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Original Article

Bioavailability and Bioaccumulation of Heavy Metals in Soil-crop System (*Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis*) and Health Risk Assessment

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Abstract: In farmland, especially in the high-quality production region, although smaller quantities of agrochemicals are applied compared to conventional farming, the repeated use of chemical fertilizers and other organic amendments can increase the accumulation of heavy metals (HMs) in soils and plants and raise human health risks for consumers. Our study provides a detailed overview of the status of soils, the soil-crop transfer, and health risks of HMs (Cr, Cu, Zn, Ni, Pb, and Cd) in a vegetable planting region (with the two studied *Brassica* species: *Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis*), in Me Linh commune, Hanoi, Vietnam. Soil contamination assessment indicates a non-HM pollution. However, the total and bioavailable fractions of HMs can exert an impact on HM bioaccumulation tendencies in vegetables. Although low transfer factors and no significant bioaccumulation of HMs in studied vegetables are observed, the high levels of Pb (more than twice as high as the permissible FAO/WHO standards), Cr, and Cd (almost reach the standards of the FAO/WHO) in the vegetables imply potential impact on product quality and human health, especially for children. The calculated Hazard Indexes (HIs) based on total HM contents in vegetables for adults are less than 1, indicating no elevated health risk. Meanwhile, the HM-related health risk assessment indicates potentially adverse health effects (HI = 6.35 for *Brassica rapa* var. *Parachinensis* and HI = 7.85 for *Brassica rapa* subsp. *Chinensis*) for children. Total Cr and Pb are the major contributors to the HI in both vegetables. Overall, an understanding of the potential enrichment of HMs in soils and vegetables can contribute to the safe and environmentally sustainable agriculture.

Keywords: Bioaccumulation, bioavailability, heavy metals, health risk assessment, soil, vegetables.

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1. Introduction

Soil contamination by heavy metals (HMs) is a major environmental issue at a global scale and is also identified as a worldwide concern due to their ability to enter the human food chain via multiple pathways [1-3]. In agriculture, repeated and long-term use of agrochemicals, fungicides, organic manure, and organic byproducts can be a variety of sources of HMs (such as Cr, Cu, Zn, Ni, Pb, Cd) in the soil [3, 4]. The rapid rise in the use of chemical fertilizers and pesticides in intensive agriculture in Vietnam over the past three decades can cause considerable pollution when soils have high HM contents [5]. In particular, in vegetable growing regions in Hanoi, such as Dong Anh and Me Linh former districts, Cu, Zn, Cd, and Pb are the main pollutants in the soil at different levels [6]. In addition, the use of organic fertilizers in agricultural practices, especially in vegetable farming, can further contribute to soil pollution over a prolonged period, as repeated applications of manure compost and organic materials may significantly increase the contents of HMs (such as Zn, Cr, Ni, and Cu) in soils [7].

Heavy metals can contaminate and persist in soils for a long time. They can accumulate in plants and affect agricultural productivity in the long term. In particular, vegetables, green leafy ones, can be prolific accumulators of HMs and may significantly pose risks to human health. Indeed, HMs can be readily taken up by root systems and bioaccumulate at high levels in the edible parts of vegetables, even with low contents of HMs in soils [4]. The soil-vegetables transfer of HMs is a complex process governed by many factors such as soil parameters, geochemical forms of HMs, plant absorption ability, weather conditions, human activities,... However, the potential risks of HMs are influenced by their bioavailability and mobility in soils.

The bioavailability of HMs has been widely used as a useful tool for evaluating the toxicity to plants [7]. In addition, vegetable consumption is a direct source of HMs intake for humans and can exert impacts on human health. Therefore, the bioaccumulation of HMs in vegetables, particularly in edible parts, is one of the most noticeable concerns. Further investigation of the bioavailability and bioaccumulation of HMs in soil-plant systems and the associated health risk is necessary to provide useful and valuable information for the development of friendly and sustainable cultivation.

On the other hand, vegetable species differ greatly in their ability to absorb and accumulate HMs, even between cultivars and varieties within the same species [8]. Although the *Brassicaceae* species, as green leafy vegetables, have abundant nutritional value and are widely consumed, they are known for high uptake capacities for HMs [9]. *Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis,* known as choy sum and pak choi, respectively, are common vegetables in Asian countries such as Vietnam and may exhibit the ability to bioaccumulate HMs from soils under certain conditions.

This study observed the bioaccumulation of HMs in both *Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis* (commonly planted in Yen Nhan Co-operative Society, Me Linh commune, Hanoi, Vietnam), complemented with health risk assessment. This region focuses on sustainable agriculture that meets the OCOP standards (One Commune, One Product), certified by the Vietnamese government. These standards include a set of criteria used to evaluate, classify, and certify products based on their quality, their origin, farming practices, and regional characteristics. We anticipate that our study can contribute to the advancement of safe and environmentally sustainable agriculture, with specific goals: i) Assessing the levels and bioavailability of target HMs (Cr, Cu, Zn, Ni, Pb, Cd) in the soil in the studied site under the impact of farming practices; ii) Evaluating if the soil-bound HMs contents are connected with those in vegetables; and iii) Calulating human health risk of target HMs in vegetables for consumers (children and adults).

2. Materials and Methods

2.1. Study Area and Sample Collection

The study site is Yen Nhan Co-operative Society, located in Me Linh commune, Hanoi, Vietnam (in the North of Vietnam). Vegetables, including *Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis,* are four-star OCOP products and the major crops at Yen Nhan Co-operative Society. In addition, this region belongs to the green vegetable belt in the North of Hanoi, providing vegetables for the inner city every day. Therefore, the authors expect that the present study could contribute to the reliable evaluation of HMs in soils and vegetables for the local region. In the study site, vegetable farming is continuously carried out at high density, especially during the main planting seasons of the year. Although the vegetable product quality almost meets the appropriate standards, there are potential factors that can affect product quality and the soil environment. Indeed, the local farmers regularly applied chemical fertilizers such as synthetic NPK, nitrogenous fertilizers, supplemented with bio-organic fertilizers or manure-derived compost. These agrochemicals and materials can cause soil pollution and exert an impact on product quality, mainly due to the accumulation of HMs in the soil and agricultural products.

On April 14, 2025, in the study site, three sampling zones were chosen for each studied *Brassicaceae* species. Accordingly, composite samples of topsoil (0-20 cm soil layer) and vegetables (edible parts) were prepared by mixing samples taken from five points based on a two-way diagonal method conducted in each sampling zone. The sampling day featured clear, dry weather with a temperature of 26°C. Samples were collected in the morning before watering time in the field. Therefore, the soil is dry and friable. Vegetables, which are ready to harvest, were collected at the corresponding soil sampling points. There are two main harvest seasons per year in the study area, which are winter-spring crop (from August to December) and spring-summer crop (from February to May).

The soil and vegetable samples were denoted, as follows: S1: Soil at Brassica rapa var. Parachinensis planting plots; S2: Soil at *Brassica rapa* subsp. *Chinensis* planting plots; V1: *Brassica rapa* var. *Parachinensis* sample; V2: *Brassica rapa* subsp. *Chinensis* sample. All samples were stored in polyethylene bags (size 30 x 40 cm) and transported to the laboratory. The soil samples were disaggregated by hand, air-dried at room temperature for a week, and sieved through a 2-mm sieve. Meanwhile, the vegetable samples were washed with distilled H_2O, dried in an oven at 40 - 45°C to a constant mass, and then ground in an agate mortar to pass through a 0.25-mm sieve.

2.2. Sample Analyses

Soil parameters such as pH, soil organic matter (SOM) content, and particle-size distribution were measured following Vietnamese Standards (TCVN). The soil pH was measured in distilled water with a soil/ water ratio of 1:2.5 using a digital pH meter (OHAUS starter 3100 pH) (TCVN 5979:2021) [10]. The SOM content was determined by the Walkley Black method, following H_2SO_4-aided oxidation of the organic matter with $K_2Cr_2O_7$ (TCVN 8941:2011) [11]. The particle-size distribution was analyzed by the pipette method with 0.1 M $Na_4P_2O_7$ (TCVN 8567:2010) [12]. All the tests were performed in triplicate.

For determining the total concentrations of HMs (Cr, Cu, Zn, Ni, Pb, and Cd) in soil samples and vegetable samples, and the contents of Mn, Fe, and Al in soil, aqua regia (HNO_3/HCl=1:3) was applied [7]. Before digestion, soil samples were ground to pass through a 0.25-mm sieve. Samples were digested in a microwave oven. Then, HM concentrations in digested solutions were determined by an inductively coupled plasma mass spectrometer (Agilent 7900 ICP-MS). For determining the bioavailable contents of HMs (Cr, Cu, Zn, Ni, Pb, Cd) in soil samples, an extraction procedure with 0.05 M Na_2-EDTA was performed as described elsewhere [13]. For that, 1.0 g of soil sample was weighed in a 50 ml centrifuge tube and then, 25 ml of 0.05 M Na_2-

EDTA was added. Samples were shaken on a shaker at 125 rpm for 1 h (Edmund Bühler SM-30 Shaker), centrifuged (at 3000 rpm for 10 min), filtered (at 0.45 µm), and then kept at 4ºC until ICP-MS analysis. The ICP-MS analysis was conducted using the Supelco Periodic Table Mix 1 for ICP TraceCERT®, which contains 33 elements at a concentration of 10 mg/L in HNO_3 as the external standard. In addition, the procedural blank and laboratory reference materials for soils were regularly checked.

2.3. Bioaccumulation Index

The transfer of HMs from the soil to the vegetable was tested by the bioaccumulation index (BAI) [14, 15]. The BAI can be applied to assess the relationship between the HM contents in the soil and the vegetables. Accordingly, the BAI is the ratio of the HM concentration in the vegetable sample to that in the soil sample. This index was calculated as follows:

$$\mathrm{BAI} = \frac{C_{vet}}{C_{soil}}$$

where: C_{vet} is the content of a given HM in the vegetable sample (mg/kg) and C_{soil} is the total content of the same HM in the corresponding soil sample (mg/kg). The C_{vet} and C_{soil} values are determined based on the dry weight.

Plants are considered HM accumulators if the BAI value is greater than 1. Conversely, a BAI less than 1 signifies higher HM contents in soils than those absorbed by plants, suggesting that plants can be excluders. Meanwhile, a BAI equal to 1 reveals no clear effects of soils on plants [16, 17].

2.4. Human Health Risk Assessment

The health risk associated with the total HM contents in the vegetables was primarily calculated for consumers, considering children and adults. Accordingly, the hazard quotient (HQ) (unitless) was calculated as the ratio of the estimated daily intake (EDI) from ingestion of vegetables and a specific reference dose (RfD) of each HM, with the following formula:

$$\mathrm{HQ} = \mathrm{EDI}/\mathrm{RfD}$$

The RfD is the HM reference dose, defined as the maximum allowable level of an HM that will not pose any harmful effects on human health. The HM reference dose was selected from the literature, as follows: Cr = 0.003, Cu = 0.04, Zn = 0.3, Ni = 0.02, Pb = 0.0035, and Cd = 0.001 [18 - 20]. While EDI (mg element/kg bodyweight/day), estimating human exposure to HMs through direct ingestion, was calculated based on USEPA methods [21], as follows:

$$\mathrm{EDI} = \frac{C_{vet}\ \mathrm{x\ SIR\ x\ EF\ x\ ED}}{\mathrm{BW\ x\ AT}}\ \mathrm{x}\ 10^{-6}$$

where C_{vet} is the content of a HM in the vegetable sample based on the dry weight (mg/kg); SIR is the ingestion rate (children: 200; adults: 100 mg/day); EF is the exposure frequency (180 days/year); ED is the exposure duration (children: 6; adults: 24 years); BW is the bodyweight (children: 15; adults: 70 kg); and AT is the averaging time (children: 6 x 365 days/year = 2190 days; adults: 8760 days). The EDI value will be compared with the acceptable daily intake (ADI) recommended by USEPA [22]. The ADI is the level of daily intake of a toxic substance that does not produce an adverse health effect.

The sum of all HQ values of each target HM is the Hazard Index (HI):

$$\mathrm{HI} = \sum \mathrm{HQ}$$

When HQ and HI values are higher than 1, an apparent probability of the occurrence of adverse health effects is indicated [21]. Meanwhile, HI < 1 shows that exposed persons are unlikely to experience dangerous health effects [19].

3. Results and Discussions

3.1. Soil Characteristics

The statistics of measured characteristics of the topsoil (0-20 cm) in the study site, such as pH, SOM, major element content (Mn, Fe, and Al), and soil particle-size distribution (sand, silt, and clay), are shown in Table 1. In general, the soil parameters did not vary significantly between the soil samples. Soils in the study plot are neutral to slightly alkaline and display a medium SOM content. According to the particle-size distribution, soils have a loam to clay loam textural characteristic with a high silt content. In addition, the low contents of Al and Fe observed in the study soil are likely associated with the clay and silt content, as these fractions naturally contain high amounts of these elements, indicating a parent material with inherently low Al and Fe [23]. In contrast, Mn is more abundant in the soil, suggesting a geogenic origin. The presence of fine soil fractions (such as clay and silt) and Fe/Mn oxyhydroxides may significantly affect the soil-bound HM contents in soils [24].

Table 1. Average values of basic soil parameters: pH, soil organic matter (SOM) contents, major element contents (Mn, Fe, Al) and particle size (sand, silt, and clay contents)

		S1 - Soil at *Brassica rapa* var. *Parachinensis* planting plots	S2 - Soil at *Brassica rapa* subsp. *Chinensis* planting plots
pH		6.93 ± 0.25	7.53 ± 0.14
SOM (%)		2.57 ± 0.17	2.91 ± 0.12
Al_2O_3 (g/kg)		9.56 ± 0.43	6.24 ± 0.85
Fe (g/kg)		12.20 ± 1.12	8.22 ± 0.34
Mn (mg/kg)		388.81 ± 32.16	261.20 ± 22.49
Soil particle sizes (%)	Sand (2-0.05 mm)	25.97 ± 1.54	15.82 ± 0.81
	Silt (0.05-0.002 mm)	49.65 ± 1.31	52.91 ± 1.85
	Clay (<0.002 mm)	24.38 ± 0.86	31.26 ± 1.94

3.2. Heavy Metals in the Studied Soils

Total contents of target HMs in the soils at *Brassica rapa* var. *Parachinensis* planting plots and in the soils at *Brassica rapa* subsp. *Chinensis* planting plots (marked as S1 and S2, respectively), which are not significantly different, except for Cu and Zn, are presented in Fig. 1. Total contents of Cu (41.30 ± 4.84 mg/kg) and Zn (125.73 ± 18,90 mg/kg) in the S2 are remarkably higher than those in the S1 (30.49 ± 3.30 mg/kg and 97.57 ± 13.10 mg/kg, respectively). The difference in the doses of chemical fertilizers used in the field can explain this situation. In addition, soil properties such as SOM content and fine-grained fractions (clay and silt) may impact total HM contents, especially Cu and Zn. As expected, previous studies indicate that these two elements have a high affinity for organic matter and fine soil fractions (mainly associated with clay minerals and Fe/Mn oxyhydroxides, contained in those fine-grained fractions) [7, 24, 26]. Therefore, with higher values of SOM, clay, and silt, the soil-bound Zn and Cu can be predominant in the S2 compared to the S1.

On the other hand, the contents of studied HMs, including Cr, Cu, Zn, Ni, Pb, and Cd are significantly lower than the pollution limit values of 150 mg/kg, 150 mg/kg, 300 mg/kg, 100 mg/kg, 200 mg/kg, and 4 mg/kg, respectively for soils figuring in Vietnamese standards (QCVN 03:2023/ BTNMT) [25]. However, the intensive use of chemical fertilizers to boost productivity can quickly increase HM levels, especially Cu and Zn content in the soil. Consequently, negative environmental effects and ecotoxicological concerns may arise. The presence of HMs in the soil, mainly due to agrochemical use, can also exert impacts on the bioavailability of these elements for plant absorption.

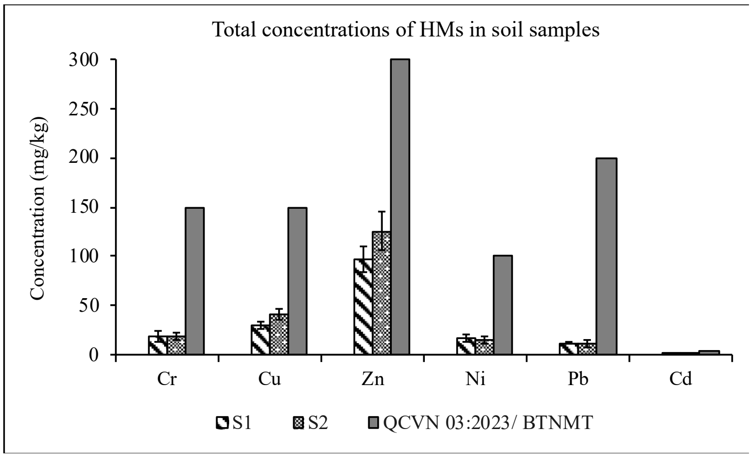

Figure 1. Total heavy metals (HMs) concentrations (mg/kg) in the studied soils (S1: Soil at *Brassica rapa* var. *Parachinensis* planting plots; S2: Soil at *Brassica rapa* subsp. *Chinensis* planting plots; QCVN 03:2023/ BTNMT: the pollution limit values of the Vietnamese standards).

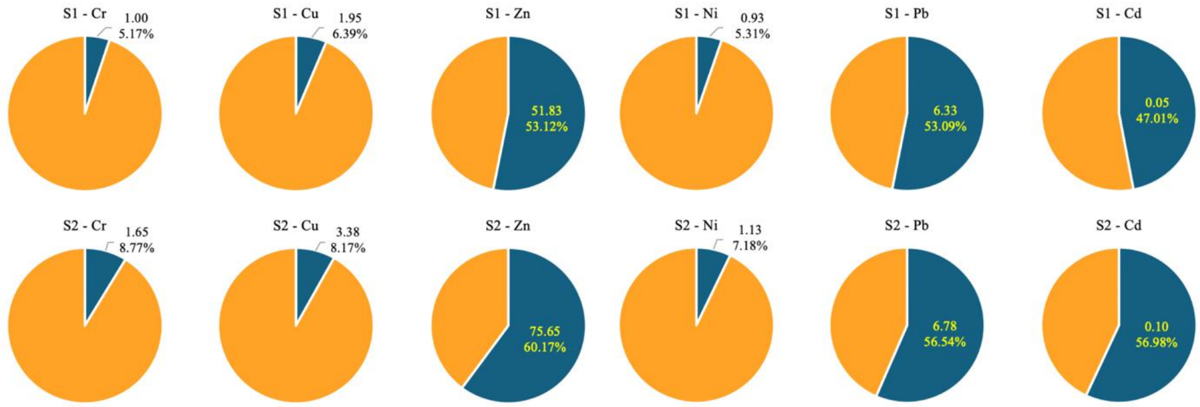

Figure 2. Contents of bioavailable heavy metals (HMs) (mg/kg) and bioavailable ratio (%) in the studied soils(S1: Soil at *Brassica rapa* var. *Parachinensis* planting plots; S2: Soil at *Brassica rapa* subsp. *Chinensis* planting plots).
*Bioavailable ratio (%) = (bioavailable HM fraction/ total HM content in soil) × 100%.

The bioavailability of HMs has been indicated as a useful tool for estimating the risk of environmental pollution and its toxicity to crops [7]. Based on the EDTA extracted HM contents (marked with X_E), Cr_E, Cu_E, and Ni_E contents in the studied soils are less than 10% of their total contents (Fig. 2). This finding indicates a strong to moderate binding of these elements to the soil. Meanwhile, Zn, Pb, and Cd show their lability in the studied soils, with overall EDTA-extracted contents exceeding 50% and reaching the highest values of 60.17% for Zn_E (Fig. 2). The retention ability of Zn, Pb, and Cd for Fe and Mn oxyhydroxides and oxides fractions (efficiently solubilized by EDTA) can explain the high bioavailable percentage of Zn, Pb, and Cd in the vineyard soil [24, 27]. On the other hand, the high proportions of bioavailable HMs in the soil also indicate that human-related sources may significantly contribute to variation in HM bioavailability. Furthermore, HM exhibits in Fe and Mn oxyhydroxides and oxides fractions may be more labile and therefore, promote HM translocation from the root to other parts of the plant if soils undergo changes in redox potential (such as under highly acidic or reducing conditions) [28].

3.3. Heavy metals in vegetable samples and bioaccumulation index

The total contents of Cr, Cu, Zn, Pb, Ni, and Cd in vegetable samples (dry weight) without any marked difference between the two Brassica species, except for Zn, are summarized in Fig. 3. A significantly higher Zn content (63.04 ± 8.47 mg/kg) is observed in Brassica rapa subsp. Chinensis compared to Brassica rapa var. Parachinensis (42.77 ± 5.87 mg/kg). The uptake of HMs in crops may depend on the type of crop, soil properties, and farming practices, in which a high content of HMs in the soil is considered an important factor. The observed levels of all target HMs in vegetable samples are below maximum permitted concentrations guided by FAO/WHO, except for Pb [29]. The Pb contents in samples V1 (0.75 ± 0.14 mg/kg) and V2 (0.77 ± 0.16 mg/kg) are more than twice as high as the permissible FAO/WHO value (0.3 mg/kg). This indicates that Pb may present a considerable risk to consumers, especially with the elevated daily intake of the vegetables. Indeed, high exposure to Pb has detrimental effects on human health, including cancer and nervous system damage [30]. In addition, the Cr and Cd contents in the vegetable samples almost reach the permissible values of the FAO/WHO. These problems can have a long-term impact on product quality and human health.

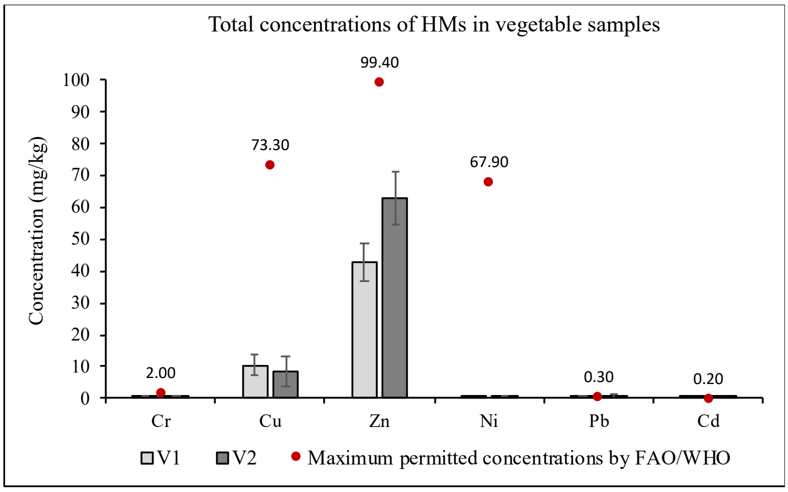

Figure 3. Total heavy metals (HMs) concentrations (mg/kg) in the studied vegetable samples (dry weight) and the corresponding FAO/WHO permissible values (V1: *Brassica rapa* var. *Parachinensis* sample; V2: *Brassica rapa* subsp. *Chinensis* sample).

On the other hand, the bioaccumulation index, defined as the ratio of the HM concentrations in the edible parts of the vegetable to the total HM concentrations in the soil, can be used to observe the general trend of vegetables to accumulate metals in their edible parts. The BAIs of *Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis* are in the order of Cd (0.89 and 0.95) > Zn (0.44 and 0.50) > Cu (0.34 and 0.21) > Pb (0.06 for both vegetables) > Cr (0.04 and 0.06) > Ni (0.02 and 0.04) (Fig. 4). The BAI values of Cd and Zn are considerably tailored by their high bioavailable percentages. Conversely, although bioavailability ratios of Pb in both studied soils are higher than 50%, the bioaccumulation of Pb is in the lowest group in the soil. The competitive nutrient uptake and low Pb total content in the soil can explain the low absorption of Pb by plants. Overall, the BAIs of vegetable samples are below 1.0, implying low transfer factors and no significant bioaccumulation of HMs in the studied vegetables. In the present study, low contents of HMs in the soil can be a plausible reason for the low accumulation of HMs in *Brassica* species, which are known as potential phytoremediation species mainly due to their tolerance to HMs, especially for non-essential HMs (such as Cd, Pb, and Cr) [29]. As expected, Zunaidi et al., (2024) reported that *Brassica* species such as *Brassica rapa* var. *Parachinensis* and *Brassica rapa* L. can exhibit high tolerance to non-essential HMs (Cd, Pb, and Cr) under various metal-spiked soil treatments [9].

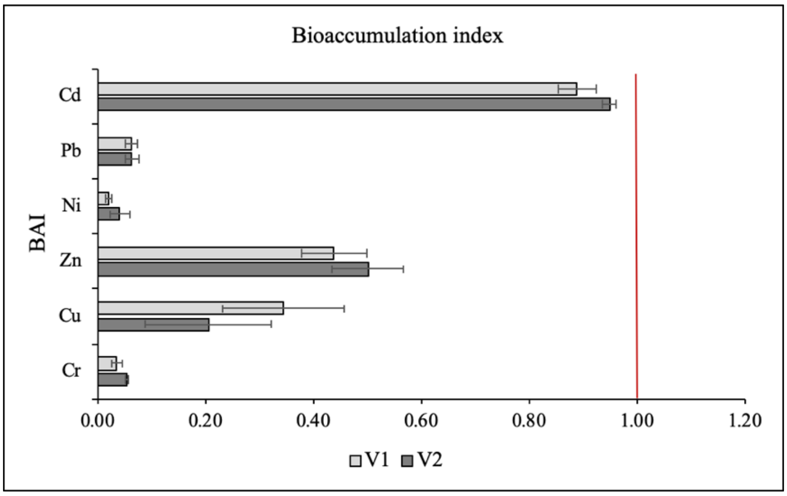

Figure 4. Bioaccumulation index (BAI) of vegetable samples based on the concentration of a HM in the vegetables relative to the concentration in the soil.
(V1: *Brassica rapa* var. *Parachinensis* sample; V2: *Brassica rapa* subsp. *Chinensis* sample)
The red line highlights BAI = 1, greater than or equal to which bioaccumulation is identified.

3.4. Human Health Risk Assessment

Table 2 shows the indices of human health risk assessment, including EDI, HQ, and HI for each vegetable for children and adults. The EDI for adults are below the recommended daily intake ADI for all target HMs. Meanwhile, for children, the EDI for Cu and Cd in both vegetables, and Zn in *Brassica rapa* subsp. *Chinensis* are higher than the recommended daily intake, indicating an elevated risk. Indeed, there are remarkable differences between HQ values for adults (indicating negligible effects) and children (indicating high effects). As expected, apart from Ni, the HQ for the other studied HMs (Cr, Cu, and Pb in both vegetables; and Zn and Cd in *Brassica rapa* subsp. *Chinensis*) is higher than 1 for children, whereas for adults, the HQs for all HMs do not exceed the limit. Accordingly, the children's HI based on all target HMs for all vegetables tested exceeds the recommended limits (HI < 1), indicating a higher risk for non-carcinogenic health risks for children (with HIs > 1) compared to adults (with HIs < 1). Generally, for children, from the individual HQs, the highest contribution percentage to the total HI is associated with Cr, reaching up to 29.43%, followed by Cu and Pb. Thus, although low concentrations of Cr and Pb are indicated, they can be reported to represent the highest risks, especially for children. These results are comparable with the findings of similar studies discussing HM-related health risks in green leafy vegetables. According to Zhou et al. (2016), although there was a high content of Pb in the soil (1090.0 mg/kg), leafy vegetables show a low bioaccumulation of Pb compared to other metals (such as Zn, Cu, and As), ranging from 0.42 to 2.36 mg/kg [8]. However, Pb remains the primary element contributing to human health risks associated with vegetable consumption, with HQ values of 1.04 for adults and 1.37 for children [8]. Similarly, Cr is indicated as a main contributor to its respective human health risk without the significant bioaccumulation level of this HM in vegetables [31]. Therefore, a high human health risk of Pb and Cr can be dominantly explained by their toxicity to humans. As expected, the RfD values of Pb and Cr are significantly lower than those of other HMs.

Table 2. Indices of human health risk assessment based on total heavy metal contents in the vegetable samples: EDI, HQ, and HI

		Brassica rapa var. *Parachinensis*			*Brassica rapa* subsp. *Chinensis*		
	ADI*	EDI	HQ	HI	EDI	HQ	HI
Aduts							
Cr	1.0E+00	4.95E-04	0.17	0.69	7.41E-04	0.25	0.85
Cu	4.0E-02	7.40E-03	0.19		6.01E-03	0.15	
Zn	3.0E-01	3.01E-02	0.10		4.44E-02	0.15	
Ni	2.0E-02	2.61E-04	0.01		4.58E-04	0.02	
Pb	4.0E-02	5.26E-04	0.15		5.43E-04	0.16	
Cd	5.0E-04	6.67E-05	0.07		1.17E-04	0.12	
Children							
Cr	1.0E+00	4.62E-03	1.54	6.35	6.92E-03	2.31	7.85
Cu	3.7E-02	6.90E-02	1.73		5.61E-02	1.40	
Zn	3.0E-01	2.81E-01	0.94		4.15E-01	1.38	
Ni	2.0E-02	2.43E-03	0.12		4.27E-03	0.21	
Pb	4.0E-02	4.91E-03	1.40		5.07E-03	1.45	
Cd	5.0E-04	6.22E-04	0.62		1.10E-03	1.10	

*ADI: the acceptable daily intake recommended by USEPA [20].

4. Conclusions

In this study, we assess the HMs (Cr, Cu, Zn, Ni, Pb, and Cd) levels in the soil of a vegetable planting region (with the two studied *Brassica* species: *Brassica rapa* var. *Parachinensis* and *Brassica rapa* subsp. *Chinensis*), in Me Linh commune, Hanoi, Vietnam, and the bioaccumulation of these HMs in the two studied *Brassica* species related to health risks. Results show that in line with Vietnamese national standards, the studied soils do not show contamination by HMs. The calculated bioaccumulation index of all target HMs for both vegetables is also below 1.0, implying low transfer factors and no significant bioaccumulation of HMs in the studied vegetables. However, the content and the toxicity of HMs to humans can be considered dominant factors in determining the health risk of HMs. Indeed, Pb and Cr, which are present in significantly higher amounts in the vegetables compared to the FAO/WHO permissible limits (more than twice as high and nearly reaching the limit, respectively), along with low maximum allowable doses for humans, are the primary contributors to their respective health risks. The health risk assessment results indicate elevated risk for children (HI > 1) and no risk for adults. The overall health risk associated with all target HMs was more than nine times higher for children than for adults. Therefore, regular monitoring and testing of the accumulation of HMs in soils and vegetables are crucial for ensuring food safety and can significantly contribute to the development of environmentally friendly vegetable farming.

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