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Research article

Transfer of heavy metals from soil to vegetables: A comparative assessment of different irrigation water sources

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ABSTRACT

This study aimed to assess the transfer factor (TF) of heavy metals (HMs) from soil to commonly consumed vegetables irrigated with different water sources. The field study covered 36 m^2 of agricultural land in Kermanshah province, Iran, divided into nine equal-sized plots. Coriander, basil, and radish were the three types of vegetables cultivated and subjected to irrigation over two months, utilizing three different water sources: treated wastewater effluent (TWE), river water (RW), and well water + nitrogen fertilizer (WWF). After the irrigation and harvesting stages, soil samples from the cultivation area and harvested vegetables were collected. These samples underwent analysis using the ICP-OES method to assess HM levels and subsequent calculation of the TF of HMs from soil to plants. The results revealed that the TF levels indicated plants' relatively weak response (TF < 1) to the absorption of HMs. For non-toxic elements (Mn, Fe, Zn, Cu, Ni), TF values were generally higher than those for toxic elements (Cd, As, Pb) across all three vegetable types and irrigation treatments. The study's findings suggest that the TF of HMs in the studied vegetables varied based on the irrigation source and vegetable type. Various factors, including the type of irrigation source and vegetable, influenced the TF of HMs, each having different impacts on the transfer rate of each HM. The study highlights the importance of monitoring irrigation water and soil quality to prevent the accumulation of HMs in cultivated vegetables, thereby mitigating potential risks to human health.

1. Introduction

The accumulation of heavy metals (HMs) and their metabolites in agricultural soils poses a significant concern related to the food chain. The entry of HMs into agricultural soils can disrupt the metal balance in the soil, leading to the transfer of these metals to

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agricultural products. Ultimately, this may increase the potential health risks for consumers of those agricultural products [1–4].

Soil HMs can originate from two primary sources, including natural and human activities. The amount of natural HMs varies from one region to another and depends on the natural characteristics of the soil in that region. Human activities, on the other hand, are related to activities carried out by humans that cause an increase in HMs in the soil. These activities include the construction of industries near agricultural lands, atmospheric deposition, burying dangerous solid waste materials in the soil, waste incineration, leakage of petrochemical products in the ground, the use of various organic and inorganic fertilizers in agricultural lands, the use of sewage sludge as fertilizer, the use of pesticides, and the use of polluted irrigation water, especially municipal and industrial sewage effluents [1,5–9].

HMs are a significant source of pollution in edible vegetables [10]. HMs that are non-biodegradable have long biological half-lives and can accumulate in various organs of the body, leading to adverse effects in humans [11–13]. Due to their solubility in water, most HMs are highly toxic and can easily be converted to toxic levels [14].

Researchers have increasingly directed their attention toward the potential hazards associated with the intake of HMs in food items, specifically vegetables, in response to the growing demand for food safety [11,12,14–16]. However, it is important to acknowledge that fruits and vegetables are essential components of the human diet, playing a critical in supplying essential nutrients. As understanding of their nutritional value increases, the consumption of vegetables rises. Therefore, the contamination of vegetables with various pollutants, especially HMs, poses a significant threat to human health [16–19].

Leafy vegetables have a high potential for accumulating HMs, posing a major concern for consumers' health. Lead (Pb) and cadmium (Cd) are among the most common and dominant HMs in vegetables, and they are also toxic [20,21]. The high level of HMs in food is associated with many diseases, especially heart, renal, neurological, and bone diseases [22–24]. In addition, these types of metals have other harmful effects, such as the induction of cancer, genetic mutations, and congenital disabilities [25,26].

Moreover, essential elements, including zinc (Zn), copper (Cu), manganese (Mn), and iron (Fe), play crucial roles in physiological and biochemical functions, contributing to the maintenance of human health. However, excessive levels of these metals can lead to adverse health effects. Zn deficiency is associated with a wide range of immune system impairments, while Cu deficiency is associated with anemia, neutropenia, and skeletal deformities [27–29]. Conversely, an excessive increase in Cu is associated with hepatic injury, and a high Zn level may result in negative nutritional interactions with Cu, leading to impaired immune system activity. Additionally, high concentrations of Fe and Mn can cause pathological conditions, such as the accumulation of iron oxides in individuals affected by Parkinson's disease [30].

The transfer or translocation factor (TF) of HMs from soil to plants is crucial for evaluating the uptake of HMs by plants [31]. TF for metals is calculated as the ratio of the concentration of HMs in the plant extract to the total concentration of HMs in the soil extract [32,33]. Total HM concentration in the soil is considered for metal TF, as the soil's storage capacity for HMs is a critical factor influencing the diffusion of HMs from the solid phase to the liquid phase [34]. The availability of metals for plants is controlled by the plants' requirements for micronutrients and their capacity to absorb or remove toxic elements [35]. This availability varies among different plants and depends on various parameters, including plant species, HM concentration in the soil, environmental and weather conditions, pH, organic carbon, cation-exchange capacity, plant growth stage, microorganisms around plant roots, active and passive transport processes, sequestration and speciation, redox states, type of plant root system, plant response to elements in seasonal cycles, and irrigation water quality [36–42]. Based on these parameters, plants are classified into three groups: excluders, indicators, and accumulators [35]. Herbs absorb fewer metals than fast-growing plants, such as lettuce, spinach, carrot, and tobacco [35].

Higher TF values ($\geq$1) indicate that the plant efficiently absorbs metals from the soil, making it more suitable for phytoextraction and phytoremediation. In contrast, lower TF values suggest that the plant has a weak response to the absorption of HMs, making it suitable for human consumption [43].

The accumulation of HMs in vegetables and their bioavailability for human consumption is an area that requires further research. To mitigate the potential health risks associated with HMs, producing vegetables with lower metal content and better compatibility with agricultural practices is important. In summary, the TF of HMs from agricultural soil to vegetables is a valuable metric for evaluating human exposure to HMs through the intake of vegetables and for assessing the health risks associated with HMs in vegetables. This study aimed to determine the TF of different elements, including Fe, Mn, Cu, Zn, lead (Pb), arsenic (As), nickel (Ni), cadmium (Cd), and chromium (Cr), in soil irrigated with different sources for coriander, basil, and radish. These vegetables were selected because they are commonly consumed in Iran and have a short life cycle. Basil and coriander are consumed as leaves, while radish contains both leaves and edible tubers. The selection of these vegetables allowed for investigating the TF of different HMs in both the edible leaves and tuber, providing more information on potential health risks associated with HMs in vegetables. The irrigation sources investigated in this study included well water with fertilizer (WWF), treated wastewater effluent (TWE), and river water (RW).

2. Materials and methods

2.1. *Characterizations of the study area*

A 36 m^2 portion of agricultural land adjacent to the sewage treatment plant in Kermanshah province was chosen as the cultivation site. The province of Kermanshah, located between 33°37′ and 35°17′ N and 45°20′ and 48°1′ E, spans an area of 24,640 km^2 in Iran. The region experiences an average annual precipitation of 450 mm, with hot, arid, clear summers and cold, partly cloudy winters. The temperature in Kermanshah typically varies between −4 °C and 38 °C throughout the year, with occasional dips below eight °C and highs above 44 °C.

2.2. Cultivation and irrigation of vegetables

The cultivation of vegetables commenced on April 19, 2021. As illustrated in Fig. 1, the selected agricultural land (36 m^2) was divided into nine parts (P), each measuring 2 × 2 m (4 m^2). The study involved the cultivation of three distinct species of vegetables: coriander, basil, and radish. These vegetables were grown in three separate portions, denoted as P1, P4, and P7 for coriander; P2, P5, and P8 for basil; and P3, P6, and P9 for radish. The planting process was carried out in an environment characterized by clear, sunny weather and balanced temperatures. Each type of vegetable was watered using three distinct water sources. Consequently, specific areas of the farmed land were allocated for cultivating each type of vegetable, with each area irrigated using a designated water supply. The three irrigation sources employed in this investigation were as follows:

1. Well water (groundwater) + nitrogen fertilizer (WWF) was used for irrigation in sections P1, P2, and P3, with nitrate nitrogen fertilizer applied to the agricultural soil at 15 g per square meter.
2. Qarasu River water (RW) was used for irrigation in sections P4, P5, and P6.
3. Treated wastewater effluent (TWE) from Kermanshah City was used for irrigation in sections P7, P8, and P9.

The mean concentration of various HM pollutants in the water samples used for irrigation is presented in Table 1. Following the cultivation and seeding of all nine sections (Fig. 1), the initial irrigation was carried out using well water. Subsequently, over two months (60 days), irrigation was performed at 20 intervals using each irrigation source, with a frequency of every three days.

A drinking tap water near the cultivation site was irrigated with WWF. On the other hand, 20-L gallons were utilized to transport the water required for irrigation and to prepare the RW and TWE. Furthermore, to ensure optimal and beneficial irrigation practices, all parts were irrigated after sunset, when the temperature had dropped. In the case of irrigation with WWF, fertilizers were applied to sections P1, P2, and P3 in three stages during the cultivation and irrigation stages.

2.3. Sampling

2.3.1. Sampling of soil

Before planting vegetables, ten composite soil samples were collected from the cultivation site at five different points (P1, P2, P5, P7, and P9) at a depth of 30 cm. These initial soil samples were labeled as soil samples without irrigation (SWI), and each sample was divided into three sections, resulting in 30 SWI samples for subsequent analysis. Following the vegetable harvest, soil samples were collected from different sections denoted as P1–P9. Six soil samples were obtained from areas P1–P3, irrigated with well water and chemical fertilizers (SWWF). Similarly, six soil samples were collected from sections P4–P6 and irrigated with river water (SRW). Additionally, six soil samples were taken from areas P7–P9, irrigated with treated sewage effluent (STWE). In total, 18 soil samples subjected to irrigation and ten samples not subjected to irrigation were collected, and each sample was subdivided into three portions. During this study phase, 84 samples were analyzed for the presence of HMs.

2.3.2. Sampling of vegetables

Five samples were taken from each type of vegetable, each produced with different watering schedules. Consequently, 45 samples were obtained and transferred to the laboratory, considering the three types of vegetables and three irrigation treatments. Each collected sample was analyzed with three repetitions, resulting in the analysis of 135 samples for the target pollutants. The leafy parts of coriander and basil were subjected to analysis. For radish, both the leaves and tubers were combined before analysis.

2.4. Sample preparation

The collected soil samples were air-dried for 24 h and were subsequently sieved through a 2 mm mesh to eliminate gravel and other impurities. To digest the soil samples, 2 g of pre-dried soil was placed into a 25 mL flask, and 15 mL of 4 N nitric acid was added. The

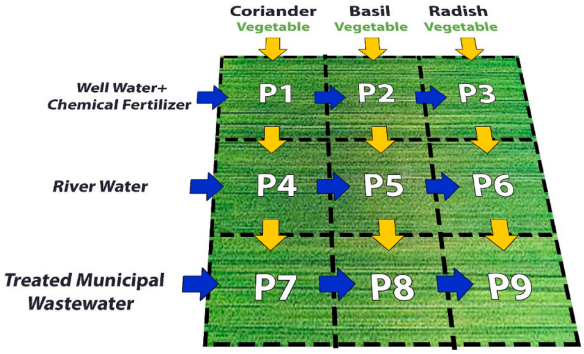

Fig. 1. The method of placing the vegetables on designated plots and watering them with different irrigating treatments.

Table 1
Concentration of HMs in various irrigation water sources.

HMs	Various irrigation water sources (mean ± SD) (mg/L)		
	RW	TWE	WW
Fe	3.700 ± 1.419	1.681 ± 0.376	0.113 ± 0.037
Zn	2.757 ± 1.110	0.258 ± 0.066	0.146 ± 0.025
Mn	1.987 ± 0.777	0.086 ± 0.062	0.042 ± 0.010
Cu	1.087 ± 0.573	0.052 ± 0.028	0.022 ± 0.006
As	0.117 ± 0.022	0.022 ± 0.007	0.004 ± 0.001
Pb	0.858 ± 0.257	0.043 ± 0.004	0.004 ± 0.001
Cd	0.082 ± 0.007	0.058 ± 0.020	0.002 ± 0.000
Cr	1.150 ± 0.082	0.029 ± 0.007	0.045 ± 0.004
Ni	1.317 ± 0.238	0.045 ± 0.012	0.042 ± 0.007

HMs: heavy metals; **RW:** river water; **TWE:** treated wastewater effluent; **WW:** well water.

mixture was thoroughly mixed and placed in a hot water bath at 80 °C for 12 h. Following cooling, the samples were filtered using a 42-μm Whatman paper filter into another 25 mL flask. Finally, the obtained extract was adjusted to volume using double-distilled water [12].

To perform acid digestion of vegetable samples, 0.2 g of dried vegetables were weighed and transferred into a 25 mL flask, followed by the addition of 4 mL of concentrated nitric acid. The flask was then placed in a hot water bath at 65 °C for 1 h, with the water bath temperature subsequently increased to 100 °C for 90 min. After cooling to laboratory temperature, 0.2 mL of 37 % H_2O_2 was added to the flask to digest organic matter, and the samples were left for half an hour to complete the process. The sample was then filtered through a Whatman paper filter into another 25 mL flask. Finally, the resulting extract was adjusted to volume using double-distilled water [12,44].

2.5. *Determination of heavy metals in soil and plants*

After the soil and vegetable samples were prepared, the HM content in each sample was measured using an inductively coupled plasma optical emission spectrometry)ICP-OES(device (SPECTRO, Germany) with the characteristics listed in Table S1. Limit of detection (LOD) of this device for metals As, Cd, Pb, Cu, Fe, Zn, Cr, Mn, and Ni was 0.179, 0.049, 0.166, 0.306, 0.160, 0.270, 0.564, 0.325, 0.240 pbb, respectively. Also, the recovery percentages for the mentioned metals were 96.8 ± 7.2, 98.5 ± 66.6, 94.6 ± 7.2, 104.5 ± 8.4, 97.6 ± 3.3, 101.4 ± 8.4, 95.4 ± 3.6, 98.5 ± 2.8, and 97.5 ± 6.7, respectively.

2.6. *Evaluation of the transfer factor*

To determine the actual amount of HMs absorption by each vegetable, the TF was computed using Eq. (1). The TF represents the ratio of the concentration of a particular pollutant in the plant to the concentration of the same pollutant in the soil [2,3,35,36,38,39]. It is important to note that the calculation of the TF requires consideration of each plant type with its corresponding soil sample.

$$TF = \frac{CmP\ (mg/kg\ dry\ weight)}{CmS\ (mg/kg\ dry\ weight)} \quad \text{Eq. (1)}$$

In this equation, TF is the transfer factor of HMs from soil to plant, while CmP and CmS refer to the concentration of HMs in the plant and soil, respectively.

Table 2
Transfer factor of HMs from soil to coriander vegetable based on the average, minimum, and maximum concentration of HMs in soil and vegetable.

Soil type	Based on the average concentration of heavy metals								
	Fe	Zn	Mn	Cu	As	Pb	Cd	Cr	Ni
SRW	0.20 ± 0.03	0.09 ± 0.02	0.19 ± 0.04	0.10 ± 0.02	0.02 ± 0.01	0.01 ± 0.01	0.05 ± 0.03	0.02 ± 0.01	0.01 ± 0.01
STWE	0.14 ± 0.02	0.21 ± 0.02	0.25 ± 0.02	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.11 ± 0.02	0.01 ± 0.01	0.03 ± 0.01
SWWF	0.13 ± 0.01	0.06 ± 0.01	0.57 ± 0.04	0.07 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.04 ± 0.01
-	Based on the minimum concentration of heavy metals								
SRW	0.17	0.07	0.11	0.06	0.01	0.01	0.02	0.01	0.01
STWE	0.10	0.17	0.21	0.02	0.01	0.01	0.08	0.01	0.02
SWWF	0.12	0.05	0.52	0.06	0.03	0.01	0.03	0.02	0.03
–	Based on the maximum concentration of heavy metals								
SRW	0.25	0.14	0.25	0.13	0.04	0.01	0.10	0.03	0.02
STWE	0.17	0.26	0.28	0.03	0.04	0.02	0.14	0.01	0.04
SWWF	0.15	0.08	0.62	0.09	0.06	0.02	0.06	0.04	0.05

SRW: Irrigated soil by river water; **STWE:** Irrigated soil by treated wastewater effluent; **SWWF:** Irrigated soil by well water and fertilizer.

2.7. Statistical analysis

To compare the TF of each HM among various soils and vegetables, a one-way analysis of variance (ANOVA) test was conducted using SPSS software version 25, with a significance level set at α = 0.05.

3. Results and discussion

3.1. Effect of different irrigation sources on the transfer factor of heavy metals in various vegetables

Tables 2–4 present the results of the TF of HMs from soil cultivated using three different types of irrigation for the three plants studied, based on the average, minimum, and maximum concentrations of HMs. The results showed that the TF of different HMs in coriander, basil, and radish varied depending on the irrigation source. For WWF irrigation source, the order of TF from the highest to the lowest level of this factor was Mn > Fe > Cu > Zn > Cd ≈ As ≈ Ni > Cr > Pb for coriander, Mn > Fe > Zn > Cu ≈ As > Ni > Cd > Cr > Pb for basil, and Mn > Fe > Zn > As > Cu > Cd ≈ Ni > Cr ≈ Pb for radish. For TWE, the order of TF was Mn > Zn > Fe > Cd > Ni ≈ Cu > As > Pb ≈ Cr for basil, Mn > Fe > Zn > Cd > Cu > As ≈ Ni > Pb ≈ Cd for radish, and Mn > Zn > Fe > Cd > Ni > Pb ≈ As ≈ Cu > Cr for coriander. For RW irrigation treatment, the order of TF was Fe > Mn > Zn > Cd > Cu ≈ Ni > Cr > As > Pb for radish, Fe > Mn > Cu > Zn > Cd > As ≈ Cr > Ni ≈ Pb for coriander, and Fe > Mn > Zn > Cd > Cu ≈ Ni > Cr > As > Pb for basil (Tables 2–4). The results consistently indicated that the TF values were less than 1 in all cases, suggesting a relatively weak response of the studied plants to the absorption of HMs. This discovery indicates that the contamination levels of HMs in the plants studied might not pose a significant barrier to consuming these vegetables. However, it remains vital to comply with environmental quality standards established by national or international regulations and the relevant authorities responsible for ensuring environmental safety. This adherence is essential to guarantee the safe consumption of vegetables.

Based on the results of the study, it is evident that the use of WWF and TWE irrigation sources for cultivating the studied vegetables increases the potential for Mn to enter the food chain compared to other HMs, while the potential for Pb and Cr to enter the food chain is the lowest in most cases. Conversely, using the RW irrigation source is associated with HM's highest and lowest potential entering the food chain for Fe and Pb, respectively. Although the characteristics of different irrigation treatments can affect the TF, the high TF rate for Mn and Fe can be explained by the high mobility of these metals in the soil. On the other hand, the low TF rate for Pb and Cr in the investigated vegetables can be attributed to their ability to bind to soil and lower mobility within the soil than other HMs [8].

Based on the results mentioned above, in all three types of vegetables and irrigation treatments, the TF of non-toxic metals (Mn, Fe, Zn, Cu, Ni) was higher than that of toxic metals (Cd, As, Pb). Furthermore, Cd's TF was higher than that of Pb in all cases. Cd is an element that readily joins the soluble part of organic matter (fulvic acid), making it highly mobile in soil and easily absorbed by plants [45]. Wang et al. [36] found that the TF of Cd from soil to plants is ten times higher than that of Pb, attributable to the greater mobility of Pb compared to Cd [36]. Cao et al. [46] demonstrated that the TF of HMs from soil to crops such as rice and vegetables follows the order of Cd > Cr > Pb [46]. The application of compost on the soil surface has the potential to alter the labile fraction of Cd in soils and promote the binding of Cd to humic and fulvic acids, thereby forming an organometallic complex that could impede the availability of Cd to plants [47].

In all cases, the TF of Zn was found to be higher than that of Cd. This observation may be due to the chemical similarity of these two elements and their antagonistic relationship, leading to competition in their absorption by vegetables. These findings align with similar studies, including Cheraghi and Ghobadi [48], where parsley grown in fields irrigated with sewage effluent exhibited the lowest (1.14 mg/kg) and the highest (25.23 mg/kg) concentrations of Cd and Zn, respectively [48]. This trend has also been noted in the studies of McKenna et al. [49] and Yildiz, [50]. Furthermore, Gebrekidan et al. [8] reported TF values of 42.89, 0.84, and 0.37 for Fe, Pb, and Cd, respectively [8].

Table 3
Transfer factor of HMs from soil to basil vegetable based on the average, minimum, and maximum concentration of HMs in soil and vegetable.

Soil type	Based on the average concentration of heavy metals								
	Fe	Zn	Mn	Cu	As	Pb	Cd	Cr	Ni
SRW	0.28 ± 0.04	0.12 ± 0.01	0.22 ± 0.03	0.05 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.07 ± 0.03	0.04 ± 0.02	0.05 ± 0.01
STWE	0.19 ± 0.02	0.26 ± 0.06	0.33 ± 0.06	0.05 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	0.08 ± 0.01	0.02 ± 0.01	0.05 ± 0.01
SWWF	0.18 ± 0.01	0.08 ± 0.01	0.29 ± 0.03	0.06 ± 0.01	0.06 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.03 ± 0.01
-	Based on the minimum concentration of heavy metals								
SRW	0.23	0.10	0.18	0.03	0.02	0.02	0.03	0.02	0.03
STWE	0.16	0.18	0.24	0.04	0.03	0.02	0.07	0.01	0.03
SWWF	0.17	0.07	0.24	0.05	0.05	0.01	0.01	0.02	0.02
–	Based on the maximum concentration of heavy metals								
SRW	0.35	0.14	0.27	0.08	0.05	0.03	0.11	0.08	0.07
STWE	0.21	0.36	0.40	0.06	0.06	0.02	0.11	0.02	0.07
SWWF	0.20	0.09	0.34	0.07	0.09	0.01	0.02	0.03	0.04

SRW: Irrigated soil by river water; **STWE:** Irrigated soil by treated wastewater effluent; **SWWF:** Irrigated soil by well water and fertilizer.

Table 4
Transfer factor of HMs from soil to radish vegetable based on the average, minimum, and maximum concentration of HMs in soil and vegetable.

Soil type	Based on the average concentration of heavy metals								
	Fe	Zn	Mn	Cu	As	Pb	Cd	Cr	Ni
SRW	0.27 ± 0.03	0.12 ± 0.01	0.13 ± 0.02	0.07 ± 0.02	0.03 ± 0.01	0.01 ± 0.00	0.08 ± 0.02	0.04 ± 0.01	0.02 ± 0.01
STWE	0.29 ± 0.02	0.13 ± 0.01	0.31 ± 0.05	0.05 ± 0.01	0.04 ± 0.01	0.01 ± 0.00	0.06 ± 0.01	0.01 ± 0.00	0.04 ± 0.01
SWWF	0.25 ± 0.01	0.10 ± 0.01	0.52 ± 0.03	0.04 ± 0.01	0.07 ± 0.01	0.01 ± 0.00	0.02 ± 0.01	0.01 ± 0.00	0.02 ± 0.01
-	Based on the minimum concentration of heavy metals								
SRW	0.24	0.10	0.10	0.05	0.02	0.01	0.04	0.02	0.01
STWE	0.26	0.12	0.23	0.04	0.03	0.01	0.04	0.01	0.03
SWWF	0.24	0.09	0.44	0.03	0.06	0.01	0.02	0.01	0.02
–	Based on the maximum concentration of heavy metals								
SRW	0.31	0.14	0.15	0.11	0.04	0.02	0.11	0.06	0.02
STWE	0.33	0.15	0.37	0.05	0.05	0.01	0.07	0.01	0.06
SWWF	0.27	0.11	0.57	0.04	0.09	0.03	0.03	0.02	0.02

SRW: Irrigated soil by river water; **STWE:** Irrigated soil by treated wastewater effluent; **SWWF:** Irrigated soil by well water and fertilizer.

3.2. Transfer factor among different irrigated soils for each specific heavy metal

The loading and accumulation of HMs in soil are contingent upon several factors, including the chemical speciation of the elements, soil pH, organic matter content, soil texture, and cation exchange capacity (CEC) [51,52]. As pH levels increase, the percentage and availability of metals decrease, alongside the content of organic matter, CEC, and clay [52]. The presence of carbonates, sulfates, phosphates, and sulfides in the soil enhances the precipitation of metals, thereby reducing their availability to crops [51,52]. Furthermore, the absorption and release of elements in the soil are influenced by plant species, growth stage, and soil solution

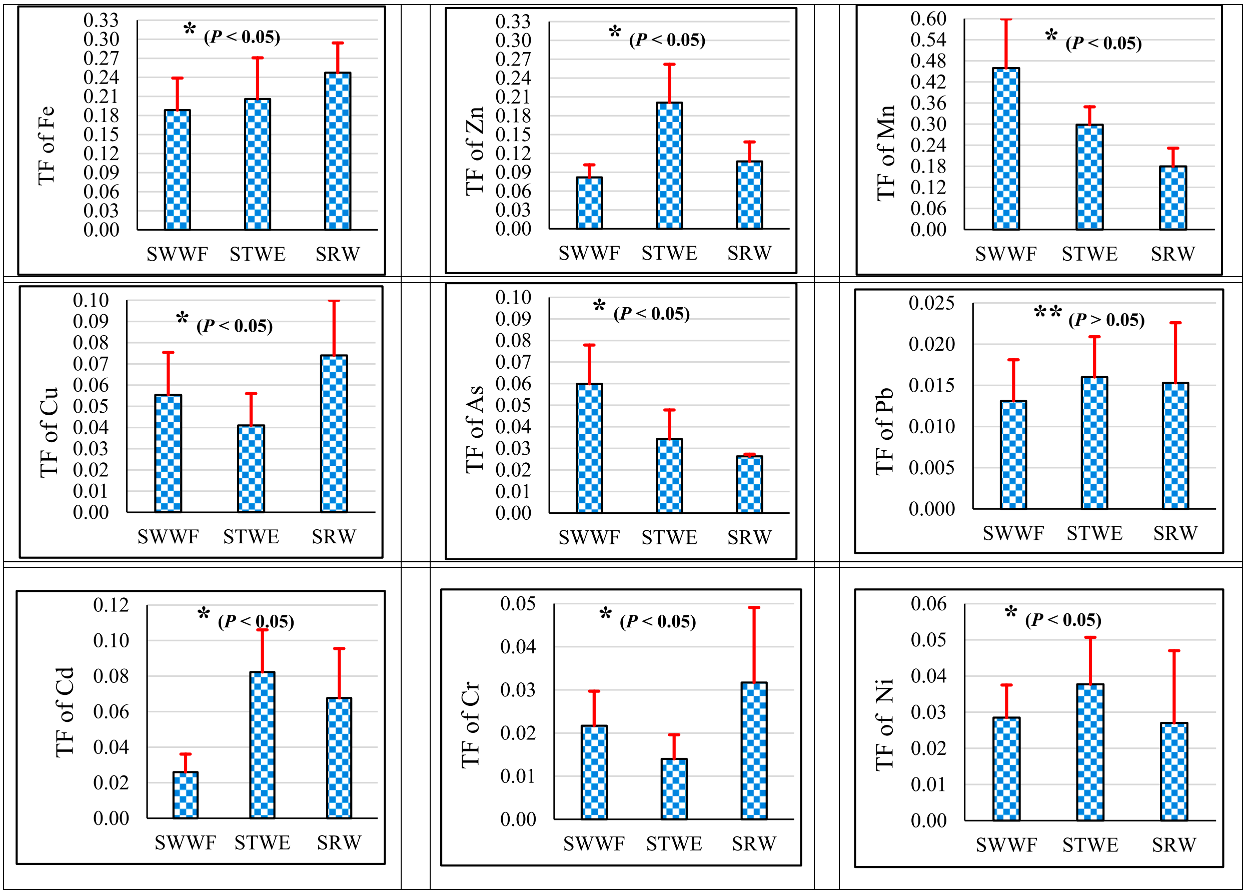

Fig. 2. The transfer factor of each specific heavy metal among various soils irrigated with different sources. *$P < 0.05$: Significant difference (It means that at least one of the pairwise comparisons was significant); **$P > 0.05$: Non-significant difference (It means that non-pairwise comparisons were significant). The depicted error bars represent the standard deviation.

composition [53].

A comparison of the TF of HMs among different irrigated soils revealed that for Fe, the order of TF was SRW > STWE > SWWF. For Zn, Pb, and Cd, the order of TF was STWE > SRW > SWWF. For Mn, the order of TF was SWWF > STWE > SRW. For As, the order of TF was SWWF > STWE > SRW. For Cu and Cr, the order of TF was SRW > SWWF > STWE. For Ni, the order of TF was STWE > SWWF > SRW (Fig. 2).

The ANOVA results showed that, except for Pb, there was at least one significant difference ($P < 0.05$) between the two irrigation treatments regarding the average TF for each of the examined metals. This suggests that, in general, a significant difference ($P < 0.05$) can be observed between different irrigation treatments in terms of the average TF for each of the examined metals (Fig. 2 & Tables S2–S10).

Based on the study results, no consistent trend was observed in the TF of different metals based on the type of irrigation treatment. Certain metals or a group of metals dominated the TF in each specific irrigation treatment. The irregularity in TF can be attributed to various factors. For instance, if a particular irrigation treatment supplies more of a specific metal to the plant, that metal becomes more accessible for absorption by the plant's roots. Additionally, the inherent properties of a metal can influence its transfer rate from soil to plant. However, the most crucial factor is that each irrigation treatment possesses unique physical and chemical properties, influencing the soil's characteristics. Consequently, these differences can impact the TF amount [49,50].

3.3. *Transfer factor among different vegetables for each specific heavy metal*

TF value measures plants' ability to accumulate elements, with higher values indicating greater accumulation [54]. By comparing the TF of HMs among different vegetables, it was found that for Fe and As, the order of TF was radish > basil > coriander; for Zn and Pb, it was basil > coriander > radish; for Mb, it was coriander > radish > basil, for Cu and Cd it was coriander > basil > radish, for Cr it was basil > radish > coriander, and for Ni, it was basil > radish ≈ coriander (Fig. 3). These findings suggest that different vegetables have varying abilities to accumulate HMs.

The accumulation and distribution of HMs in plants is a complex process influenced by various factors. These factors include the plant species, the levels of metals in the soil, the types of elements and their bioavailability, the pH of the soil, the cation exchange capacity, the climate conditions, and the growing season [55]. The continuous absorption and translocation of HMs in plants can increase the concentration of these metals in plant tissues, even in soils with low metal concentrations [56].

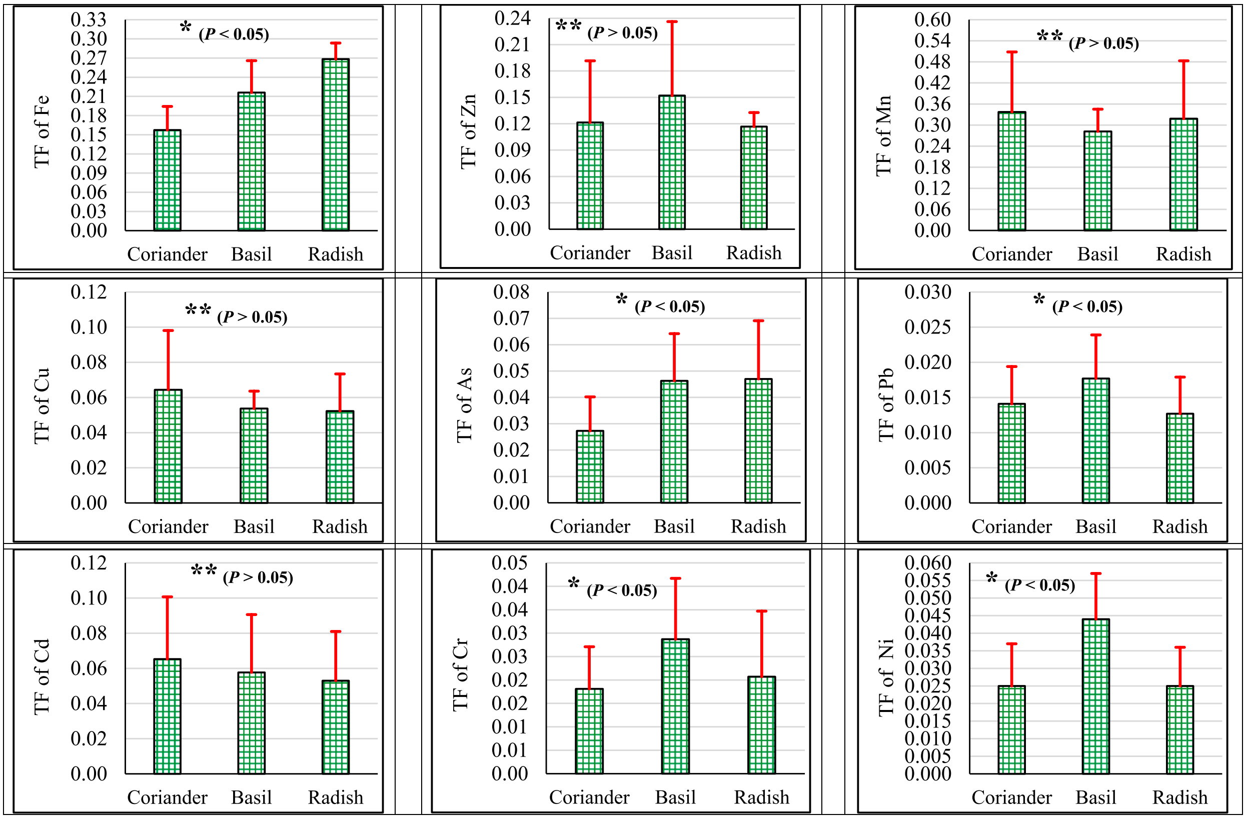

Fig. 3. The transfer factor of each specific heavy metal among various vegetables irrigated with different sources. *$P < 0.05$: Significant difference (It means that at least one of the pairwise comparisons was significant); **$P > 0.05$: Non-significant difference (It means that non-pairwise comparisons were significant). The depicted error bars represent the standard deviation.

The ANOVA results showed that for Fe, As, Pb, Cr and Ni, there was at least one significant difference ($P < 0.05$) between the two vegetables regarding the average TF for each examined metal (Fe, As, Pb, Cr and Ni), whereas, for Zn, Mn, Cu and Cd, no significant difference ($P > 0.05$) was observed in vegetables (Fig. 3 & Tables S11–S19).

The TF of HMs in different vegetables is primarily related to their physical and physiological characteristics. Factors such as the rate of metal transfer from the root surface to the interior of the root, the movement of metals from inside the root to other parts of the plant, the plant's potential to absorb mobile ions from the soil and water, the volume and surface area of the plant's root, and other plant characteristics can collectively impact the TF of metals [50]. Moreover, Liu et al. [57] investigated the absorption of Cr, Cd, and Pb elements by plants such as cabbage, barley, and spinach. The study reported that the TF of elements from soil to plants differs, with the TF for Cd being greater than that of Cr and Pb [57]. Xiao et al. [58] also found that the TF of Cd from root to leaf is higher than from root to stem [58].

4. Conclusions

The study revealed variations in the TF of HMs in vegetables, which were influenced by the irrigation source and vegetable type. The TF levels consistently indicated a relatively weak response (TF < 1) in plants to HM absorption. Notably, Cd always exhibited a higher TF than Pb, and Zn had a higher TF than Cd in all cases. The TF of non-toxic metals consistently exceeded that of toxic metals. Different vegetables demonstrated varying abilities to accumulate HMs; radish exhibited the highest TF for Fe and As, while basil led in Zn and Pb TF. The difference in TF among different metals in various vegetables can be attributed to the plants' physical and physiological characteristics, including the metal transfer rate from the root surface to the interior and movement within the plant. Furthermore, the TF of different metals did not exhibit a consistent trend based on the type of irrigation treatment. This irregularity may result from factors such as the quantity of a specific metal provided by an irrigation treatment, the inherent properties of the metal, and the distinct physical and chemical characteristics of various irrigation treatments. The study highlights the critical importance of monitoring irrigation water and soil quality to prevent the accumulation of toxic HMs in cultivated vegetables, which poses substantial risks to human health. It supports adopting sustainable and safe irrigation practices to safeguard the environment and public health. Further, this study highlights the necessity for additional research on the influence of the physicochemical properties of soil on the extent of HM accumulation in plants. It also suggests evaluating the long-term effects of HM accumulation in vegetables and its potential consequences for human health.

Data availability statement

Data included in article/supp. material/referenced in article.

Ethical statement

Ethical approval was not required for this study as it does not involve human or animal participants.

CRediT authorship contribution statement

Kiomars Sharafi: Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization. **Abdullah Khalid Omer:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Borhan Mansouri:** Writing – review & editing, Visualization, Methodology, Investigation. **Tooraj Massahi:** Writing – original draft, Investigation. **Hamed Soleimani:** Writing – review & editing, Methodology, Formal analysis. **Masoud Moradi:** Writing – review & editing, Methodology, Formal analysis. **Kimya Parnoon:** Writing – original draft, Investigation. **Gholamreza Ebrahimzadeh:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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References

[1] C. Bilos, J.C. Colombo, C.N. Skorupka, M.J. Rodriguez Presa, Sources, distribution and variability of airborne trace metals in La Plata City area, Argentina, Environ. Pollut. 111 (2001) 149–158, https://doi.org/10.1016/S0269-7491(99)00328-0.

[2] K. Chojnacka, A. Chojnacki, H. Górecka, H. Górecki, Bioavailability of heavy metals from polluted soils to plants, Sci. Total Environ. 337 (2005) 175–182, https://doi.org/10.1016/j.scitotenv.2004.06.009.

[3] J. Zhang, H. Li, Y. Zhou, L. Dou, L. Cai, L. Mo, J. You, Bioavailability and soil-to-crop transfer of heavy metals in farmland soils: a case study in the Pearl River Delta, South China, Environ. Pollut. 235 (2018) 710–719, https://doi.org/10.1016/j.envpol.2017.12.106.

[4] K. Sharafi, R.N. Nodehi, M. Yunesian, A.H. Mahvi, M. Pirsaheb, S. Nazmara, Human health risk assessment for some toxic metals in widely consumed rice brands (domestic and imported) in Tehran, Iran: uncertainty and sensitivity analysis, Food Chem. 277 (2019) 145–155.

[5] M. Koch, W. Rotard, On the contribution of background sources to the heavy metal content of municipal sewage sludge, Water Sci. Technol. 43 (2001) 67–74, https://doi.org/10.2166/wst.2001.0074.

[6] J. Hlavay, K. Polyák, M. Weisz, Monitoring of the natural environment by chemical speciation of elements in aerosol and sediment samples, J. Environ. Monit. 3 (2001) 74–80, https://doi.org/10.1039/B006567F.

[7] M.J. McLaughlin, B.R. Singh, in: M.J. McLaughlin, B.R. Singh (Eds.), Cadmium in Soils and Plants BT - Cadmium in Soils and Plants, Springer Netherlands, Dordrecht, 1999, pp. 1–9, https://doi.org/10.1007/978-94-011-4473-5_1.

[8] A. Gebrekidan, Y. Weldegebriel, A. Hadera, B. Van der Bruggen, Toxicological assessment of heavy metals accumulated in vegetables and fruits grown in Ginfel river near Sheba Tannery, Tigray, Northern Ethiopia, Ecotoxicol. Environ. Saf. 95 (2013) 171–178, https://doi.org/10.1016/j.ecoenv.2013.05.035.

[9] H. Soleimani, B. Mansouri, A. Kiani, A.K. Omer, M. Tazik, G. Ebrahimzadeh, K. Sharafi, Ecological risk assessment and heavy metals accumulation in agriculture soils irrigated with treated wastewater effluent, river water, and well water combined with chemical fertilizers, Heliyon 9 (2023) e14580.

[10] K. ur Rehman, S.M. Bukhari, S. Andleeb, A. Mahmood, K.O. Erinle, M.M. Naeem, Q. Imran, Ecological risk assessment of heavy metals in vegetables irrigated with groundwater and wastewater: the particular case of Sahiwal district in Pakistan, Agric. Water Manag. 226 (2019) 105816, https://doi.org/10.1016/j.agwat.2019.105816.

[11] M.I. Zaidi, A. Asrar, A. Mansoor, M.A. Farooqui, The heavy metal concentration along roadside trees of Quetta and its effects on public health, J. Appl. Sci. 5 (2005) 708–711.

[12] T. Ahmadi-Jouibari, H. Ahmadi Jouybari, K. Sharafi, M. Heydari, N. Fattahi, Assessment of potentially toxic elements in vegetables and soil samples irrigated with treated sewage and human health risk assessment, Int. J. Environ. Anal. Chem. 103 (2023) 2351–2367, https://doi.org/10.1080/03067319.2021.1893704.

[13] M.H. Habibollahi, K. Sharafi, A.K. Omer, Analysis of minerals and toxic elements in commonly consumed herbal medicines in Zahedan, Iran, and associated human health risk assessment, J. Food Protect. 85 (2022) 1797–1806.

[14] M. Pirsaheb, M. Hadei, K. Sharafi, Human health risk assessment by Monte Carlo simulation method for heavy metals of commonly consumed cereals in Iran-Uncertainty and sensitivity analysis, J. Food Compos. Anal. 96 (2021) 103697, https://doi.org/10.1016/j.jfca.2020.103697.

[15] M. Arora, B. Kiran, S. Rani, A. Rani, B. Kaur, N. Mittal, Heavy metal accumulation in vegetables irrigated with water from different sources, Food Chem. 111 (2008) 811–815, https://doi.org/10.1016/j.foodchem.2008.04.049.

[16] K. Sharafi, B. Mansouri, A.K. Omer, P. Bashardoust, G. Ebrahimzadeh, S. Sharifi, T. Massahi, H. Soleimani, Investigation of health risk assessment and the effect of various irrigation water on the accumulation of toxic metals in the most widely consumed vegetables in Iran, Sci. Rep. 12 (2022) 20806, https://doi.org/10.1038/s41598-022-25101-9.

[17] S. Khan, S. Rehman, A. Zeb Khan, M. Amjad Khan, M. Tahir Shah, Soil and vegetables enrichment with heavy metals from geological sources in Gilgit, northern Pakistan, Ecotoxicol. Environ. Saf. 73 (2010) 1820–1827, https://doi.org/10.1016/j.ecoenv.2010.08.016.

[18] A. Ashfaq, Z.I. Khan, Z. Bibi, K. Ahmad, M. Ashraf, I. Mustafa, A.A. Nudrat, R. Perveen, S. Yasmeen, Heavy metals uptake by Cucurbita maxima grown in soil contaminated with sewage water and its human health implications in peri-urban areas of Sargodha city, Pakistan J. Zool. 47 (2015).

[19] A. Kiani, K. Sharafi, A.K. Omer, B.K. Matin, R. Davoodi, B. Mansouri, H. Sharafi, H. Soleimani, T. Massahi, E. Ahmadi, Accumulation and human health risk assessment of nitrate in vegetables irrigated with different irrigation water sources- transfer evaluation of nitrate from soil to vegetables, Environ. Res. 205 (2022) 112527, https://doi.org/10.1016/j.envres.2021.112527.

[20] K. Steenland, P. Boffetta, Lead and cancer in humans: where are we now? Am. J. Ind. Med. 38 (2000) 295–299.

[21] B. Yargholi, A.A. Azimi, A. Baghvand, A.M. Liaghat, G.A. Fardi, Investigation of cadmium absorption and accumulation in different parts of some vegetables, Am. J. Agric. Environ. Sci. 3 (2008) 357–364.

[22] K.M. Powers, T. Smith-Weller, G.M. Franklin, W.T. Longstreth, P.D. Swanson, H. Checkoway, Parkinson's disease risks associated with dietary iron, manganese, and other nutrient intakes, Neurology 60 (2003) 1761–1766.

[23] A. Ikem, N.O. Egiebor, Assessment of trace elements in canned fishes (mackerel, tuna, salmon, sardines and herrings) marketed in Georgia and Alabama (United States of America), J. Food Compos. Anal. 18 (2005) 771–787, https://doi.org/10.1016/j.jfca.2004.11.002.

[24] A.K. Mitra, A. Haque, M. Islam, S. Bashar, Lead poisoning: an alarming public health problem in Bangladesh, Int. J. Environ. Res. Publ. Health 6 (2009) 84–95.

[25] I. IARC, Beryllium, cadmium, mercury, and exposures in the glass manufacturing industry, Int. Agency Res. Cancer Monogr. Eval. Carcinog. Risks to Humans. 58 (1993) 119–237.

[26] H.C. Pitot, Y.P. Dragan, Chemical Carcinogenesis in Casarett and Doull's Toxicology: the Basic Science of Poison, Six Ed., 2001, pp. 164–165.

[27] A. Prentice, Does mild zinc deficiency contribute to poor growth performance? Nutr. Rev. 51 (1993) 268–270.

[28] N. Roney, J. Colman, Interaction profile for lead, manganese, zinc, and copper, Environ. Toxicol. Pharmacol 18 (2004), 231–4.

[29] M.C. Linder, M. Hazegh-Azam, Copper biochemistry and molecular biology, Am. J. Clin. Nutr. 63 (1996) S797–S811.

[30] Anonymous, Institute of Medicine (US) Panel on Micronutrients, Dietary Reference Intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc, Dietary Reference Intakes (2002), https://doi.org/10.17226/10026. https://www.ncbi.nlm.nih.gov/books/NBK222310/.

[31] S. Bose, A. Jain, V. Rai, A.L. Ramanathan, Chemical fractionation and translocation of heavy metals in Canna indica L. grown on industrial waste amended soil, J. Hazard Mater. 160 (2008) 187–193.

[32] Y. Cui, Y.-G. Zhu, R. Zhai, Y. Huang, Y. Qiu, J. Liang, Exposure to metal mixtures and human health impacts in a contaminated area in Nanning, China, Environ. Int. 31 (2005) 784–790, https://doi.org/10.1016/j.envint.2005.05.025.

[33] S. Khan, Q. Cao, Y.M. Zheng, Y.Z. Huang, Y.G. Zhu, Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China, Environ. Pollut. 152 (2008) 686–692, https://doi.org/10.1016/j.envpol.2007.06.056.

[34] P.S. Hooda, Trace Elements in Soils, Wiley Online Library, 2010.

[35] A.-I. Smical, V. Hotea, V. Oros, J. Juhasz, E. Pop, Studies on transfer and bioaccumulation of heavy metals from soil into lettuce, Environ. Eng. Manag. J. 7 (2008) 609–615.

[36] G. Wang, M.-Y. Su, Y.-H. Chen, F.-F. Lin, D. Luo, S.-F. Gao, Transfer characteristics of cadmium and lead from soil to the edible parts of six vegetable species in southeastern China, Environ. Pollut. 144 (2006) 127–135, https://doi.org/10.1016/j.envpol.2005.12.023.

[37] H. Zhou, W.-T. Yang, X. Zhou, L. Liu, J.-F. Gu, W.-L. Wang, J.-L. Zou, T. Tian, P.-Q. Peng, B.-H. Liao, Accumulation of heavy metals in vegetable species planted in contaminated soils and the health risk assessment, Int. J. Environ. Res. Publ. Health 13 (2016) 289.

[38] Y.-J. Cui, Y.-G. Zhu, R.-H. Zhai, D.-Y. Chen, Y.-Z. Huang, Y. Qiu, J.-Z. Liang, Transfer of metals from soil to vegetables in an area near a smelter in Nanning, China, Environ. Int. 30 (2004) 785–791, https://doi.org/10.1016/j.envint.2004.01.003.

[39] J.R. Twining, T.E. Payne, T. Itakura, Soil–water distribution coefficients and plant transfer factors for 134Cs, 85Sr and 65Zn under field conditions in tropical Australia, J. Environ. Radioact. 71 (2004) 71–87, https://doi.org/10.1016/S0265-931X(03)00142-5.

[40] A. Kabata-Pandias, A. Kabata-Pandias, H. Pendias, Trace Elements in Soils and Plants, CRC Press, Incorporated, 1984.

[41] M.M. Lasat, Phytoextraction of metals from contaminated soil: a review of plant/soil/metal interaction and assessment of pertinent agronomic issues, J. Hazard. Subst. Res. 2 (1999) 5.
[42] P. Khanna, Assessment of heavy metal contamination in different vegetables grown in and around urban areas, Res. J. Environ. Toxicol. 5 (2011) 162.
[43] S.S. Rangnekar, S.K. Sahu, G.G. Pandit, V.B. Gaikwad, Accumulation and translocation of nickel and cobalt in nutritionally important Indian vegetables grown in artificially contaminated soil of Mumbai, India, Res. J. Agric. For. Sci. (2013) 6063.
[44] L. Tabande, M. Taheri, Evaluation of exposure to heavy metals Cu, Zn, Cd and Pb in vegetables grown in the olericultures of Zanjan Province's fields, Iran. J. Health Environ. 9 (2016).
[45] J.B. Christensen, T.H. Christensen, The effect of pH on the complexation of Cd, Ni and Zn by dissolved organic carbon from leachate-polluted groundwater, Water Res. 34 (2000) 3743–3754, https://doi.org/10.1016/S0043-1354(00)00127-5.
[46] H. Cao, J. Chen, J. Zhang, H. Zhang, L. Qiao, Y. Men, Heavy metals in rice and garden vegetables and their potential health risks to inhabitants in the vicinity of an industrial zone in Jiangsu, China, J. Environ. Sci. 22 (2010) 1792–1799.
[47] E. Gutiérrez, E. Chávez, K.H.H. Gamage, D. Argüello, M.B. Galkaduwa, G.M. Hettiarachchi, Cadmium fractionation in soils affected by organic matter application: transfer of cadmium to cacao (Theobroma cacao L.) tissues, Front. Environ. Sci. 10 (2022) 954521.
[48] M. Cheraghi, A. Ghobadi, Health risk assessment of heavy metals (cadmium, nickel, lead and zinc) in withdrawed parsley vegetable from some farms in Hamedan city, Toloo-E-Behdasht. 13 (2014).
[49] I.M. McKenna, R.L. Chaney, F.M. Williams, The effects of cadmium and zinc interactions on the accumulation and tissue distribution of zinc and cadmium in lettuce and spinach, Environ. Pollut. 79 (1993) 113–120, https://doi.org/10.1016/0269-7491(93)90060-2.
[50] N. Yildiz, Response of tomato and corn plants to increasing Cd levels in nutrient culture, Pakistan J. Bot. 37 (2005).
[51] M.C. Jung, Heavy metal concentrations in soils and factors affecting metal uptake by plants in the vicinity of a Korean Cu-W mine, Sensors 8 (2008) 2413–2423.
[52] N. Mirecki, R. Agic, L. Sunic, L. Milenkovic, Z.S. Ilic, Transfer factor as indicator of heavy metals content in plants, Fresenius Environ. Bull. 24 (2015) 4212–4219.
[53] U. Förstner, Chemical forms and reactivities of metals in sediments, in: Chem. Methods Assess. Bio-Available Met. Sludges Soils, Semin., 1985, pp. 1–31.
[54] C. Saglam, Heavy metal accumulation in the edible parts of some cultivated plants and media samples from a volcanic region in Southern Turkey, Ekoloji 22 (2013) 1–8.
[55] R. Filipović-Trajković, Z.S. Ilić, L. Šunić, S. Andjelković, The potential of different plant species for heavy metals accumulation and distribution, J. Food Agric. Environ. 10 (2012) 959–964.
[56] A.A. Yusuf, T.A. Arowolo, O. Bamgbose, Cadmium, copper and nickel levels in vegetables from industrial and residential areas of Lagos City, Nigeria, Food Chem. Toxicol. 41 (2003) 375–378.
[57] W. Liu, J. Zhao, Z. Ouyang, L. Söderlund, G. Liu, Impacts of sewage irrigation on heavy metal distribution and contamination in Beijing, China, Environ. Int. 31 (2005) 805–812.
[58] Q. Xiao, S. Wang, Y. Chi, Accumulation and chemical forms of cadmium in tissues of different vegetable crops, Agronomy 13 (2023) 680.