VNU Journal of Science: Mathematics – Physics, Vol. 41, No. 3 (2025) 45-55

VNU Journal of Science: Mathematics - Physics

Journal homepage: https://js.vnu.edu.vn/MaP

Original Article

Multivariate Assessment of Nutrient Absorption and Soil-to-Plant Transfer Factors in Moc Chau Crops Using k_0-INAA

Bui Thi Hong[1], Vu Ngoc Ba[2], Ha Thi Thuy Linh[1], Pham Thi Mai[1], Ngo Thu Trang[1], Tran Hoai Nam[3], Nguyen Dang Khue[4], Bui Van Loat[1,*]

[1]VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam
[2]University of Science, Vietnam National University Ho Chi Minh City, 227 Nguyen Van Cu, Cho Quan, Ho Chi Minh, Vietnam
[3]Phenikaa University, Nguyen Trac, Duong Noi, Hanoi, Vietnam
[4]Dalat Nuclear Research Institute, Vietnam Atomic Energy Institute, 1 Nguyen Tu Luc, Lam Vien-Da Lat, Lam Dong, Vietnam

Received 19th March 2025
Revised 01st July 2025; Accepted 8th September 2025

Abstract: Absorption and accumulation of nutrients in various crop species in Moc Chau town in Son La province of Vietnam, have been examined using multivariate analysis. The nutrient concentration in soil decreases in the following order: K > Fe > Na > Mn > Zn > Rb. Crops prioritize the absorption of nutrients based on their growth requirements, with potassium (K) being the most abundant nutrient in the plants, followed by trace elements such as iron (Fe), sodium (Na), manganese (Mn), zinc (Zn), and rubidium (Rb). The average transfer coefficients for K, Fe, Na, Mn, Zn, and Rb are 2.91, 0.00307, 0.45, 0.037, 0.15, and 0.22, respectively. Multivariate analysis indicates that the ability to absorb and accumulate elements are species-dependent, highlighting the influence of plant type. The findings imply that plants within the same group require similar fertilization and soil treatment strategies.

Keywords: Nutrient, soil-to-plant transfer factor, PCA, AHC.

1. Introduction

The absorption and accumulation of elements from soil to plants represent a crucial step in the process of transferring these elements into the human food chain [1]. The transfer factor (TF) is one of

* Corresponding author.
E-mail address: buivanloat@hus.edu.vn

https//doi.org/10.25073/2588-1124/vnumap.4996

the simplest approaches used to explain the nutrient absorption process in crops [1]. However, the TF is influenced by several factors such as the plant's genotype, soil structure, soil pH, biological activity in soil, cultivation practices, and the competition among nutrients absorbed by plants [2], making it difficult to predict the transfer of elements. Although plant absorption primarily occurs passively, plants can actively regulate the uptake process. Moreover, soil conditions and interactions among different elements also play a significant role, influencing nutrient availability, uptake efficiency, and the subsequent accumulation and distribution of elements within plant tissues [2]. Due to the complexity of these influencing factors, multivariate analysis is a powerful statistical method for processing and representing a dataset with multiple variables. Especially in environmental, agricultural, and biological fields, this method allows exploring the complex relationships between various factors [3, 4]. Multivariate analysis helps trace the origins of elements and analyze the absorption and accumulation of metals from soil into plants [5-7]. This method can also assist in grouping plants based on their ability to accumulate specific elements, aiding in the selection of suitable crops for different soil conditions [8, 9]. Furthermore, multivariate analysis is applied to identify pollution sources and assess their impact on ecosystems [10-12].

Moc Chau, located in Son La province (Vietnam), is a region known for its diverse agricultural activities, producing many characteristic agricultural products such as tea, milk, and vegetables and fruits. With favorable climate and soil conditions, Moc Chau has become a major center for vegetable and fruit production in the Northwest region of Vietnam. However, systematic studies on nutrient absorption and accumulation patterns in vegetables in this region remain limited. This study aims to determine the concentrations and the TFs of nutrient elements from soil to plants across various plant species. The investigation focuses on commonly cultivated vegetables in Moc Chau, including mustard greens, eggplant, radish, bell pepper, cabbage, taro, and pumpkin, along with their corresponding soils. In this study, the instrumental neutron activation analysis (INAA) based on the k_0-standardization method, a highly sensitive, non-destructive analytical technique, was utilized to determine the concentrations of essential nutrient elements in representative soil and plant samples. The transfer factors were then evaluated, and multivariate analysis was performed to elucidate the elemental absorption characteristics of different plant species.

2. Materials and Method

2.1. Sampling Location

Moc Chau has a total natural area of 107,170 hectares and is a mountainous district located in the southeastern border of Son La Province. Its geographical coordinates are 20°40' – 21°07' north latitude and 104°26'–105°05' east longitude, with a shared border length of 40.6 km. The region features a diverse topography, with plateaus, plains, valleys, and rivers interspersed. At an average altitude of 1,050 m above sea level, Moc Chau enjoys a temperate, cool climate year-round, with two distinct seasons: the rainy season (from April to September) and the dry season (from October to March). This region is characterized by two main types of soil: red-brown feralit soil and ancient alluvial soil, which are suitable for growing industrial crops (tea and coffee), fruit trees (avocado, plum, and persimmon), rice cultivation, and food crops [13]. Moc Chau is also known for some mineral resources, including peat, copper ores, limestone, and clay[1]. The sitemap and sampling locations are illustrated in Fig. 1.

[1] Moc Chau District Department of Agriculture.

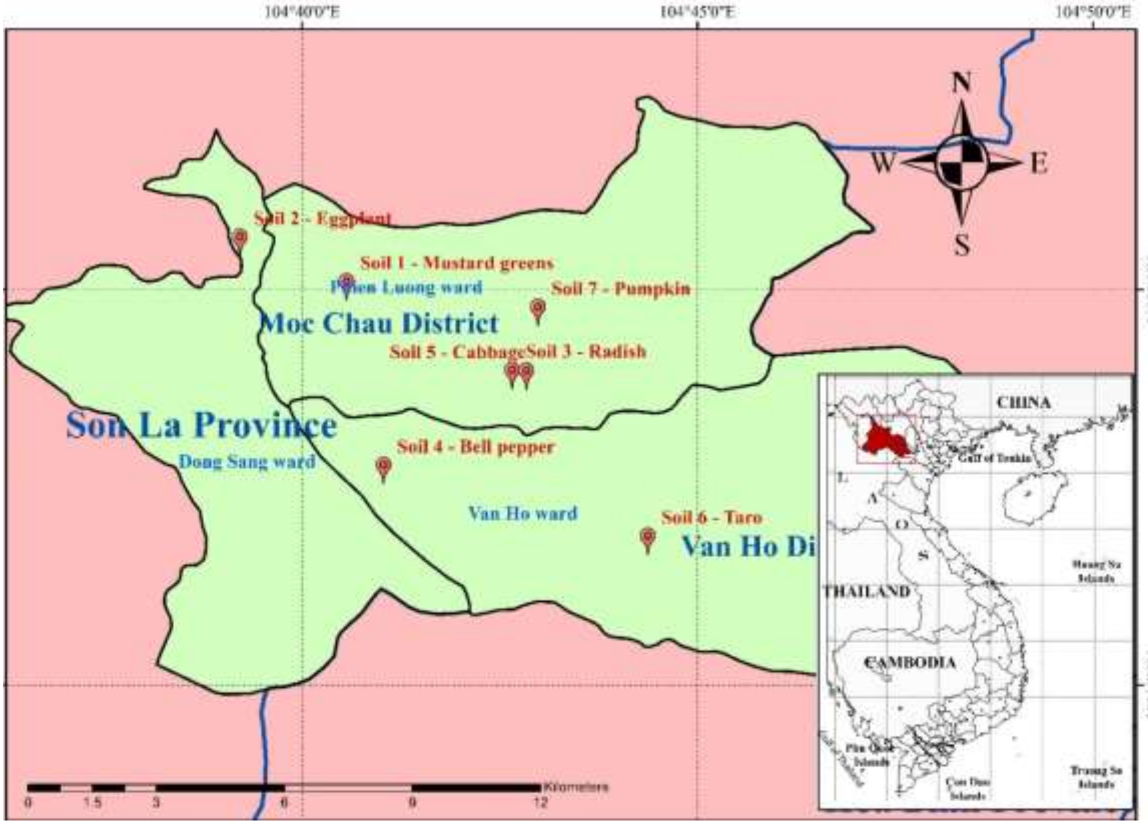

Figure 1. Sitemap and sampling locations in Moc Chau.

2.2. Sample Collection and Preparation

The soil and vegetable samples were collected in October and November 2024, corresponding to the local harvest period. To ensure the accuracy and consistency of the analytical results, two independent samples were taken from each site. The sampling and preparation procedures were conducted following the method described by [14]. At each sampling site, approximately 1 kg of topsoil (0 - 20 cm depth) was collected. In the laboratory, the soil samples were cleaned to remove gravel, roots and organic debris, then air-dried at room temperature. After air-drying, the soil was finely ground and oven-dried at 105 °C for 24 hours to eliminate remaining moisture. For the vegetable samples, approximately 3 kg of each was collected from the same site as the soil samples. Only edible parts were selected, washed with clean water, and then air-dried at room temperature. The dried plant material was cut into small pieces and further oven-dried at 65 °C until a constant mass was achieved. The samples were then ground into a fine powder using a stainless-steel blender. After grinding, both the soil and vegetable samples were sieved through a 2 mm mesh and stored in labeled polyethylene bags. The samples were kept in a desiccator until neutron activation analysis (NAA) was performed.

2.3. Irradiation Regime, Sample Measurement and Calculation of Elemental Concentration

Sample irradiation was conducted at the Dalat Nuclear Research Reactor using two separate processes: irradiation at channel 7-1 (60 seconds for soil samples and 120 seconds for plant samples) for short-lived isotopes, and irradiation on a Rotary Specimen Rack (RSR) (10 hours for soil samples and 15 hours for plant samples) for long-lived isotopes. The thermal neutron flux (ϕ_{th}), thermal-to-fast neutron ratio (f), and thermal neutron spectrum shift factor (α) were 4.8×10^{12} (n cm^{-2} s^{-1}), 9.8, -0.038 respectively for samples irradiated at channel 7-1, and 3.8×10^{12} (n cm^{-2} s^{-1}), 39.5, 0.071 respectively for samples irradiated on the RSR. After irradiation, the samples were allowed to decay for an appropriate time according to the group of elements and were measured using a gamma spectrometer equipped with a high-purity germanium detector (GMX-30190 from ORTEC, USA) with a relative detection efficiency of 30% and an energy resolution of 2.1 keV at 1332.5 keV from ^{60}Co. The gamma spectrum was collected using the MASTRO software [15].

The concentration of element X is determined as follows:

$$p_X\,(ppm) = \frac{\left[\dfrac{N_P/t_m}{SDCW}\right]_X}{\left[\dfrac{N_P/t_m}{SDCW}\right]_{Au}} \cdot \frac{1}{k_{0,Au(X)}} \cdot \frac{G_{th,Au}\,f + G_{e,Au}Q_{0,Au}(\alpha)}{G_{th,X}\,f + G_{e,X}Q_{0,X}(\alpha)} \cdot \frac{\varepsilon_{Au}}{\varepsilon_X}.10^6 \quad (1)$$

where X and Au represent the sample and the neutron flux monitor, respectively; W corresponds to the mass of the sample (in grams); N_P is the net peak area of the full absorption peak; and S, D, and C are the saturation factor (irradiation time correction), decay factor (decay time correction), and measurement factor (measurement time correction), respectively; t_m is the measuring time; G_{th} and G_e are the correction factors for thermal and epithermal neutron self-shielding, respectively; ε is the full energy photopeak efficiency of the detector; $Q_0(\alpha)$ is the thermal activation cross section [16, 17]. k_0-INAA is a method that simplifies the process of quantifying elemental concentration in a sample without the need for preparing individual standards for each element. In this method, the k_0 factor is considered independent of neutron flux and the characteristics of the detector.

The detection limit of INAA is calculated using Currie's formula, with the note that this formula is valid only when the gamma-ray background is a major interference [18]:

$$DL = 2.71 + 4.56 \times B \quad (2)$$

where DL is the detection limit and B represents the background under a gamma-ray peak.

2.4. Soil to Plant Transfer Factor of Metal Elements

The soil-to-plant TF indicates the efficiency with which a nutrient element is absorbed from the soil and accumulated in the plant according to the following equation:

$$TF = \frac{C_{plant}}{C_{soil}} \quad (3)$$

where, C_{plant} and C_{soil} are the concentrations of the element in the corresponding plant and soil samples, respectively [19, 20].

2.5. Statistical Analysis

In this work we used XLSTAT 2024 to analyze the relationship between the transport of nutrients from soil to plant in Moc Chau, using two methods: Principal Component Analysis (PCA) and Agglomerative Hierarchical Clustering (AHC). PCA is a technique used to reduce the number of variables in a dataset while retaining as much information as possible. AHC is a hierarchical clustering method that follows a bottom-up (agglomerative) approach. It organizes data into a hierarchical tree (dendrogram), where initially separate objects are gradually grouped together based on their similarity [3, 4].

3. Results and Discussions

3.1. Soil-to-plant Transfer of Elements

Table 1 presents the concentration of metal elements in soil and vegetables from Moc Chau. In the soil, the average concentration of elements decreases in the order of Fe > K > Mn > Na > Zn > Rb. The iron (Fe) and potassium (K) concentrations in the soil samples range (average) from 72,600 to 103,600 mg/kg (87,306 mg/kg) and from 7,516 to 24,250 mg/kg (15,561 mg/kg), respectively. The average Fe concentration in this area is about twice that in the Earth's crust (46,500 mg/kg) [21]. This can be attributed to Moc Chau's location primarily on limestone mountain terrain, where weathering processes have formed two main types of soil: red-brown feralit soil and ancient alluvial soil, which are rich in iron concentration [22, 23]. Potassium concentration varies widely, and this variation may be linked to the specific fertilization practices used at different vegetable cultivation sites. The average concentrations of elements such as Na, Mn, Zn, and Rb are 591 mg/kg, 1,087 mg/kg, 189 mg/kg and 99.3 mg/kg, respectively. Despite the small sampling area, there is a wide range of variation in the elemental concentrations in the soil samples. The abundance of these elements in soil may be due to weathering from the parent rock [24] and human activities in agriculture, such as fertilization, irrigation, and pesticide use [25].

Table 1. The concentrations of elements in soil and plant

Information of sample	Element in soil (mg/kg)						Element in vegetable (mg/kg)					
	K	Na	Rb	Fe	Zn	Mn	K	Na	Rb	Fe	Zn	Mn
Soil 1 - Mustard greens	15,740 (866)	938 (35)	105 (26)	74,820 (1721)	266 (24)	963 (24)	68,870 (2548)	637 (27)	28.5 (1.4)	1060 (35)	55.4 (13.8)	111 (5)
Soil 2 - Eggplant	9,630 (819)	325 (14)	85.7 (17.1)	91,490 (2287)	270 (26)	1,801 (32)	58,880 (2120)	253 (11)	34.5 (1.5)	207 (10)	45.3 (7.00)	37.0 (2.6)
Soil 3 - Radish	14,990 (779)	345 (14)	111 (14)	87,030 (2002)	143 (20)	715 (14)	23,390 (865)	86.9 (4.0)	25.9 (0.9)	55.1 (13.0)	22.3 (1.5)	17.9 (0.7)
Soil 4 - Bell pepper	7,516 (691)	408 (22)	56.1 (12.9)	84,240 (2780)	219 (16)	2,148 (286)	24,990 (825)	151 (5)	11.5 (0.4)	66.9 (4.0)	25.5 (1.1)	12.1 (0.4)
Soil 5 - Cabbage	14,940 (926)	386 (20)	65.9 (13.9)	72,600 (2396)	162 (18)	579 (17)	35,060 (974)	377 (14)	17.8 (1.2)	183 (9)	36.9 (4.1)	48.3 (2.1)
Soil 6 - Taro	24,250 (1,722)	1,023 (58)	134 (32)	97,360 (3700)	135 (16)	951 (29)	36,710 (918)	50.5 (2.0)	4.03 (0.22)	66.9 (5.0)	14.9 (0.4)	3.1 (0.1)
Soil 7 - Pumpkin	21,860 (1,421)	711 (39)	137 (12)	103,600 (3,937)	132 (11)	455 (16)	25,770 (696)	40.8 (1.0)	14.0 (0.8)	37.6 (6.0)	11.9 (1.0)	3.2 (0.3)
Min	*7,516 (691)*	*325 (14)*	*56.1 (12.9)*	*72,600 (2396)*	*132 (11)*	*455 (16)*	*23,390 (865)*	*40.8 (1.0)*	*4.03 (0.22)*	*37.6 (6.0)*	*11.9 (1.0)*	*3.1 (0.1)*
Max	*24,250 (1,722)*	*1,023 (58)*	*137 (12)*	*103,600 (3,937)*	*270 (26)*	*2,148 (286)*	*68,870 (2,548)*	*637 (27)*	*34.5 (1.5)*	*1,060 (35)*	*55.4 (13.8)*	*111 (5)*
Average	*15,561*	*591*	*99.3*	*87,306*	*189*	*1,087*	*39,096*	*228*	*19.5*	*239*	*30.3*	*33.2*
SE	*2,267*	*112*	*11.9*	*4,270*	*23.1*	*242*	*6,767*	*82.0*	*4.03*	*139*	*6.10*	*14.5*
SD	*5,997*	*297*	*31.5*	*11,297*	*61.0*	*641*	*17,903*	*217*	*10.7*	*368*	*16.1*	*38.3*

Table 2. Comparison of element concentrations in soil (*the value was converted from mg/kg to %)

Element	**Moc Chau** (This study)	**Da Lat** [6]	**Mekong Delta** ([26])	**Red River Delta** ([27])	**Earth's crust** ([21])
K (%)	1.5*	1.5	2	2	2.5
Na (%)	0.6*	0.1	0.5	0.5	2.5
Fe (%)	9.7*	4.7	3.5	4.4	4.6
Rb (mg/kg)	99.3	65	123	119	150
Zn (mg/kg)	189	207	90	110	83
Mn (mg/kg)	1,087	598	302	527	1,000

Table 2 presents a comparison of the mean elemental concentrations in soil in Moc Chau with that in three other regions: Da Lat, the Mekong Delta and the Red River Delta. Most of the element concentrations in soil in Moc Chau are not significantly different from that in the three regions and the Earth's crust, except for Fe and Mn. The manganese concentration in the soil samples in Moc Chau is close to its concentration in the Earth's crust, but it is two to three times higher than the three regions [6, 26, 27]. According to the FAO (2003) report, the soils in Moc Chau consist of 18% igneous rock and 8% metamorphic rock — two types of rocks that are naturally rich in Fe and Mn [13]. In contrast, the soils in the Red River Delta and the Mekong Delta are primarily formed from young alluvial deposits, which have not undergone prolonged weathering processes [26, 27], resulting in lower Fe and Mn accumulation compared to Moc Chau.

There is a difference in the order of element concentrations in vegetables compared to soil, with the order of K > Fe > Na > Mn > Zn > Rb. The difference can be attributed to the selective uptake mechanisms of plants, which are influenced by their physiological needs, the bioavailability of elements in soil, and interactions between elements during absorption and transport [2, 28, 29]. The average K concentration in vegetables is 39,096 mg/kg, which is more than twice the average concentration in soil. Crops require large amounts of potassium not only for healthy growth but also to carry out a range of physiological and biochemical processes within the plant [30, 31]. Fe is absorbed by plants in small amounts, with an average of 239 mg/kg, compared to its higher concentration in soil. In the feralit soil in Moc Chau, iron mainly exists in the form of Fe^{3+}, which is less soluble and difficult for plants to absorb, whereas plants can easily absorb iron in the form of Fe^{2+} [32, 33]. Additionally, plants require iron as a micronutrient for physiological and biochemical processes. A deficiency in iron results in stunted growth and poor development, but an excess of iron can cause iron toxicity, which hinders the absorption of other micronutrients such as Mn and Zn due to competitive interactions [33-35].

Table 3. Transfer factors of elements from soil to plant

Information of sample	**Transfer factor**					
	K	**Na**	**Rb**	**Fe**	**Zn**	**Mn**
Soil 1 - Mustard greens	4.38 (0.29)	0.68 (0.04)	0.27 (0.07)	0.0142 (0.0006)	0.21 (0.06)	0.115 (0.006)
Soil 2 - Eggplant	6.11 (0.56)	0.78 (0.05)	0.40 (0.08)	0.0023 (0.0001)	0.17 (0.03)	0.021 (0.001)
Soil 3 - Radish	1.56 (0.10)	0.25 (0.02)	0.23 (0.03)	0.0006 (0.0002)	0.16 (0.02)	0.025 (0.001)
Soil 4 - Bell pepper	3.32 (0.31)	0.37 (0.02)	0.20 (0.05)	0.0008 (0.0001)	0.12 (0.01)	0.006 (0.002)
Soil 5 - Cabbage	2.35 (0.16)	0.98 (0.06)	0.27 (0.06)	0.0025 (0.0001)	0.23 (0.03)	0.083 (0.004)
Soil 6 - Taro	1.51 (0.11)	0.049 (0.003)	0.03 (0.01)	0.0007 (0.0001)	0.11 (0.01)	0.0033 (0.0001)
Soil 7 - Pumpkin	1.18 (0.08)	0.057 (0.003)	0.10 (0.01)	0.0004 (0.0001)	0.09 (0.01)	0.007 (0.001)
Min	*1.18 (0.12)*	*0.050 (0.004)*	*0.03 (0.02)*	*0.0004 (0.0001)*	*0.09 (0.01)*	*0.0033 (0.0001)*
Max	*6.11 (0.56)*	*0.98 (0.06)*	*0.40 (0.08)*	*0.0142 (0.0006)*	*0.23 (0.03)*	*0.115 (0.006)*
Average	*2.91*	*0.45*	*0.22*	*0.0031*	*0.15*	*0.037*
SE	*0.68*	*0.14*	*0.05*	*0.0019*	*0.02*	*0.017*

The highest concentrations of elements were found in the mustard greens, except for Rb. Mustard greens have a short growing period and are primarily consumed by their leaves. Due to their rapid growth, these plants require larger amounts of nutrients to sustain photosynthesis and development [30]. Previous studies indicated that nutrients are absorbed and accumulated more in the leaves [6, 36]. The concentrations of Fe, Mn, Zn, and Rb in the cabbage and bell pepper samples in Moc Chau are higher than that in the cabbage and bell pepper samples in Romania, while the concentration of K is lower [37]. In contrast, the concentrations of these elements in the stems of vegetable samples in Da Lat are higher than that in the vegetable samples in Moc Chau [6].

The soil-to-plant TFs of elements are shown in Table 3. The TFs of K, Na, Rb, Zn, Mn, and Fe are 2.91, 0.45, 0.22, 0.15, 0.037, and 0.0031, respectively. Among these, the TF of K is greater than unity, while the other elements are smaller than unity. This indicates that crops have a significant ability to absorb and accumulate K in various plant parts. This finding is supported by previous studies [14, 36]. The results also suggest that crops have difficulty in absorbing Fe and Mn. In fact, Fe exists in the form of insoluble oxides in soil, making it less accessible to plants compared to other elements [32]. Additionally, Mn may bind with iron oxides in soil, remaining in an insoluble compound form [34]. The TF of Na, Fe, Mn, and Zn reported by Thien et al., (2021) are 1.27, 0.004, 0.55, and 0.25, respectively, which are higher than that obtained in this study. Notably, the TF of Na is greater than unity [9]. The differences in the TFs are closely related to the biological characteristics of the plant species [2], soil properties and soil pH [38, 39].

3.2. The Relationship Between TF and Concentrations in Soil

Table 4. Squared cosines of the variables

Vegetable	F1	F2	F3	F4	F5
Mustard greens (MG)	0.350	**0.493**	0.145	0.004	0.007
Eggplant (EP)	**0.533**	0.265	0.067	0.126	0.009
Radish (RD)	0.220	0.022	**0.493**	0.047	0.179
Bell pepper (BB)	0.107	**0.665**	0.007	0.216	0.004
Cabbage (CB)	0.349	0.136	**0.485**	0.002	0.026
Taro (TR)	**0.892**	0.018	0.042	0.012	0.030
Pumpkin (PK)	**0.953**	0.000	0.000	0.027	0.004

Table 4 shows the squared cosines, a value representing the degree of contribution of each observed variable to the principal components without being affected by their directions. The first principal component (F1) is mainly influenced by the TFs of Eggplant (belong to the *Solanaceae* family), Taro (*Araceae*), and Pumpkin (*Cucurbitaceae*), while F2 is dominated by the TFs of Mustard greens (*Brassicaceae*) and Bell pepper (*Solanaceae*). F3 is influenced by the TFs of Radish (*Brassicaceae*) and Cabbage (*Brassicaceae*). F4 and F5 are less influenced by the transport coefficients of the vegetables. Figure 1 depicts the Multivariate Principal Component Analysis of the relationship between the transport coefficient and the concentrations of elements in soil. The two principal components, F1 and F2, together explain nearly 80% of the variation in the data, with the contribution of 54.13% and 24.38%, respectively. The observed variables are separated into four data groups, indicating differences in characteristics among the groups, with variables in the same group being related to each other. The results show that the absorption and accumulation trends of the vegetables are divided into four groups based on the TFs and the element concentrations: mustard greens – cabbage, taro – pumpkin, radish, bell pepper – eggplant. The mustard greens – cabbage group is in the first quadrant, while the bell pepper – eggplant group is in the fourth quadrant of the PCA chart. The vegetables in the same group share similar characteristics such as morphology, structure, physiology, and genetics [40]. Previous studies have shown that vegetables of the same species tend to have similarities in nutrient absorption and accumulation patterns [2, 6]. The taro – pumpkin group located in the second quadrant. In fact, although taro and pumpkin are from two different species-pumpkin being a climbing plant and taro growing underground, both have highly developed root systems, helping them efficiently absorb nutrients from soil. Radish falls into the third quadrant. These four vegetable groups are located in different quadrants of the coordinate system created by the two axes, F1 and F2, indicating the differences in the absorption and accumulation abilities of various species.

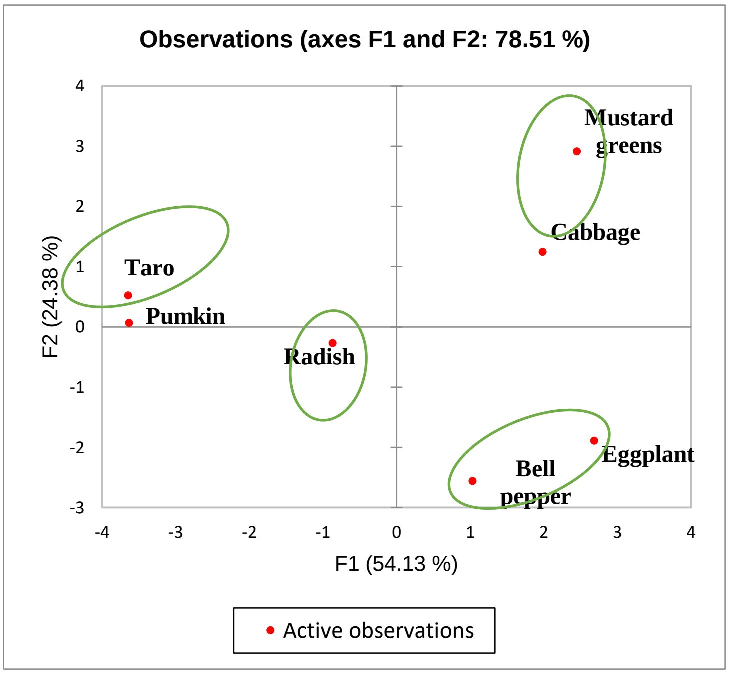

Figure 1. PCA plot of the relationships between TF and element concentration in soil.

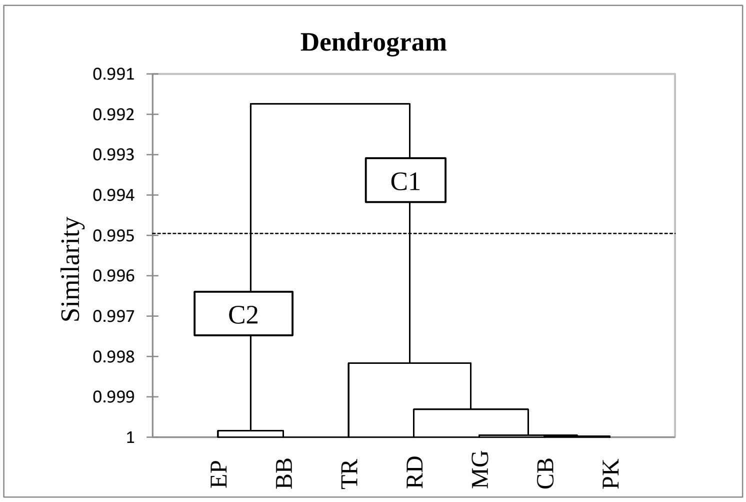

Figure 2. Dendrogram of plants based on the TFs and the element concentrations in soil.

Figure 2 illustrates the dendrogram of vegetable objects based on the TFs and the concentrations of elements in the soil. The vertical axis represents the similarity between the plant groups, with higher values indicating greater differences among the groups. The horizontal axis represents the categorized plant types. The lower the connection of a plant, the higher the similarity, and vice versa. The chart shows that the plants are divided into two groups, C1 and C2, with significant differences in their absorption and accumulation trends of elements. Group C1 includes radish, mustard greens, cabbage, pumpkin, and taro. Among these, mustard greens, cabbage, and pumpkin show the highest similarity, approximately unity. The similarity gradually decreases within this group, first with radish and then with taro. Group C2 consists of eggplant and bell pepper, which have relatively high similarity, but still lower than that of mustard greens, cabbage, and pumpkin in group C1. The dendrogram not only proves that vegetables from the same family show high similarity in nutrient absorption characteristics but also identifies those with similar nutrient accumulation abilities. This means that vegetables within the same group may require similar fertilization and soil treatment strategies.

4. Conclusion

The absorption and accumulation of nutrients in various crop species in Moc Chau were investigated. The concentrations of K, Na, Rb, Fe, Zn, and Mn in soil are 15,561 mg/kg, 591 mg/kg, 99.3 mg/kg, 87,306 mg/kg, 189 mg/kg, and 1,087 mg/kg, respectively. The plants absorb these nutrients in the following order: K is the macronutrient with an average concentration of 39,096 mg/kg; the other micronutrients follow the order of Fe > Na > Mn > Zn > Rb. The transport coefficient for K is greater than unity, while the other micronutrients are less than unity. The vegetables are divided into four groups based on the nutrient concentrations in soil and their TFs: mustard greens – cabbage, taro – pumpkin, radish, and bell pepper – eggplant. The two groups were divided based on the similarity of nutrient absorption and accumulation abilities: group 1 consists of taro, radish, mustard greens, cabbage, and pumpkin, with mustard greens, cabbage, and pumpkin showing the highest similarity; group 2 consists of eggplant and bell pepper. Multivariate analysis has shown that plants from the same family and with similar nutrient uptake patterns exhibit a high degree of similarity in their nutrient absorption abilities.

Acknowledgments

This work was funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.04-2021.131.

References

[1] F. E. Adeleke, I. O. Olarinoye, M. M. Idris, K. U. Isah, K. U., Estimation of Soil-to-Plant Transfer Factors for ^{238}U, ^{232}Th, ^{40}K and ^{137}Cs Radionuclides for some Selected Medicinal Plants in Some Part of Minna and Kaduna, Nigeria, Journal of Radioanalytical and Nuclear Chemistry, Vol. 6, 2021, pp. 171-178, http://dx.doi.org/10.18576/jrna/060211.

[2] M. Greger, Uptake of Nuclides by Plants, Technical Report TR-04-14, Department of Botany, Stockholm University, 2004.

[3] A. C. Rancher, W. F. Christensen, Methods of Multivariate Analysis, Wiley Series in Probability and Statistics, First Edition, Wiley, 2012.

[4] A. P. Dempster, An Overview of Multivariate Data Analysis, Journal of Multivariate Analysis, Vol. 1, 1971, pp. 316-346, https://doi.org/10.1016/0047-259X(71)90006-6.

[5] K. P. Pradhoshini, B. Santhanabharathi, M. Priyadharshini, M. S. Ahmed, K. Murugan, P. Sivaperumal, L. Alam, D. V. Hao, M. S. Musthafa, Microbial Consortium and Impact of Industrial Mining on the Natural High Background Radiation Area (NHBRA), India – Characteristic Role of Primordial Radionuclides in Influencing the Community Structure and Extremophiles Pattern, Environmental Research, Vol. 244, 2024, Article 118000, https://doi.org/10.1016/j.envres.2023.118000.

[6] V. N. Ba, B. N. Thien, H. T. Phuong, T. T. H. Loan, T. T. Anh, Bioconcentration and Translocation of Elements from Soil to Vegetables and Associated Health Risk, Journal of Food Composition and Analysis, Vol. 132, 2024, Article 106296, https://doi.org/10.1016/j.jfca.2024.106296.

[7] P. Yang, M. Yang, R. Mao, H. Shao, Multivariate-Statistical Assessment of Heavy Metals for Agricultural Soils in Northern China, The Scientific World Journal, 2014, Article 517020, https://doi.org/10.1155/2014/517020.

[8] I. Shtangeeva, D. Alber, G. Bukalis, B. Stanik, F. Zepezauer, Multivariate Statistical Analysis of Nutrients and Trace Elements in Plants and Soil from Northwestern Russia, Plant and Soil, Vol. 322, 2009, pp. 219-228, http://dx.doi.org/10.1007/s11104-009-9910-7.

[9] B. N. Thien, V. N. Ba, M. T. Man, T. T. H. Loan, Analysis of the Soil to Food Crops Transfer Factor and Risk Assessment of Multi-Elements at the Suburban Area of Ho Chi Minh City, Vietnam Using Instrumental Neutron Activation Analysis (INAA), Journal of Environmental Management, Vol. 291, 2021, Article 112637, https://doi.org/10.1016/j.jenvman.2021.112637.

[10] Z. Wang, D. Jia, S. Song, J. Sun, Assessments of Surface Water Quality Through the Use of Multivariate Statistical Techniques: A Case Study for the Watershed of the Yuqiao Reservoir, China, Frontiers in Environmental Science, Vol. 11, 2024, https://doi.org/10.3389/fenvs.2023.1107591.

[11] J. Osei, F. Nyame, T. Armah, S. Osae, S. Dampare, J. R. Fianko, Application of Multivariate Analysis for Identification of Pollution Sources in the Densu Delta Wetland in the Vicinity of a Landfill Site in Ghana, Journal of Water Resource and Protection, Vol. 2, 2010, pp. 1020-1029, http://dx.doi.org/10.4236/jwarp.2010.212122.

[12] A. Ibrahim, H. Juahir, M. Toriman, A. Mustapha, A. Azid, H. Isiyaka, Assessment of Surface Water Quality Using Multivariate Statistical Techniques in the Terengganu River Basin, Malaysia, Journal of Analytical Sciences, Vol. 19, 2015, pp. 338-348.

[13] N. K. Quynh, T. V. The, L. V. Luu, Vietnam Agricultural Science Institute Project: Report on Participatory Rural Environmental Management in the Northern Upland Areas (Moc Chau District, Son La Province), Hanoi, Vietnam, 2003 (in Vietnamese).

[14] B. T. Hong, B. V. Loat, D. V. Hao, D. T. Thang, L. N. Thiem, T. D. Khoa, T. V. Khanh, H. T. T. Linh, P. T. T. Giang, T. V. Hoang, H. V. Khanh, T. H. Nam, Transfer of Natural Radionuclides from Soil to Water Spinach (Ipomoea Aquatica Forssk) under Flooded and Unflooded Conditions in Hanoi, Vietnam, Journal of Environmental Radioactivity, Vol. 277, 2024, Article 107445, https://doi.org/10.1016/j.jenvrad.2024.107445.

[15] S. Said, H. Bounouira, H. Amsil, I. Aarab, A. Badague, S. El Basraoui, A. Moussaif, B. Benazzouz, Major and Trace Elements Determination in Organic and Conventional Moroccan Vegetables Using the k0-Standardisation Method of Neutron Activation Analysis, Nuclear Analysis, Vol. 3, 2024, Article 100127, https://doi.org/10.1016/j.nucana.2024.100127.

[16] L. Hamidatou, H. Slamene, T. Akhal, B. Zouranen, Concepts, Instrumentation and Techniques of Neutron Activation Analysis, in Imaging and Radioanalytical Techniques in Interdisciplinary Research – Fundamentals and Cutting Edge Applications, IntechOpen, 2013, http://dx.doi.org/10.5772/53686.

[17] M. Blaauw, G. D'Agostino, M. Di Luzio, H. M. Dung, R. Jacimovic, M. Da Silva Dias, The 2021 IAEA Software Intercomparison for k0-INAA, Journal of Radioanalytical and Nuclear Chemistry, Vol. 332, 2023, pp. 3387-3400, https://doi.org/10.1007/s10967-022-08626-1.

[18] International Atomic Energy Agency, Use of Research Reactors for Neutron Activation Analysis, IAEA-TECDOC-1215, Vienna, 2001.

[19] J. Y. Kim, J. H. Lee, A. Kunhikrishnan, D. W. Kang, M. J. Kim, J. H. Yoo, Transfer Factor of Heavy Metals from Agricultural Soil to Agricultural Products, Korean Journal of Environmental Agriculture, Vol. 31, 2012, http://dx.doi.org/10.1101/gr.089417.108.

[20] N. Mirecki, R. Agic, L. Šunić, L. Milenkovic, Z. Ilic, Transfer Factor as Indicator of Heavy Metals Content in Plants, Fresenius Environmental Bulletin, Vol. 24, 2015, pp. 4212-4219.

[21] A. Yaroshevsky, Abundances of Chemical Elements in the Earth's Crust, Geochemistry International, Vol. 44, 2006, pp. 48-55.

[22] N. V. Bo, B. D. Dinh, H. Q. Duc, B. H. Hien, D. T. Loc, T. Phien, N. V. Ty, The Basic Information of Main Soil Units of Vietnam, The Gioi Publishers, Hanoi, 2002.

[23] N. V. Breemen, P. Buurman, Ferralitization, in Soil Formation, Springer Netherlands, Dordrecht, New York, 2002, pp. 121-158.

[24] M. Kulkarni, Trace Elements in Soils and Plants, South African Journal of Botany, Vol. 80, 2012, pp. 1-10, https://doi.org/10.1016/j.sajb.2012.03.008.

[25] N. Gupta, K. K. Yadav, V. Kumar, S. Kumar, R. P. Chadd, A. Kumar, Trace Elements in Soil-Vegetables Interface: Translocation, Bioaccumulation, Toxicity and Amelioration – A Review, Science of the Total Environment, Vol. 651, 2019, pp. 2927-2942, https://doi.org/10.1016/j.scitotenv.2018.10.047.

[26] N. P. Thuy, H. Ruppert, T. Pasold, B. Sauer, Paddy Soil Geochemistry, Uptake of Trace Elements by Rice Grains (Oryza sativa) and Resulting Health Risks in the Mekong River Delta, Vietnam, Environmental Geochemistry and Health, Vol. 42, 2020, pp. 2377-2397, https://doi.org/10.1007/s10653-019-00333-3.

[27] N. P. Thuy, H. Ruppert, B. Sauer, T. Pasold, Harmful and Nutrient Elements in Paddy Soils and Their Transfer into Rice Grains (Oryza sativa) Along Two River Systems in Northern and Central Vietnam, Environmental Geochemistry and Health, Vol. 42, 2020, pp. 191-207, https://link.springer.com/article/10.1007/s10653-019-00333-3.

[28] L. Gulan, J. Stajic, B. Milenkovic, T. Zeremski, S. Milić, D. Krstic, Plant Uptake and Soil Retention of Radionuclides and Metals in Vineyard Environments, Environmental Science and Pollution Research, Vol. 28, 2021, https://doi.org/10.1007/s11356-021-14239-0.

[29] J. Tuma, M. Skalicky, L. Tumova, P. Bláhová, M. Rosůlková, Potassium, Magnesium and Calcium Content in Individual Parts of Phaseolus Vulgaris L. Plant as Related to Potassium and Magnesium Nutrition, Plant Soil Environment, Vol. 50, 2004, pp. 18–26. https://doi.org/10.17221/3637-PSE.

[30] P. Shrivastav, M. Prasad, T. Singh, A. Yadav, D. Goyal, A. Ali, P. K. Dantu, Role of Nutrients in Plant Growth and Development, in Contaminants in Agriculture, Springer, 2020, pp. 43–59. http://dx.doi.org/10.1007/978-3-030-41552-5_2.

[31] P. Marschner, Z. Rengel, Nutrient Availability in Soils, in Marschner's Mineral Nutrition of Plants, Academic Press, 2023, pp. 499–522. https://doi.org/10.1016/B978-0-12-819773-8.00003-4.

[32] R. M. Cornell, U. Schwertmann, The Iron Oxides, 2nd ed., Wiley-VCH, 2003, pp. 433-474.

[33] G. Rout, Role of Iron in Plant Growth and Metabolism, Reviews in Agricultural Science, Vol. 3, 2015, pp. 1-2, http://dx.doi.org/10.7831/ras.3.1.

[34] J. Wang, P. M. Wang, Y. Gu, F. Zhao, P. Wang, Iron-Manganese (Oxyhydro) Oxides, Rather than Oxidation of Sulfides, Determine the Mobilization of Cd During Soil Drainage in Paddy Soil Systems, Environmental Science & Technology, Vol. 53, 2019, pp. 1234-1245, https://pubs.acs.org/doi/abs/10.1021/acs.est.8b06863.

[35] J. Morrissey, M. Guerinot, Iron Uptake and Transport in Plants: The Good, the Bad, and the Ionome, Chemical Reviews, Vol. 109, 2009, pp. 4553-4567.

[36] H. T. Phuong, V. N. Ba, B. N. Thien, T. T. H. Loan, Accumulation and Distribution of Nutrients, Radionuclides and Metals by Roots, Stems and Leaves of Plants, Nuclear Engineering and Technology, Vol. 55, 2023, pp. 2650-2655, https://doi.org/10.1016/j.net.2023.03.039.

[37] O. A. Culicov, A. Pantelica, A. Ene, M. Gugiu, C. Ciortea, O. Constantinescu, INAA and PIXE Comparison on Some Vegetable Species, Romanian Reports in Physics, Vol. 63, 2011, pp. 997-1008.

[38] J. O. Miller, Soil pH Affects Nutrient Availability, University of Maryland Extension, 2016, https://doi.org/10.13016/M2PN59.

[39] N. J. Barrow, A. E. Hartemink, The Effects of pH on Nutrient Availability Depend on Both Soils and Plants, Plant and Soil, Vol. 487, 2023, pp. 21-37, https://doi.org/10.1007/s11104-023-05960-5.

[40] J. Duminil, M. D. Michele, Plant Species Delimitation: A Comparison of Morphological and Molecular Markers, Plant Biosystems, Vol. 143, 2009, pp. 528-542, https://doi.org/10.1080/11263500902722964.