
23. Mi, B.B., Wang, D. H., Zhang, Z. Q., et al. (2019). Safety evaluation of vegetables under different cadmium concentrations in soil. Hunan Agricultural Sciences, 2(49–53). (in Chinese)

24. Moulis, J.M., Thévenod, F., 2010. New perspectives in cadmium toxicity: an introduction. Biometals 23, 763–768.
25. National Environmental Protection Agency. (1995). GB15618-1995 Soil environmental quality standards. Beijing: China Standard Press.
26. National Environmental Protection Agency. (2006). HJ/T332-2006 Standards for the environmental quality evaluation of agricultural product origins. Beijing: China Standard Press.
27. National Standardization Management Committee of the People's Republic of China. (2022). GB 2762 – 2022, Food safety national standard - Limits of contaminants in food [S]. Retrieved from http://www.std.gov.cn
28. Risk Assessment Guidance for Superfund (RAGS) Volume III Part A: Process for Conducting Probabilistic Risk Assessment (2001)
29. Singh, S., Zacharias, M., Kalpana, S., & Mishra, S. (2012). Heavy metals accumulation and distribution pattern in different vegetable crops. Journal of Environmental Chemistry and Ecotoxicology, 4(10), 170–177.
30. Sun, H., Zhu, L., & Zhou, D. (2018). POLSOIL: research on soil pollution in China. Environmental Science and Pollution Research, 25, 1–3.
31. USEPA, 2011. Exposure Factors Handbook. final edition. EPA/600/R-09/052F, Washington,
32. Wan, J. Y., Peng, W. H., He, X. G. D., et al. (2019). Cadmium accumulation characteristics in edible parts of typical vegetables and health risk assessment [J]. Journal of China University of Metrology, 30(2), 255–264. (in Chinese)
33. Xiao W.D, Ye X.Z, Zhang Q, Chen D, Hu J, Gao N (2018) Evaluation of cadmium transfer from soil to leafy vegetables: influencing factors, transfer models, and indication of soil threshold contents. Ecotox Environ Safe 164:355–362.
34. Yang, J., Guo, H., Ma, Y., Wang, L., Wei, D., & Hua, L. (2010). Genotypic variations in the accumulation of Cd exhibited by different vegetables. Journal of environmental sciences, 22(8), 1246–1252.
35. Zhang, T-R., Zhang Y., Li W., et al. (2021). Occurrence and dietary exposure of heavy metals in marketed vegetables and fruits of Shandong Province, China[J], Food science and nutrition, 9(9): 5166–5173.
36. Zhao X.R., Yang X., Chen G., H., et al. Study on the enrichment ability of different vegetable varieties to heavy metals in Chengdu Plain [J]. Journal of Southwest Agricultural University, 2010, 23(4): 1142–1146. (in Chinese)
37. Zheng N, Wang Q, Zhang X, Zheng D, Zhang Z, Zhang S.(2007). Population health risk due to dietary intake of heavy metals in the industrial area of Huludao city, China. Sci. Total Environ. 387:96–104.
38. Zheng, S-N., Wang Q., Yuan Y-Z., Sun, W-M., et al. (2020). Human health risk assessment of heavy metals in soil and food crops in the Pearl River Delta urban agglomeration of China[J], Food Chemistry, 316: 126213.

39. Zhou H, Yang W-T, Zhou X, Liu L, Gu J-F, Wang W-L, Zou J-L, Tian T, Peng P-Q, Liao B-H. (2016). Accumulation of Heavy Metals in Vegetable Species Planted in Contaminated Soils and the Health Risk Assessment. International Journal of Environmental Research and Public Health. 13(3):289.
40. Zou, C., Shi, Z., Yang, Y., Zhang, J., Hou, Y., & Zhang, N. (2023). The Characteristics, Enrichment, and Migration Mechanism of Cadmium in Phosphate Rock and Phosphogypsum of the Qing** Phosphate Deposit, Southwest China. Minerals, 13(1), 107.

Figures

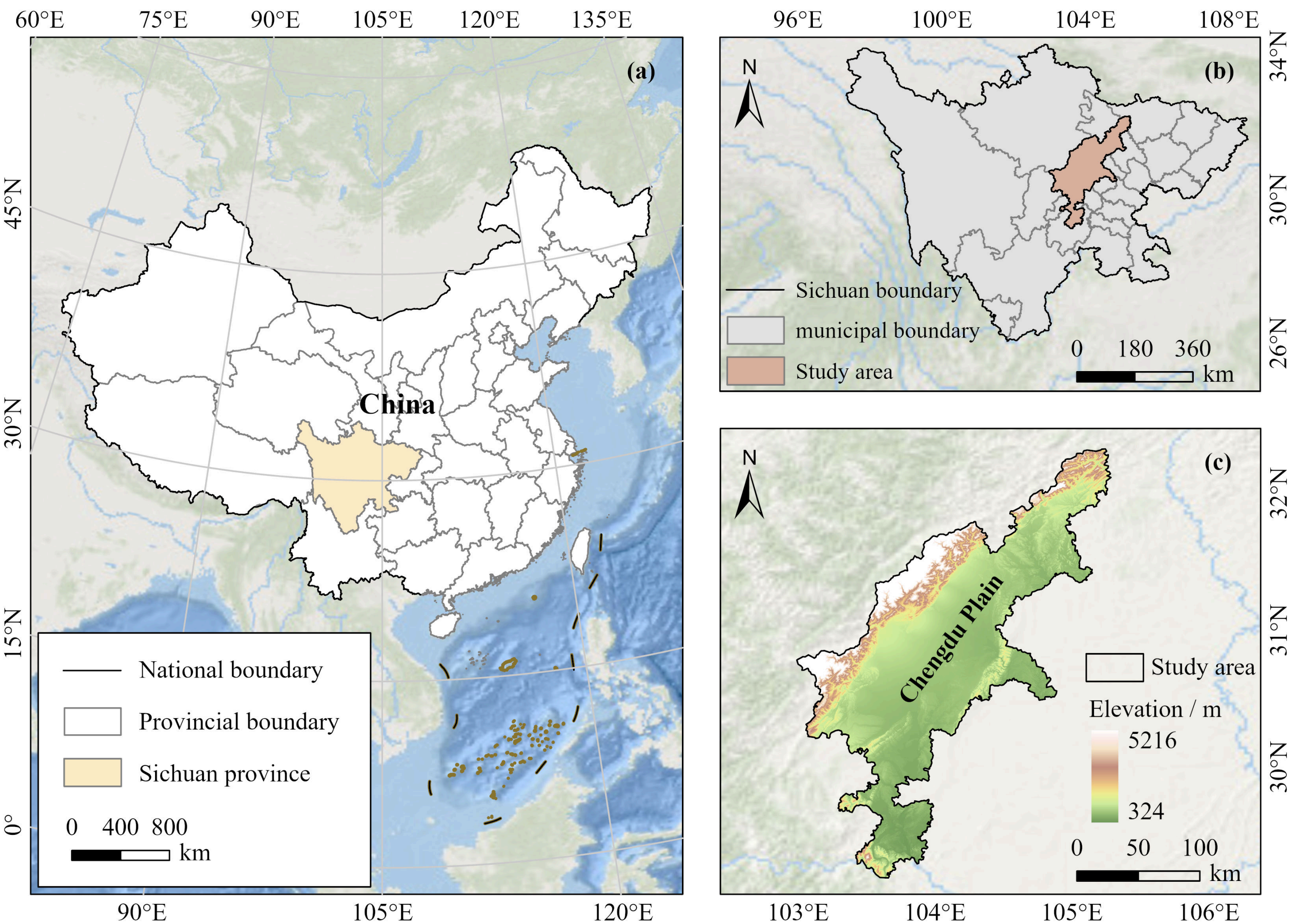

Figure 1

Study area of the Chengdu Plain

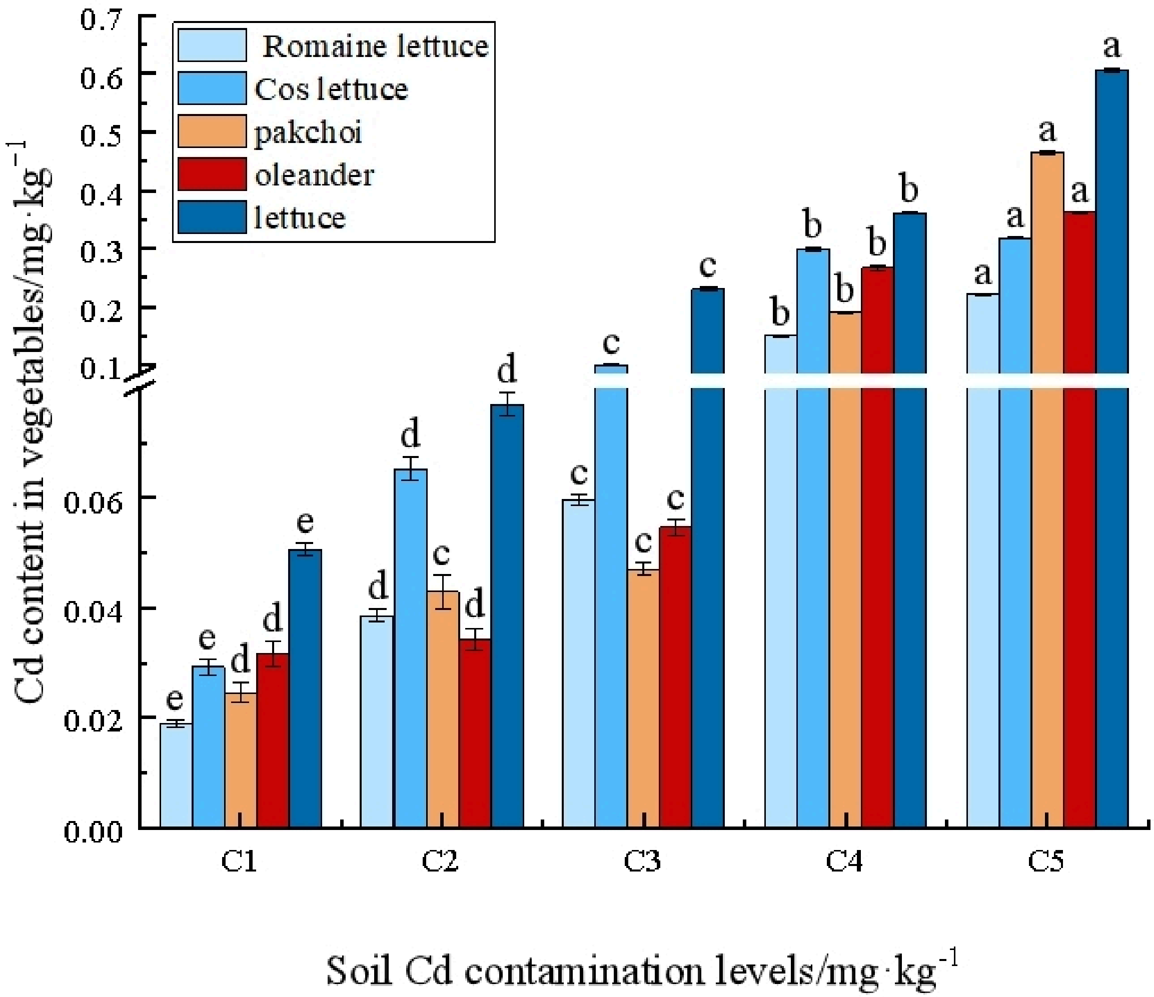

Figure 2

Cd content in vegetables under different soil Cd pollution levels

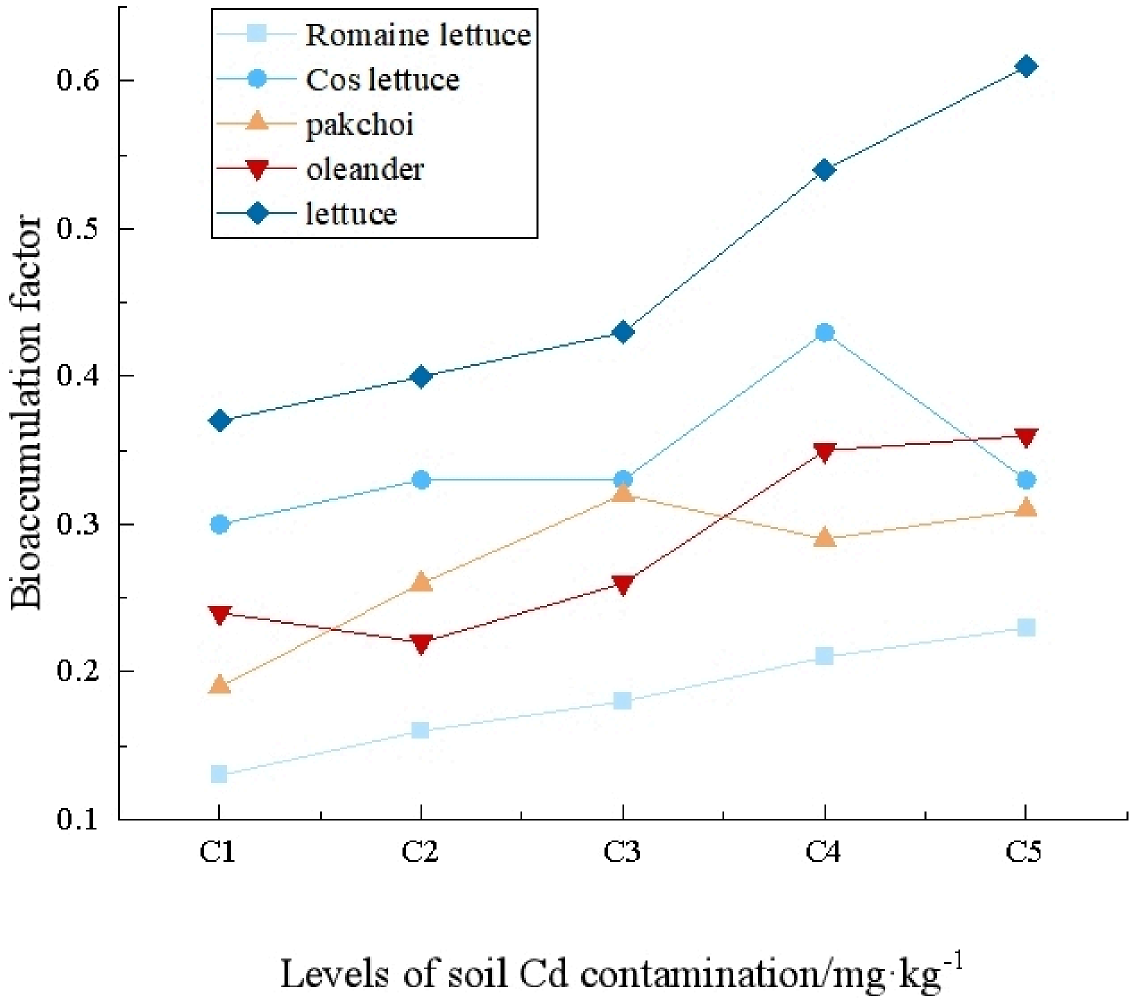

Figure 3

Bioaccumulation factor of vegetables under varying levels of soil Cd contamination

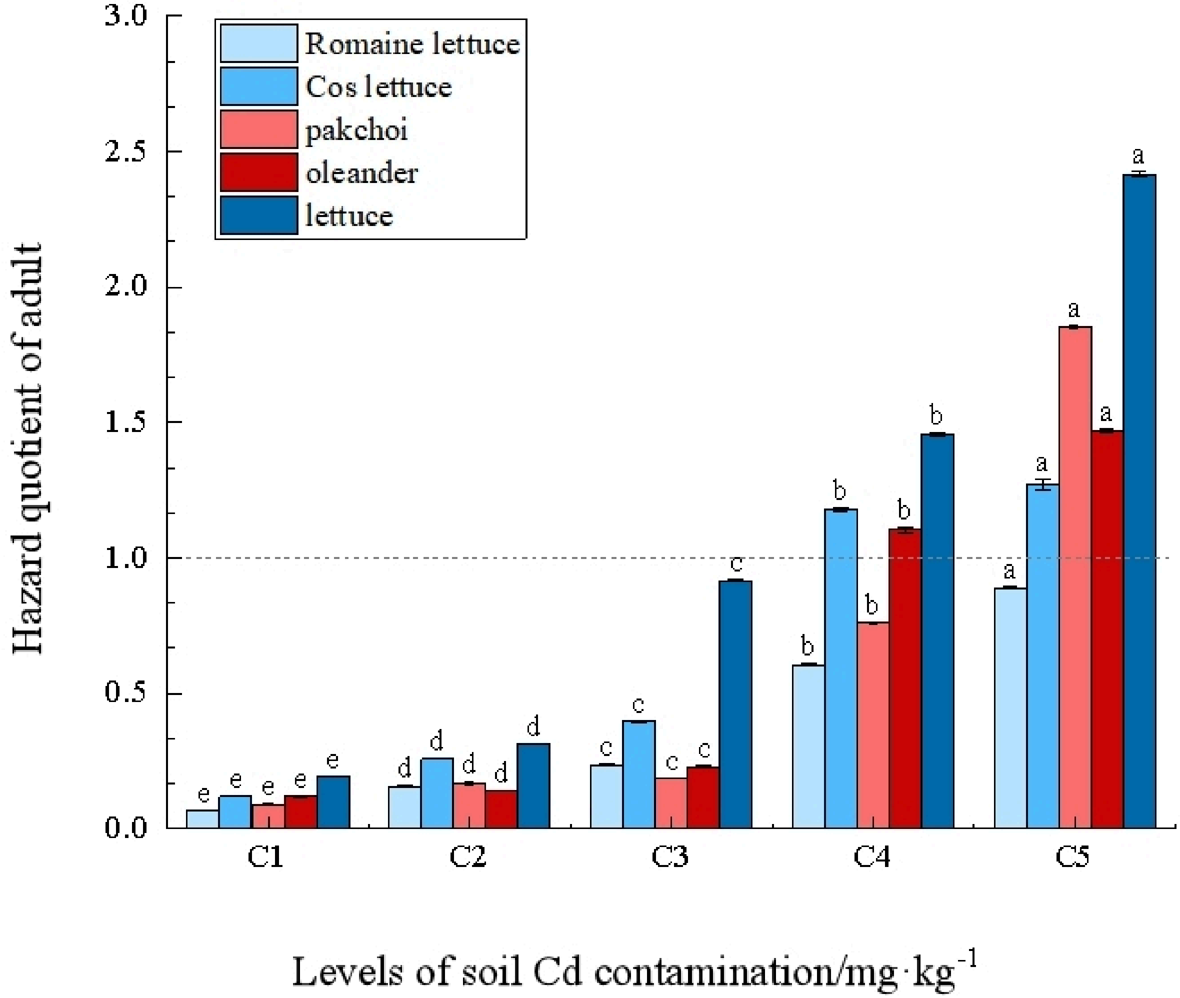

Figure 4

Hazard quotient for adults ingesting vegetables with different levels of soil Cd contamination

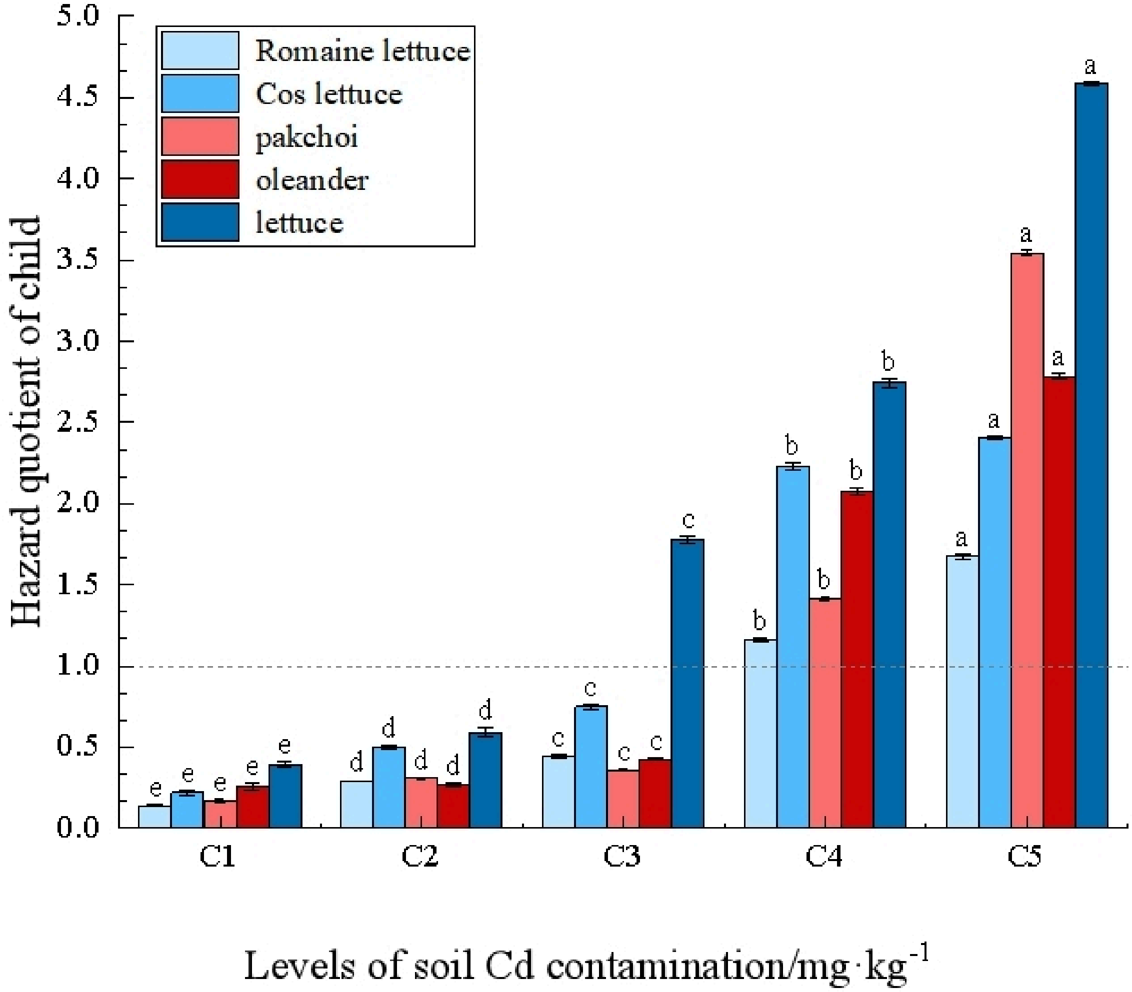

Figure 5

Hazard quotient for children ingesting vegetables with different levels of soil Cd contamination