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Original Article

X-ray Fluorescence (XRF)-based Assessment of Elements in Leafy Vegetables from Phu Tho Province

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Abstract: This work employed X-ray fluorescence (XRF) to analyze the concentrations of essential and potentially toxic elements in leafy vegetables (mustard greens, cabbage, and lettuce). In addition, nutritional element levels determined and the target hazard quotient (THQ) as well as the hazard index (HI) calculated. The results showed that K was the most abundant, reflecting a typical nutritional characteristic of leafy vegetables. Comparative analysis with United States Department of Agriculture (USDA) and Ministry of Health of Vietnam (MHV) data revealed that the studied vegetables contained generally higher levels of Ca and Fe in lettuce. Mustard greens and cabbage also showed elevated concentrations of K, Ca, and Mg. These results suggest significant nutritional potential. Chromium (Cr) was identified as the major contributor to non-carcinogenic risk, accounting for 58–90% of the HI values. These findings highlight both the nutritional value and potential health risk associated with leafy vegetable consumption, emphasizing the importance of monitoring Cr contamination in agricultural soils and irrigation water.

Keywords Leafy vegetable, XRF, nutrient element, chromium contamination, health risk assessment.

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1. Introduction

Green leafy vegetables are an essential component of the human diet. They provide energy as well as vital nutrients and trace elements necessary for growth and health maintenance [1, 2]. Leafy vegetables provide numerous significant health benefits. They are nutrient-dense, containing high levels of vitamins (A, C, K, and folic acid), minerals, and dietary fiber, which contribute to digestive support and the prevention of constipation [3]. Additionally, potassium (K) in leafy vegetables plays a crucial role in regulating blood pressure, preventing coagulation disorders, and enhancing bone strength [4]. Among them, Brassicaceae vegetables such as mustard greens (Brassica juncea), cabbage (Brassica oleracea), and lettuce (Lactuca sativa) are widely consumed due to their high nutritional value and associated health benefits [2]. Nevertheless, these vegetables are also capable of accumulating various elements, including toxic metals, from soil and the surrounding environment [2, 5]. Excessive exposure to these elements poses serious health risks, including cancer, genetic mutations, neurological disorders, and congenital malformations [2, 6, 7]. Health risk assessments based on hazard indices have identified leafy vegetables as a significant pathway for heavy metal exposure. For example, As, Cd, and Pb have been reported as the primary contributors to health risks in leafy vegetables [8], whereas Cr concentrations exceeding the permissible limit have been associated with potential risks of chronic diseases and cancer [6]. The increased accumulation of heavy metals in leafy vegetables originates from various sources, including anthropogenic activities such as industrial processes, transportation, fertilizer application. Tannery operations have led to soil contamination in vegetable cultivation areas, resulting in concentrations of heavy metals such as Cr, Zn, Ni, Cs, and Cu exceeding permissible limits, with Cr being particularly elevated [6]. The use of industrial wastewater for irrigation has also contributed to elevated levels of Pb, Zn, and Cu in vegetables [5]. Additionally, heavy metals including Pb, Cd, Cr, Zn, Fe, Cu, and Mn have been detected in leafy vegetables due to the application of pesticides [1]. Other pollution sources such as emissions from industrial zones and road dust have been identified as significant contributors to Pb accumulation in leafy vegetables [8]. In addition to anthropogenic factors, geological conditions also play a significant role in contributing to heavy metal contamination in vegetables. Phu Tho province, located in northern Vietnam, is characterized by complex geological features with the presence of numerous mineral deposits, including iron ore and associated minerals. These natural characteristics can increase the concentration of certain elements in the soil, thereby directly affecting the elemental composition of vegetables cultivated in the region [9-11]. Therefore, assessing the elemental concentrations in leafy vegetables in Phu Tho is not only important for determining their nutritional value but also crucial for identifying potential environmental and health risks.

In this work, X-ray fluorescence (XRF) technique was employed to investigate the elemental composition of several leafy vegetable samples collected from cultivation areas in Phu Tho province. The results aim to provide information on the nutritional quality and safety levels of these vegetables.

2. Materials and Method

2.1. Sampling Sites and Sample Preparation

Within the framework of our research series on assessing radioactivity levels and metal concentrations in soil and vegetables in several regions of Northern Vietnam [12-14], this study focuses on three vegetables: mustard greens, cabbage, and lettuce, collected from communes in Phu Tho province (Fig. 1).

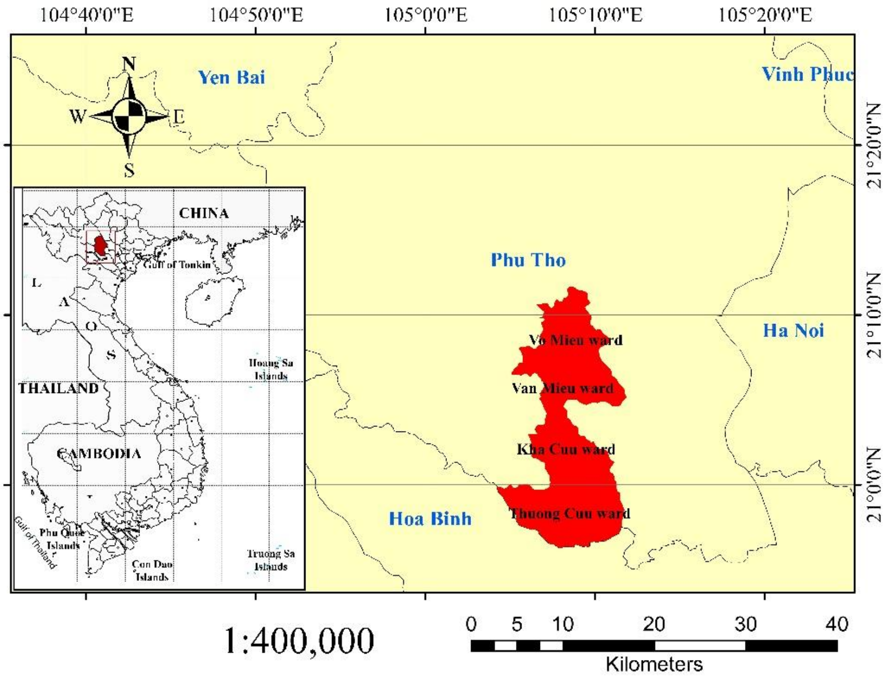

Figure 1. Sampling area map.

This area is known for its iron ore deposits and sites where radioactivity has been detected. The aim of the study is to determine the concentrations of nutrient elements in these vegetable samples. Table 1 presents the list of collected vegetable samples.

Table 1. List of investigated vegetable samples

Symbol	Vegetable	Scientific name	Family name
B1	Mustard greens 1	Brassica juncea	Brassicaceae
B2	Mustard greens 2	Brassica juncea	Brassicaceae
B3	Mustard greens 3	Brassica juncea	Brassicaceae
B4	Cabbage 1	Brassica oleracea	Brassicaceae
B5	Cabbage 2	Brassica oleracea	Brassicaceae
B6	Cabbage 3	Brassica oleracea	Brassicaceae
B7	Lettuce 1	Lactuca sativa	Asteraceae
B8	Lettuce 2	Lactuca sativa	Asteraceae

After being collected in the field, the vegetable samples were transported to the laboratory, where damaged leaves and roots were removed. The samples were then washed with tap water and air-dried at room temperature, followed by oven-drying at approximately 100 °C until constant weight was achieved. The dried samples were ground using a mechanical mill and sieved through a 250-mesh sieve. About 1–2 g of the powdered sample was pressed into circular pellets (15 mm in diameter) using a hydraulic press, in order to ensure stability and homogeneity prior to analysis [12]. Fig. 2 shows the sample pellet before measurement.

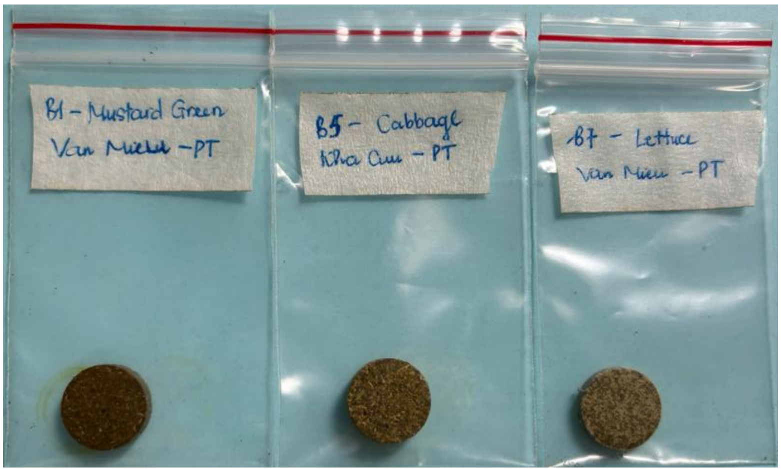

Figure 2. Sample pellet.

2.2. X-ray Fluorescence

The X-ray fluorescence (XRF) analysis method was employed to determine the elemental concentrations in solid samples without destruction. The principle of XRF is based on irradiating the sample with a high-energy X-ray beam, which excites atoms to emit characteristic fluorescent radiation specific to each element. This fluorescence signal is recorded and analyzed to provide both qualitative and quantitative information on the elements present. XRF offers several advantages, including speed, accuracy, and the ability to analyze multiple elements simultaneously without complex chemical treatment, with detection limits down to the ppm level. Therefore, it has been widely applied in environmental, geological, and material studies as well as in quality control [15]. In this study, XRF analysis was performed using the VietSpace 5006-2020 instrument, developed in Vietnam, which is capable of detecting elements from Mg to U with an energy resolution of 125 eV at the 5.89 keV line. The system is equipped with specialized spectrum processing software XRF-FP, enhancing the accuracy and reliability of elemental analysis in soil and vegetable samples.

Before the measurement of samples, the spectrometer was calibrated using the certified reference material SRM 1547 (Peach Leaves), issued by NIST on November 14, 2022. After calibration, the analytical performance was verified through the measurement of additional plant reference materials, namely PTNATIAEA19. The measured concentrations were compared with the certified reference values, and sample analysis was conducted only when the deviation was within 10% (see Appendix, Table A1 for details).

In this work, the minimum detectable amount (MDA) was determined using the following equation [16]:

$$MDA = \frac{3}{m}\sqrt{\frac{S_B}{t_B}} \quad (1)$$

where S_B and t_B are background count rate (counts/s) and counting time (s); m is the sensitivity (net counts/s per unit concentration).

2.3. Health Risk Assessment

The health risk from vegetable consumption was evaluated using the Target Hazard Quotient (THQ) and Hazard Index (HI), calculated as in Eqs. (2) and (3). The parameters include element concentration

(Ci) and the conversion factor from fresh to dry weight (Cf). The daily vegetable intake (FIR) is 0.1573 kg/day for adults in Vietnam [17]. EF represents the exposure frequency (365 days/year), while ED denotes the exposure duration (70 years). B_W is the average body weight (60 kg). R_fD values applied were 0.7, 0.14, 0.04, 0.3, 0.003 for Fe, Mn, Cu, Zn, and Cr respectively [18]. The average exposure time (T_A) was calculated as 365 × exposure duration [19]. Values of THQ or HI below 1 indicate no significant non-carcinogenic health risk [20].

$$THQ = \frac{C_i \times C_f \times F_{IR} \times E_F \times E_D}{B_w \times R_F D \times T_A} \quad (2)$$

$$HI = \sum_{i=1}^{n} THQ \quad (3)$$

3. Results and Discussion

3.1. Elemental Concentrations in Leafy Vegetable

The results of elemental concentration analysis by the XRF method are presented in Table 2 and Fig. 2. The elements are classified into three main groups: macronutrients, mesonutrients, and micronutrients. The group of macronutrients includes K, Ca, Mg, P, and S, which are predominant in the vegetable samples. Among them, K shows the highest concentration, being 4 to 7 times greater than the other macronutrients—a typical characteristic of leafy vegetables. The average concentrations of these elements in descending order are: K (45474 mg/kg), Ca (14622 mg/kg), S (8690 mg/kg), Mg (5404 mg/kg), and P (5589 mg/kg). These elements are all essential nutrients that work synergistically to promote growth and improve the quality of vegetables such as cabbage, mustard greens, and lettuce. Adequate and balanced supply of these macronutrients is crucial for optimizing leaf growth, yield, and nutritional value of vegetables [21-23]. The group of mesonutrients consists of Cl and Si, with average concentrations of 10389 and 1561 mg/kg, respectively. In addition to their roles in plant physiological processes, Cl and Si also contribute to enhancing stress tolerance in plants, particularly in vegetable species belonging to the Brassicaceae and Asteraceae families [24, 25]. The group of micronutrients includes Fe, Mn, Zn, and Cu, with average concentrations of 213, 44.3, 27.6, and 18.5 mg/kg, respectively. Although absorbed in small amounts, these micronutrients play indispensable roles in metabolic processes, tissue development, and improving stress resistance in vegetables [22, 26].

Table 2. Element concentrations in vegetables (mg/kg dry weight).

	Element	Mean	SD	Min.	Max.
Macronutrient	K	45474	9749	33721	59999
	Ca	14622	4959	8029	20726
	Mg	5404	3737	2881	14251
	P	5589	1187	4543	7777
	S	8690	4717	3053	15697
Mesonutrient	Cl	10389	4506	4296	17044
	Si	1561	869	1041	3668
Micronutrient	Fe	213	102	113	435
	Mn	44.3	19.5	22.8	75.8
	Zn	27.6	6.9	19.6	41.9
	Cu	18.5	3.4	11.8	23.7

Fig. 2 illustrates the differences in elemental concentrations among the three vegetables: mustard greens, cabbage, and lettuce. Overall, mustard greens tend to accumulate higher levels of K, S, Si, Zn, and Cu, while cabbage shows higher concentrations of Mg, P, and Mn. In contrast, lettuce contains markedly higher levels of Ca, Cl, and especially Fe compared to the other two vegetables. Each plant species has distinct mechanisms of nutrient uptake and transport, which are influenced by differences in root systems, ion transport membranes, and physiological requirements [27].

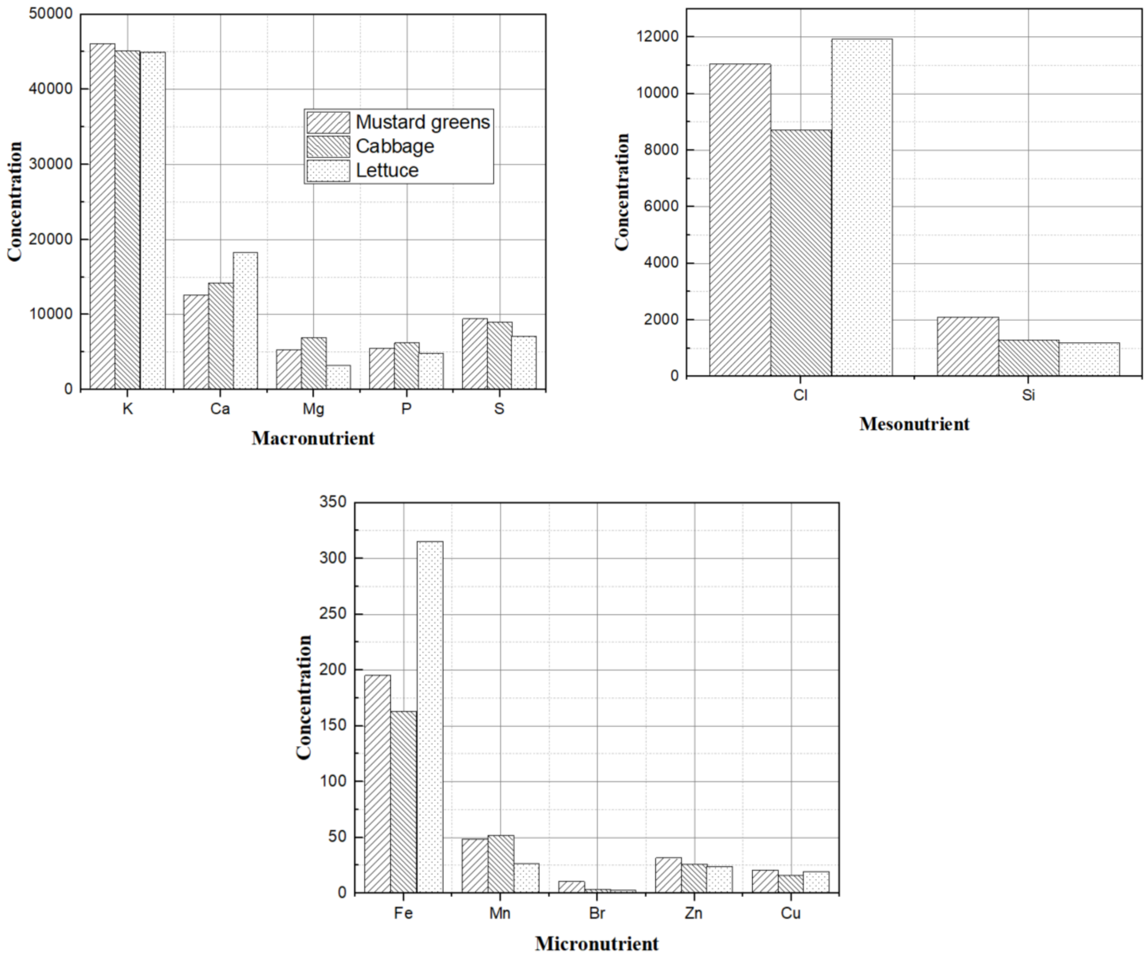

Figure 2. Concentration of elements in three leafy vegetables (mg/kg dry weight).

Table 3 compares the concentrations of major nutrient elements (K, Ca, Mg, P, Fe, Zn, and Cu) in mustard greens, cabbage, and lettuce between the results of this study and the data reported by the USDA[1] and the Ministry of Health of Vietnam (MHV) [28]. The results showed that, for mustard greens, the concentrations of K, Ca, and Mg were comparable or slightly lower than the USDA data but consistently higher than those reported by the MHV. In contrast, the levels of Fe, Zn, and Cu tended to be lower than both references, with values of 1.38, 0.22, and 0.15 mg/100 g, respectively. Overall, mustard greens demonstrated relatively high and stable nutrient element concentrations compared with

[1] https://fdc.nal.usda.gov/food-search?type=Foundation.

both national and international data. For cabbage, the concentrations of K, Ca, Mg, and P were markedly higher than those reported by both USDA and MHV. The Fe concentration reached 1.00 mg/100 g, substantially higher than USDA (0.07 mg) and nearly equivalent to MHV (1.1 mg). Similar to mustard greens, the Zn and Cu levels in cabbage were significantly lower than those recorded in the MHV database. For lettuce, the Ca concentration was 95 mg/100 g, more than three times higher than USDA (31 mg) and MHV (38 mg). The Fe concentration was also elevated (1.65 mg), greatly exceeding USDA (0.26 mg) and MHV (1.1 mg), highlighting the remarkable Fe accumulation capacity of lettuce under the studied conditions. The remaining elements showed concentrations relatively consistent with both USDA and MHV data.

The comparative results indicate that vegetables cultivated under the studied conditions contained high levels of essential nutrients, particularly Fe and Ca in lettuce, as well as K, Ca, and Mg in mustard greens and cabbage. These concentrations not only meet but may also provide significant supplementation to daily dietary micronutrient requirements. The positive differences observed in comparison with USDA and Vietnam Ministry of Health data suggest that locally grown vegetables possess outstanding nutritional value and can effectively contribute to improving dietary quality and diversifying food intake.

Table 3. Comparison of nutrient concentration with USDA and MHV

Element	Concentration (mg/100g)								
	Mustard green			Cabbage			Lettuce		
	This work (*)	USDA	MHV	This work (*)	USDA	MHV	This work (*)	USDA	MHV
K	325	384	221	276	207	190	235	249	254
Ca	89	115	89	87	42	48	95	31	38
Mg	38	32	23	42	13.9	13	17	11	18
P	38.6	58	14	38	27	31	25	23	37
Fe	1.38	1.64	1.9	1.00	0.07	1.1	1.65	0.26	1.1
Zn	0.22	0.25	0.9	0.16	0.21	0.81	0.13	0.26	0.4
Cu	0.15	0.165	0.12	0.10	<0.025	0.18	0.10	0.04	0.18

*The concentration values were converted from dry weight to fresh weight.

3.2. Metal Hazard Indices

Table 3 presents the target hazard quotient (THQ) values of five non-carcinogenic toxic elements (Fe, Mn, Cu, Zn, and Cr), along with the hazard index (HI) associated with the consumption of the studied vegetables. Among the analyzed elements, Cr consistently accounted for the largest contribution to HI, with THQ values ranging from 0.25 (B6) to 1.14 (B4), representing approximately 58–90% of the total HI. This indicates that Cr is the primary non-carcinogenic risk factor in this study. These findings are consistent with the results of [29], which identified Cr as the element with the highest THQ in leafy vegetables such as kale and spinach. However, other studies, such as [30], reported Mn as the major contributor to THQ in most leafy vegetables. The predominance of Cr in THQ values may be attributed to its chemical properties and high bioaccumulation potential. In the environment, Cr mainly exists as Cr(III) and Cr(VI), of which Cr(VI) is more toxic, highly soluble, and easily absorbed by plants through the root system [31]. Leafy vegetables, with their large surface area and rapid growth rate, are more prone to the uptake and accumulation of heavy metals, including Cr, from soil and irrigation water compared to other crops [5]. In addition, Cr levels in cultivated soils may be influenced by industrial emissions, the use of chemical fertilizers, or agricultural waste, thereby increasing its accumulation in plants [31, 32]. These results highlight the necessity of strict monitoring of Cr concentrations in soils and irrigation water, particularly for leafy vegetables, which tend to accumulate this element at elevated levels.

In contrast, Fe, Mn, Cu, and Zn are essential trace elements that play vital physiological roles; however, at excessive levels they may pose health risks. In this study, their contribution to the overall HI was only marginal, generally accounting for less than 17%, with individual THQ values not exceeding 0.11. This indicates that dietary exposure to these elements through vegetable consumption is negligible. The HI values of the samples ranged from 0.42 (B6) to 1.27 (B4). Notably, the cabbage sample B4 and mustard greens sample B2 showed HI > 1, exceeding the safety threshold, while mustard greens B3 and lettuce B8 showed HI values close to 1, suggesting potential public health concerns if consumed regularly. However, the average HI across all samples remains below 1. The elevated HI values in certain samples were mainly attributed to Cr, which may be linked to the geological characteristics of the study area. Consistent with these findings, a previous study [29] also highlighted the risk of heavy metal exposure from leafy vegetables, where most of the examined samples exhibited HI values greater than 1, with rocket showing an HI exceeding 2. Similarly, research [6] reported that the cultivation of leafy vegetables in industrial areas resulted in all risk indices for the studied vegetables surpassing the safe threshold of 1.

Table 4. Health risk index from leafy vegetables consumption.

Vegetable	THQ					HI
	Fe	Mn	Cu	Zn	Cr	
B1	0.04	0.05	0.11	0.02	0.42	0.63
B2	0.07	0.10	0.09	0.03	0.73	1.02
B3	0.04	0.04	0.08	0.02	0.75	0.93
B4	0.03	0.04	0.05	0.01	1.14	1.27
B5	0.04	0.09	0.07	0.02	0.64	0.85
B6	0.04	0.05	0.07	0.01	0.25	0.42
B7	0.08	0.02	0.07	0.01	0.41	0.60
B8	0.04	0.03	0.06	0.01	0.75	0.90
Mean	0.05	0.05	0.08	0.02	0.64	0.83
Max.	0.08	0.10	0.11	0.03	1.14	1.27
Min.	0.03	0.02	0.05	0.01	0.25	0.42

4. Conclusion

The obtained results demonstrate that leafy vegetables grown under the studied conditions are rich sources of essential nutrients, particularly K, Ca, and Fe, which are vital for human health. Mustard greens and cabbage showed high levels of K, Ca, and Mg, while lettuce exhibited outstanding Ca and Fe accumulation compared with both national and international reference data. This indicates that these vegetables can play an important role in enhancing dietary mineral intake. However, health risk assessment revealed that chromium possesses a significant non-carcinogenic risk. In contrast, the contributions of Fe, Mn, Cu, and Zn to health risks were minimal. Overall, the study underscores the dual significance of leafy vegetables as valuable nutrient sources and as potential exposure pathways to

Cr contamination. Continuous monitoring of soil and irrigation water quality is therefore essential to ensure food safety and sustainable vegetable production. Further research should extend exposure assessment to a wider variety of vegetables commonly consumed in Phu Tho. This will help clarify whether the elevated chromium risk observed in leafy vegetables is also present in other types of vegetables and provide a more comprehensive understanding of dietary exposure.

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Appendix A1. Comparison of measured and certified values in the standard sample
(Measurement date: July 31, 2025)

Element	Measurement (mg/kg)	Reference (mg/kg) [33]	Deviation (%)
Mg	2294 ± 285	2300	0.3
Si	458 ± 45	460	0.4
P	2285 ± 78	2420	5.6
S	919 ± 30	840	-9.4
K	10501 ± 81	11200	6.2
Fe	91 ± 4.0	89	-2.2
Zn	31.6 ± 3.3	32.6	3.1

Appendix A2. MDA values for elements in the studied samples

Element	B1	B2	B3	B4	B5	B6	B7	B8
K	11.6	12.3	12.5	12.4	11.6	11.5	11.6	12.3
Ca	8.0	7.9	9.0	7.9	8.0	7.2	8.0	7.8
Mg	110	261	221	118	89.3	105	89.3	104
P	10.5	16.0	14.6	11.9	9.5	12.4	9.5	10.4
S	8.7	11.5	11.0	10.7	7.8	10.3	7.8	8.6
Cl	7.8	3.8	3.5	10.3	6.9	8.8	6.9	8.0
Si	14.9	14.5	12.2	17.1	13.3	18.3	13.3	15.3
Fe	1.4	1.7	1.6	1.5	1.2	1.4	1.2	1.4
Mn	1.7	1.9	1.8	1.7	1.5	1.7	1.5	1.5
Zn	0.9	0.8	0.8	0.9	0.8	0.8	0.8	0.8
Cu	1.3	1.3	1.2	1.4	1.3	1.3	1.3	1.3