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GEOGRAPHICAL CLASSIFICATION OF VIETNAMESE DRAGON FRUIT (*Hylocereus spp.)* USING ICP-MS AND PCA

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ABSTRACT

A geographical classification is a systematic framework for organizing and categorizing location-based data, facilitating the comparative analysis and interpretation of spatial distributions and regional characteristics. This study investigates the elemental composition and nutritional profiles of dragon fruits (*Hylocereus spp.*) collected from four major cultivation provinces in Vietnam: Tien Giang, Vinh Long, Long An, and Binh Thuan, using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Principal Component Analysis (PCA). A total of 80 samples (20 per province) were analyzed, revealing significant regional differences in elemental concentrations. Notably, Binh Thuan samples exhibited the highest levels of Nickel (34.09±1.98 µg/g), Chromium (86.11±4.16 µg/g), and Iron (3.08±0.21 µg/g), reflecting unique soil characteristics. Nutritional assessments indicated that Tien Giang samples had the highest Vitamin C content (30.65±0.16 mg/100 g) and acidity (5.80±0.40 mg/100 g). The PCA demonstrated clear clustering of samples by region, with elements such as Manganese, Yttrium, Barium, Potassium, Titanium, Sodium, Arsenic, and Cadmium contributing most to classification. Protein, lipid, and total sugar levels showed minimal variation across regions. These results highlight ICP-MS and PCA as effective tools for geographic traceability and quality control of agricultural products, supporting Vietnam's dragon fruit industry in meeting global export standards. Future applications include integrating traceability systems to enhance product authenticity and safety in international markets.

Keywords: dragon fruit, geographical classification, ICP-MS, Principal Component Analysis.

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INTRODUCTION

Dragon fruit (*Hylocereus* spp.), commonly referred to as pitaya, belongs to the Cactaceae family and is widely cultivated across tropical regions of Southeast Asia and South America. This genus comprises 14 recognized species, with the most prevalent ones being *Hylocereus undatus* (red peel, white pulp), *Hylocereus megalanthus* (yellow peel, white pulp), and *Hylocereus costaricensis* (red peel, red pulp)(Arivalagan *et al.*, 2021). The pigmentation of the peel and pulp in dragon fruit is determined by betalains and other secondary metabolites, which are known to exhibit antioxidant, anti-mutagenic, and anti-inflammatory properties (Pietta, 2000; Pojer *et al.*, 2013; Nishikito *et al.*, 2023). These bioactive compounds have made dragon fruit a highly sought-after crop due to its health benefits, including cardiovascular disease prevention, liver protection, and inhibition of tumor cell metastasis (Ellinger *et al.*, 2012; Poulose *et al.*, 2012; Chatterjee *et al.*, 2024). As a result, dragon fruit has gained increasing popularity in global markets, driven by consumer demand for functional foods with proven nutritional and medicinal value.

Vietnam is one of the world's leading producers and exporters of dragon fruit, with approximately 40,000 hectares dedicated to its cultivation (Nancy Jung Chen, 2019; UNDP, 2023). The majority of production is concentrated in the provinces of Binh Thuan, Tien Giang, and Long An, which collectively account for over 80% of the country's cultivation area. Binh Thuan alone contributes 50.73%, followed by Tien Giang at 16.42% and Long An at 15.15% (Hung, 2023). The domestic cultivation of dragon fruit in Vietnam reached nearly 55,000 hectares by 2022, making it one of the top eight fruit crops in terms of production scale. Export statistics further emphasize the economic importance of this crop; Vietnam's fruit and vegetable exports in the first eight months of 20-23 reached $3.55 billion, marking a 61.8% increase compared to the same period in 2022. Dragon fruit remains one of the key export items, with annual export revenues surpassing $1 billion from 2017 to 2020, peaking at $1.27 billion in 2018 (Hung, 2023). These figures underscore the pivotal role of dragon fruit in Vietnam's agricultural economy and its strategic significance in global trade.

Given its economic and nutritional importance, accurately classifying and authenticating the geographical origin of dragon fruit is essential for ensuring product quality, maintaining consumer trust, and preventing fraudulent practices. Geographical traceability has become an indispensable tool in modern agricultural practices, allowing stakeholders to verify the origin of food products and adhere to international quality standards. Recent advances in analytical chemistry, particularly the use of multi-element analysis, have revolutionized geographic traceability. Techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) enable the precise quantification of trace elements in agricultural products, providing a chemical fingerprint that reflects the unique environmental conditions of the cultivation site(Owens *et al.*, 2016; Richter *et al.*, 2019). These elemental fingerprints, combined with statistical methods like Principal Component Analysis (PCA), have proven to be highly effective in differentiating samples based on their geographical origin. Statistical approaches such as PCA and Cluster Analysis (CA) are widely used in food classification and evaluation due to their ability to handle large, multivariate datasets (Kaufmann, 2020; Bui *et al.*, 2024). PCA reduces the dimensionality of datasets by identifying patterns and highlighting the most influential variables, thereby simplifying complex datasets for easier interpretation. Previous studies have demonstrated the effectiveness of combining PCA with advanced analytical techniques like ICP-MS for geographic traceability. For instance, Yan Wang (2021) successfully utilized PCA and ICP-MS to classify *Oryza sativa*(rice)samples based on their production regions, while Nguyen-Quang *et al.* (2023) applied the same approach to distinguish cashew nut brands. Similarly, Bui *et al.* (2024) used PCA to classify processed meat products such as sausages based on their multi-element composition. These studies highlight the versatility of PCA in food authentication and its potential to enhance quality control in agricultural supply chains.

Dragon fruit, like other high-value crops, is influenced by a wide range of environmental and agricultural factors, including soil composition, irrigation practices, and climate conditions. These factors collectively determine the elemental composition and nutritional profile of the fruit, which can serve as reliable indicators of geographical origin. Studies have shown that trace elements such as Manganese (Mn), Iron (Fe), and Zinc(Zn) are highly sensitive to soil properties, including pH and mineral content (Rengel, 2015). Similarly, climatic factors such as temperature and rainfall influence the synthesis of bioactive compounds like Vitamin C and betalains, which contribute to the fruit's antioxidant capacity(Aubert and Chalot, 2018). In this context, the integration of multi-element data with nutritional parameters offers a novel approach to enhance the traceability and quality evaluation of dragon fruit.

This study aims to leverage the capabilities of ICP-MS and PCA to classify dragon fruit samples based on their geographical origin and nutritional composition. By integrating multi-element data with key nutritional parameters such as Vitamin C, acidity, and sugar content, the research seeks to provide a comprehensive framework for geographic traceability. This approach not only addresses the limitations of previous studies, which primarily focused on either elemental composition or nutritional analysis, but also offers a scalable solution for quality control in agricultural supply chains. Furthermore, the findings of this study have implications for food safety, fraud prevention, and market differentiation, contributing to the broader discourse on sustainable agricultural practices and global trade.

MATERIALS AND METHODS

Sample Collection and Homogenization: Eighty dragon fruit samples (*Hylocereus undatus*) were collected from multiple plantations in four distinct provinces: Tien Giang, Vinh Long, Binh Thuan, and Long An (20 samples from each region), as these are the top dragon fruit providers in the country(Hung, 2023)(**Fig 1**.).

Fig 1. Morphological Variations in Dragon Fruit Samples from Four Provinces (a: Tien Giang, b: Long An, c: Vinh Long, d: Binh Thuan)

These provinces are located in the Southern part of Vietnam within a tropical monsoon climate with two seasons, rainy and dry. All samples are collected within 2 weeks of June (within the main harvest period). Samples are packed in individual zip-lock bags, stored in cooler boxes, and shipped directly to the lab within the same day. The samples were then carefully prepared by removing the skin. Subsequently, the fruit pulp was homogenized using a Seka SK200 grinder to achieve uniformity in composition. The homogenized samples were stored at 4°C for subsequent analysis.

Elemental Analysis by ICP – MS(CEM Corporation): Approximately 0.2 grams of each homogenized sample were accurately weighed and placed into individual Teflon digestion tubes. To each tube, 4 mL of 65% nitric acid (HNO_3) and 2 mL of 30% hydrogen peroxide (H_2O_2) were added. The tubes were then allowed to rest overnight to optimize the digestion process. The following day, the sample tubes were subjected to microwave-assisted digestion in a MARS6 microwave oven (CEM Corporation, Matthews, NC, USA) at 190°C for 30 minutes. After cooling to ambient temperature, the digested solutions were diluted with deionized water using 50mL volumetric flasks. The resulting solutions were filtered with an 11 µm filter paper to remove particulate matter before analysis (Table 1).

Table 1. ICP-MS Operating Parameters for Elemental Analysis

Parameter	Setting
RF Power	1400 W
Plasma gas flow rate	15 L/min
Carrier gas flow rate	1.05 L/min
Makeup gas flow rate	0.9 L/ min
Spray chamber temperature	2 ℃
Points per spectral peak	3
Sweeps per reading	10

The experiments were conducted in triplicate, and data were expressed as mean and standard deviation. The results were presented through a screening histogram showing the contribution of each principal component to the PCA model, a score scatter plot indicating the differentiation among the four distinct groups, a loading scatter plot illustrating the factors of clustering, and a moving range graph showing the means and overall distribution of variables across the samples(Nguyen-Quang *et al.*, 2021; Bui *et al.*, 2024).

Vitamin C Determination: For the determination of vitamin C content, 100g of the homogenized sample was blended with 50 mL distilled water, and the mixture was filtered through cheesecloth. The extract was then made up to 100mL in a Volumetric flask. A 20 mL aliquot of the sample solution was pipetted into a 250 mL conical flask, followed by the addition of 150 mL of distilled water and 1 mL of starch indicator solution. The sample was titrated with 0.005 mol/L iodine solution, and the endpoint was identified by the first permanent appearance of a dark blue-black color due to the starch-iodine complex. The concentration of ascorbic acid in the solution was calculated in mol/L and converted to mg/100 mL or mg/100g of fruit(Vietnam General Department of Standards Metrology and Quality, 2015).

Determination of titratable acidity: The acidic level of the samples was determined using potentiometric titration with a standard sodium hydroxide (NaOH) solution(Vietnam General Department of Standards Metrology and Quality, 2007). A minimum of 25 g of the test sample was weighed and transferred to a conical flask, to which 50 mL of hot water was added. The mixture was thoroughly stirred and heated for 30 min in a boiling water bath. After cooling, the contents were transferred to a volumetric flask, diluted to the mark, and filtered. A 25 mL aliquot of the diluted sample was placed in a beaker, and titration was performed by adding NaOH solution until the pH reached 7 ± 0.2, then slowly continued until the pH was 8.1±0.2.

The titratable acidity was calculated as millimoles of H^+ per 100 ml of product, considering the dilution factor, and is calculated using the following formula.

$$\frac{250}{V} \times V_1 \times c \times \frac{100}{V_0} = \frac{1000V_1 c}{V_0}$$

Where:
V: Volume of the test sample (mL), specifically 25 ml.
V_0: Volume of the test portion (mL).
V_1: Volume of the sodium hydroxide solution used for titration (mL).
c: Exact concentration of the sodium hydroxide solution (mol/L).

Protein determination: Protein content was determined following the Kjeldahl method for nitrogen quantification(Sáez-Plaza *et al.*, 2013). A 2g sample was placed into a Kjeldahl flask, followed by 2/3 teaspoon of K_2SO_4 catalyst, 5 mL of $CuSO_4$, and 10 mL of concentrated H_2SO_4. The flask was heated slowly until a clear or light blue solution was obtained. After cooling, the contents were rinsed with deionized water and transferred to a nitrogen distillation unit. The solution was titrated with 0.1 N HCl, and the nitrogen content was calculated using the formula:

$$N\% = \frac{V_1 \times n_1 \times MWn}{m \times 10}$$

In which:
V_1: Volume of HCl consumed(mL)
n_1: Equivalent concentration of HCl
MWn: Molar mass of nitrogen (14.007 g/mol)

m: Sample mass (mg)
The protein content in the sample is determined by the formula.

$$Protein\% = N\% \times 6.25 \times F$$

Where:
F: Dilution factor

Total Sugar Analysis: Total sugar content was determined following the Vietnamese standard protocol TCVN 4594:1988 using the volumetric method with Fehling's solution(Vietnam General Department of Standards Metrology and Quality, 1988). A 5-20 g sample was transferred to a 250 mL triangular flask, and the sample was mixed with distilled water. After heating in a water bath at 80°C for 15 minutes, the sample was cooled, and 10 mL of 10% lead acetate was added to precipitate proteins. The solution was filtered, and the filtrate was transferred to a volumetric flask. Hydrolysis was carried out by adding 15 mL of hydrochloric acid and boiling for 15 minutes. The solution was neutralized with 30% NaOH, and then the reducing sugars were determined by titration with 0.1 N potassium permanganate solution. The total sugar content (X) was calculated using the following formula:

$$X = \frac{a \times V_1 \times V_3 \times 100}{m \times V \times V_2}$$

Where:
a: amount of glucose (g);
V: Volume of the deproteinized sample(mL)
V_1: Volume of sample used for hydrolysis (mL)
V_2: Volume of the volumetric flask for the hydrolyzed sample(mL)
V3: Volume of sample for the Fehling reaction (mL)
m: Sample weight (g)

Total Lipid Content: Lipid content was determined using a Soxhlet extraction method(AOAC International, 2019). A 12g sample was placed into a Falcon tube, followed by 30 mL of concentrated HCl to hydrolyze the fats. After boiling for 1 hour and filtering the sample, the residue was dried to a constant mass. The dried residue was then subjected to Soxhlet extraction with hexane for 12 hours. The lipid content was determined by measuring the mass of the extracted lipid after solvent removal.

$$m_{lipid} = m_{Final} - m_{container}$$

$$lipid\% = \frac{m_{lipid}}{m_{sample}} \times 100$$

Statistical analysis: Statistical analysis of the data was performed using XLSTAT (Lumivero, Denver, USA) and STATISTICA 12 (Dell Software, USA). Elements with concentrations below the limit of detection (LOD) in all four regions were excluded from further analysis. For elements with data below the LOD in some regions, a value of zero was assigned for the analysis. Principal component analysis (PCA) was performed on the data of 29 elements (Nickel (Ni), Lithium (Li), Beryllium (Be), Sodium (Na), Magnesium (Mg), Aluminum (Al), Potassium (K), Calcium (Ca), Chromium (Cr), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Lead (Pb), Manganese (Mn), Scandium (Sc), Titanium (Ti), Vanadium (V), Iron (Fe), Cobalt (Co), Rubidium (Rb), Strontium (Sr), Yttrium (Y), Molybdenum (Mo), Silver (Ag), Tin (Sn), Antimony (Sb), and Barium (Ba)).

Analysis of variance (ANOVA) was conducted to check the significance, and a post-hoc test was used to separate the means. Principal Component Analysis (PCA) was applied to all of the collected data. The multivariate statistical analysis provided a score scatter plot depicting the differentiation of the four distinct groups, a loading scatter plot elucidating the impact of factors on clustering, (Templ and Templ, 2021).

These analytical techniques allowed for precise characterization and verification of the geographical origin and authenticity of the mango samples, ensuring that the data provided a robust basis for distinguishing between different sources of mangoes. This methodology enhances the traceability and authenticity of the mangoes, protecting both consumer health and the reputation of authentic producers.

RESULTS

Elemental Composition of Dragon Fruit Samples: The elemental composition analysis using ICP-MS revealed significant variations in the concentration of key elements across the four sampled provinces (Table 2). Notably, Binh Thuan showed the highest concentrations for several elements, such as Ni (34.09±1.98 µg/g), Cr (86.11±4.16 µg/g), Fe (3.08±0.21µg/g), and Co (1.18±0.05 µg/g), surpassing the levels observed in the other provinces by substantial margins. For instance, the Ni content in Binh Thuan was nearly 30 times higher than in Tien Giang (1.15±0.07 µg/g) and over 130 times higher than in Long An (0.25±0.01 µg/g). Similarly, Cr in Binh Thuan was over 66 times higher than in Tien Giang (1.30±0.07 µg/g) and 319 times higher than in Long An (0.27±0.01 µg/g). These significant discrepancies suggest that environmental factors, such as soil composition and agricultural practices, may play a critical role in influencing the elemental content of dragon fruit in different regions.

In contrast, elements such as Be, Hg, Se, Cs, and Tl were consistently below the limit of detection (LOD) across all provinces. Elements like Li, Y, and Mo showed negligible variation, with concentrations either undetectable (as in Long An) or uniformly low (e.g., Li: 0.01±0.001 µg/g in Tien Giang and Binh Thuan, 0.02±0.001 µg/g in Vinh Long). While these elements contribute minimally to regional differentiation, they provide baseline data for food safety and quality monitoring.

Table 2. Elemental Composition of Dragon Fruit Samples Across Four Provinces and ANOVA means analysis(µg/g).

Element (µg/g)	Long An	Vinh Long	Tien Giang	Binh Thuan
Ni	0.25±0.01^{a}	0.47±0.03^{a}	1.15±0.07^{b}	34.09±1.98^{c}
Li	<LOD^{NS}	0.02±0.001	0.01±0.001	0.01±0.001
Be	<LOD	<LOD	<LOD	<LOD
B	0.98±0.05^{a}	18.58±0.93^{b}	2.46±0.12^{c}	2.13±0.10^{d}
Na	6.18±0.33^{a}	25.08±1.52^{b}	21.94±1.22^{c}	8.77±0.61^{d}
Mg	136.94±5.20^{a}	188.48±7.65^{b}	189.76±8.40^{b}	158.26±7.62^{c}
Al	1.64±0.09^{a}	19.16±1.01^{b}	24.64±1.92^{c}	5.39±0.29^{d}
K	1,099.4±57.2^{a}	1,812.9±67.3^{b}	1,933.0±97.8^{c}	1,734.3±91.6^{d}
Ca	10.90±0.59^{a}	12.94±0.64^{b}	29.74±1.17^{c}	19.25±1.17^{d}
Cr	0.27±0.01^{a}	0.59±0.03 ^{a}	1.30±0.07^{a}	86.11±4.16^{b}
Cu	0.52±0.03^{a}	1.19±0.06^{b}	1.27±0.05^{c}	2.07±0.10^{d}
Zn	3.78±0.11^{a}	7.48±0.41^{b}	18.39±0.83^{c}	9.10±0.51^{d}
As	<LOD^{a}	0.01±0.01^{a}	0.03±0.01^{a}	0.03±0.01^{a}
Cd	<LOD^{a}	0.01±0.01^{a}	0.01±0.01^{a}	<LOD^{a}
Hg (µg/kg)	<LOD	<LOD	<LOD	<LOD
Pb	0.05±0.01^{a}	0.60±0.04^{b}	0.96±0.04^{c}	0.44±0.02^{d}
Mn	1.69±0.10^{a}	1.83±0.12^{b}	2.44±0.11^{c}	6.16±0.25^{d}
Sc	25.56±1.70^{a}	88.46±4.98^{b}	119.72±5.24^{c}	78.31±6.43^{d}
Ti	0.06±0.01^{a}	0.29±0.02^{b}	0.35±0.01^{c}	0.19±0.01^{d}
V	<LOD^{a}	0.01±0.001^{b}	0.02±0.001^{c}	0.65±0.04^{d}
Fe	3.81±0.21^{a}	11.98±0.53^{b}	17.61±0.92^{c}	3.08±0.21^{d}
Co	0.01±0.001^{a}	0.02±0.001^{a}	0.04±0.01^{b}	1.18±0.05^{c}
Se	<LOD	<LOD	<LOD	<LOD
Rb	3.69±0.20^{a}	7.47±0.41^{b}	19.23±1.25^{c}	9.39±0.54^{d}
Sr	<LOD^{a}	0.01±0.001^{a}	0.03±0.001^{a}	0.03±0.001^{a}
Y	<LOD^{a}	0.01±0.001^{a}	0.01±0.001^{a}	0.01±0.001^{a}
Mo	<LOD^{a}	<LOD^{a}	<LOD^{a}	0.01±0.001^{a}
Ag	0.05±0.01^{a}	0.60±0.03^{b}	0.97±0.05^{c}	0.45±0.02^{d}
Sn	0.03±0.01^{a}	0.08±0.01^{b}	0.34±0.02^{c}	0.14±0.01^{d}
Sb	<LOD^{a}	0.01±0.001^{a}	0.03±0.001^{a}	0.49±0.002^{a}
Cs	<LOD	<LOD	<LOD	<LOD
Ba	0.10±0.01^{a}	0.46±0.03^{b}	0.67±0.04^{c}	0.48±0.03^{d}
Tl	<LOD	<LOD	<LOD	<LOD

Means±SD with different letters within a column differ significantly from each other at p≤0.05
LOD: limit of detection (3x standard deviation = 0.003 µg/kg); NS: Non-significant

ANOVA grouped the mean concentrations of each element, revealing that the concentrations of most elements vary significantly by region; however, Ni exhibited similar concentrations in samples from Long An and Vinh Long, while Mg in Vinh Long and Tien Giang and Co in Long An and Vinh Long did not differ significantly and were thus grouped together.

Table 3 highlights the differences in nutrient content among the provinces, with Tien Giang samples exhibiting the highest nutritional value. Vitamin C concentration in Tien Giang (30.65±0.16 mg/100 g) significantly exceeded that of Binh Thuan (23.16±0.20 mg/100 g), which recorded the lowest value. Similarly, the acidic level in Tien Giang (5.80±0.40 mg/100 g) was more than twice that of Vinh Long (2.49±0.03 mg/100 g). Total sugar content followed the same trend, with Tien Giang samples having the highest concentration (5.68±0.39 g/100 g), compared to Binh Thuan (4.29±0.60 g/100 g). These results indicate that dragon fruit from Tien Giang may possess superior organoleptic qualities and a higher nutritional profile, which could influence consumer preferences and market value.

Table 3. Nutritional Composition of Dragon Fruit Samples by Province and ANOVA means analysis.

Province	Vitamin C (mg/100g)	Acidic level (mg/100g)	Protein (g/100g)	Total sugar (g/100g)	Lipid (g/100g)
Tien Giang	30.65±0.16^{a}	5.80±0.40^{a}	1.08±0.06^{a}	5.68±0.39^{a}	1.15±0.07^{NS}
Vinh Long	29.14±0.19^{b}	2.49±0.03^{b}	1.08±0.09^{a}	4.66±0.11^{b}	1.19±0.05
Long An	24.95±0.38^{c}	2.50±0.05^{b}	1.19±0.06^{b}	4.68±0.14^{b}	1.09±0.09
Binh Thuan	23.16±0.20^{d}	2.46±0.12^{b}	1.04±0.09^{a}	4.29±0.60^{b}	1.22±0.05

Means±SD with different letters within a column differ significantly from each other at p≤0.05
NS: Non-significant

ANOVA grouped the mean nutritional composition by province, revealing significant regional variations: for vitamin C, Tien Giang (30.65 ± 0.16 mg/100g, group a) was significantly higher than Vinh Long (29.14 ± 0.19 mg/100g, group b), Long An (24.95 ± 0.38 mg/100g, group c), and Binh Thuan (23.16 ± 0.20 mg/100g, group d); the acidic level in Tien Giang (5.80 ± 0.40 mg/100g, group a) was notably greater compared to the statistically similar lower values in Vinh Long (2.49 ± 0.03 mg/100g, group b), Long An (2.50 ± 0.05 mg/100g, group b), and Binh Thuan (2.46 ± 0.12 mg/100g, group b); while protein content was statistically similar among Tien Giang (1.08 ± 0.06 g/100g, group a), Vinh Long (1.08 ± 0.09 g/100g, group a), and Binh Thuan (1.04 ± 0.09 g/100g, group a), Long An (1.19 ± 0.06 g/100g, group b) exhibited a significantly higher value; additionally, total sugar was significantly greater in Tien Giang (5.68 ± 0.39 g/100g, group a) than in the other provinces (4.66–4.68 g/100g, group b), while lipid content did not differ significantly across provinces (all group a). These small differences suggest that protein and lipid content may not be suitable indicators for differentiating dragon fruit based on geographic origin.

Multivariate Analysis and Principal Component: To ensure compatibility with the Principal Component Analysis (PCA) algorithm, undetected results (<LOD) from Table 2 were replaced with a value of zero. The PCA scatter plots in Figure 2 clearly show distinct clustering of dragon fruit samples based on their geographical origin. Samples from Binh Thuan are prominently located in the second quadrant, Long An occupies the third quadrant, while Tien Giang and Vinh Long overlap in the fourth quadrant. The variable scatter plot highlights the contribution of individual variables to the PCA model, with variables closer to the origin contributing less. Elements such as Be, Hg, Se, Cs, and Tl, which were below detection limits, had no significant impact on the differentiation of dragon fruit samples. Similarly, protein, total sugar, lipid content, and boron (B) displayed minimal contribution when compared to Vitamin C, acidic level, and elemental compositions.

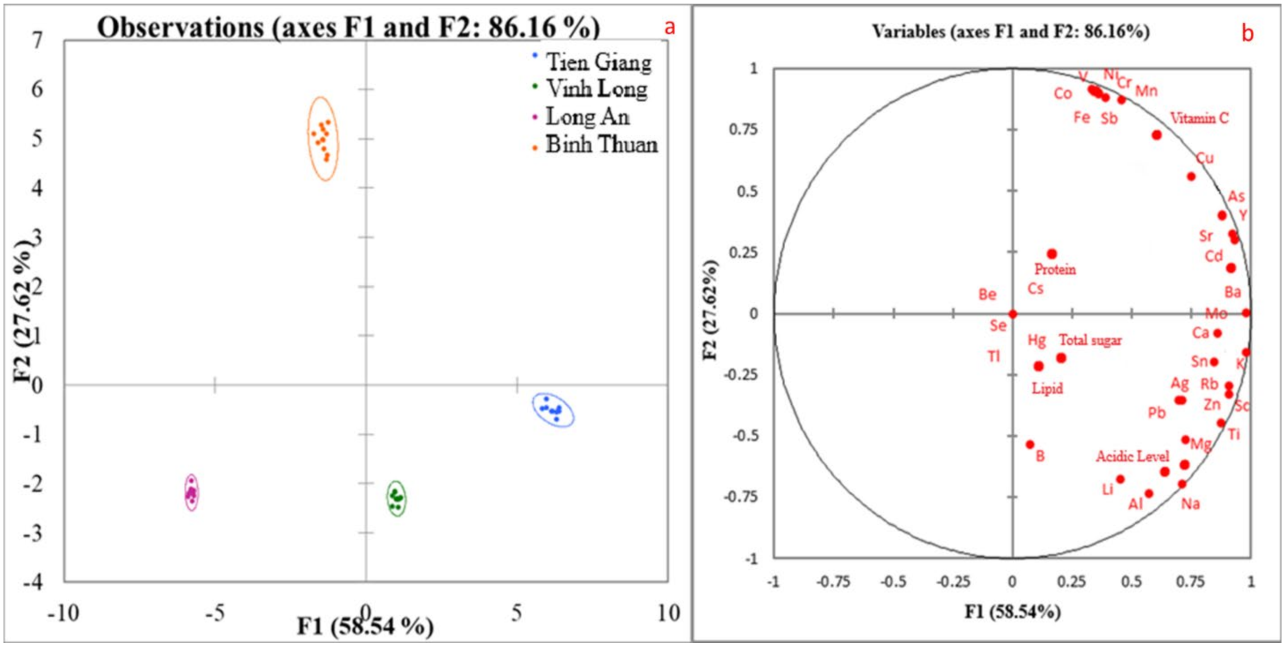

Fig 2. PCA Scatter Plot Illustrating Geographical Differentiation of Dragon Fruit Samples (a: scatter plot differentiation of sample regions, b: the influence of variables on the PCA algorithm)

PCA proved to be an effective tool for reducing the complexity of the dataset, simplifying the analysis of the multivariate data generated by high-throughput techniques like ICP-MS. This dimensional reduction enabled a clearer interpretation of regional distinctions among the samples. The clustering pattern suggests that the Tien Giang samples exhibited a tighter distribution with minimal variability, possibly due to smaller cultivation areas and consistent environmental conditions. Conversely, the samples from Binh Thuan were strongly differentiated, reflecting unique soil properties and potentially diverse cultivation practices. The successful application of PCA in this study demonstrates its potential as a robust approach for geographic traceability and quality assessment of agricultural products. By integrating elemental and nutritional data into comprehensive databases, this method offers enhanced reliability for product authentication, quality control, and supply chain management.

DISCUSSION

This study demonstrated that the geographical origin of Vietnamese dragon fruit (*Hylocereus* spp.) can be reliably distinguished through a combination of elemental composition analysis by ICP-MS and multivariate statistical approaches such as Principal Component Analysis (PCA). The analysis revealed significant interregional variations in both trace elements and select nutritional parameters. In particular, samples from Binh Thuan exhibited strikingly high levels of Ni, Cr, and Fe, findings that likely reflect unique soil mineralogy and semi-arid climatic conditions (Feng *et al*., 2024). In contrast, other provinces—Tien Giang, Vinh Long, and Long An—displayed lower levels of these elements, enabling clear differentiation based on geographic provenance (Yan Wang, 2021).

The differentiation observed in trace element profiles—especially for elements such as Mn, Y, Ba, K, Ti, Na, As, and Cd— demonstrates the possibility of using elemental fingerprints as intrinsic markers of regionality (Bui *et al*., 2024). These fingerprints are largely governed by environmental factors, including soil pH, mineral content, and water quality. For instance, the semi-arid conditions prevalent in Binh Thuan may foster the accumulation of specific heavy metals through reduced leaching and increased soil retention (Feng*et al*., 2024). Moreover, the higher vitamin C content and acidity in samples from regions like Tien Giang suggest that climatic stressors, such as variations in light intensity and temperature, could enhance the synthesis of metabolites that play a protective role under environmental stress (Mitra, 2024).

Our findings are consistent with earlier studies where ICP-MS combined with PCA has successfully differentiated other agricultural products based on regional characteristics. Previous research on rice (Yan Wang, 2021) and processed foods like sausages (Bui *et al*., 2024) supports the view that trace elemental profiles are significant indicators of geographical origin. In the present study, similar behavior was observed in the macronutrient data (protein, lipid, and total sugar) across regions, suggesting that these components are more strongly controlled by the intrinsic biological nature of the fruit rather than by environmental conditions. This relative invariance reinforces the idea that trace elements and certain nutraceutical markers (such as vitamin C and acidity) are more effective discriminators for product authentication and quality control (Bui *et al.*, 2024).

Furthermore, the consistently low or undetectable levels of certain toxic elements (e.g., beryllium, mercury, selenium, cesium, and thallium) in all samples provide additional reassurance regarding the food safety of Vietnamese dragon fruit, thus meeting international standards (Vietnam General Department of Standards Metrology and Quality, 2015). These quality indicators are essential for maintaining consumer confidence and supporting the fruit's marketability in both domestic and international markets.

It is important to acknowledge that while the study has provided robust evidence of regional distinctions, some limitations remain. The sample size (20 per province) may restrict the generalizability of the results across broader cultivation conditions. Additionally, although ICP-MS and PCA offer powerful insights, integrating complementary analytical techniques, such as Fourier Transform Infrared (FTIR) or Nuclear Magnetic Resonance (NMR) spectroscopy, could further refine the characterization of bioactive compounds and volatile organic compounds that influence flavor and shelf-life (Al-Mekhlafi *et al.*, 2021). Emerging technologies such as blockchain integration into supply chain management could further enhance transparency and consumer trust (Yasmin *et al.*, 2024).

Conclusion: Principal Component Analysis (PCA) effectively distinguishes the geographic origins of dragon fruit by integrating inductively coupled plasma mass spectrometry (ICP-MS) data. Key elements such as Mn, Y, Ba, K, Ti, Na, As, and Cd are crucial for regional classification, while variations in acidity and Vitamin C concentration further enhance differentiation. In contrast, protein, total sugar, and lipid levels have minimal impact due to their low variability. This study highlights the significance of PCA in managing complex datasets and emphasizes the importance of advanced statistical methodologies for food quality control, traceability, and agricultural product classification.

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REFERENCES

Al-Mekhlafi, N.A., A. Mediani, N.H. Ismail, F. Abas, T. Dymerski, M. Lubinska-Szczygeł, S. Vearasilp and S. Gorinstein (2021). Metabolomic and antioxidant properties of different varieties and origins of Dragon fruit. Microchem. J. 160: 105687. DOI: https://doi.org/10.1016/j.microc.2020.105687.

AOAC International (2019). Official Methods of Analysis of the Association of Official Analytical Chemists: Official Methods of Analysis of AOAC International. AOAC, Washington DC.

Arivalagan, M., G. Karunakaran, T.K. Roy, M. Dinsha, B.C. Sindhu, V.M. Shilpashree, G.C. Satisha and K.S. Shivashankara (2021). Biochemical and nutritional characterization of dragon fruit (*Hylocereus* species). Food Chem. 353: 129426. DOI: https://doi.org/10.1016/j.foodchem.2021.129426.

Aubert, C. and G. Chalot (2018). Chemical composition, bioactive compounds, and volatiles of six table grape varieties (*Vitis vinifera* L.). Food Chem. 240: 524-533. DOI: 10.1016/j.foodchem.2017.07.152.

Bui, Q. M., Q.T. Nguyen, T.T. Nguyen, H.M. Nguyen, T.T. Phung, V.A. Le, N.M. Truong, T.V. Mac, T.D. Nguyen, L.T.A. Hoang, H.M.D. Tran, V. N. Le and MD. Nguyen (2024). Multivariate statistical analysis for the classification of sausages based on physicochemical attributes, using attenuated total reflectance-fourier transform infrared (ATR-FTIR) and inductively coupled plasma-mass spectrometry (ICP-MS). J. Anal. Methods Chem. 2024(1): 1329212. DOI: https://doi.org/10.1155/2024/1329212.

CEM Corporation Method Note, CEM Corporation.

Chatterjee, D., S. Mansuri, N. Poonia, P. Kesharwani, V. Lather and D. Pandita (2024). Therapeutic potential of various functional components presents within dragon fruit: A review. Hybrid Adv. 6: 100185. DOI: https://doi.org/10.1016/j.hybadv.2024.100185.

Ellinger, S., A. Gordon, M. Kürten, E. Jungfer, B. F. Zimmermann, B. Zur, J. Ellinger, F. Marx and P. Stehle (2012). Bolus consumption of a specifically designed fruit juice rich in anthocyanins and ascorbic acid did not influence markers of antioxidative defense in healthy humans. J. Agric. Food Chem. 60(45): 11292-11300. DOI: 10.1021/jf300719t.

Feng, F., J. Sun, L. Ding, W. Su, Y. Zhou, Z. Tao, W. Shang and Y. Li (2024). Migration patterns of heavy metals from solid waste stockpile soils by native plants for ecological restoration in arid and semi-arid regions of Northwest China. Environ. Res. 251: 118607.

Hung, H. (2023). Increasing competitiveness for Dragon fruit exports. People.

Kaufmann, A. (2020). Multivariate statistics as a classification tool in the food laboratory. J. AOAC Int. 80(3): 665-675. DOI: 10.1093/jaoac/80.3.665.

Mitra, S. (2024). Postharvest Management. Dragon Fruit: Botany, Production and Uses, CABI GB**:** 236-254.

Nancy Jung Chen, R.E.P. (2019). Overall dragon fruit production and global marketing.

Nguyen-Quang, T., M. Bui-Quang, T. Pham-Van, N. Le-Van, K. Nguyen-Hoang, D. Nguyen-Minh, T. Phung-Thi, A. Le-Viet, D. Tran-Ha Minh, D. Nguyen-Tien, T.A. Hoang-Le and M. Truong-Ngoc (2023). Classification of Vietnamese cashew nut (*Anacardium occidentale* L.) products using statistical algorithms based on ICP/MS aata: A study of food categorization. J. Anal. Methods Chem. 2023(1): 1465773. DOI: https://doi.org/10.1155/2023/1465773.

Nguyen-Quang, T., G. Do-Hoang and M. Truong-Ngoc (2021). Multielement analysis of pakchoi (*Brassica rapa* L. ssp. chinensis) by ICP-MS and their classification according to different small geographical origins. J. Anal. Methods Chem. 2021: 8860852. DOI: 10.1155/2021/8860852.

Nishikito, D.F., A.C.A. Borges, L.F. Laurindo, A. Otoboni, R. Direito, R.A. Goulart, C.C.T. Nicolau, A.M.R. Fiorini, R.V. Sinatora and S.M. Barbalho (2023). Anti-inflammatory, antioxidant and other health effects of dragon fruit and potential delivery systems for its bioactive compounds. Pharmaceutics 15(1). DOI: 10.3390/pharmaceutics15010159.

Owens, P.N., W.H. Blake, L. Gaspar, D. Gateuille, A. Koiter, D.A. Lobb, E.L. Petticrew, D. Reiffarth, H.G. Smith and J. Woodward (2016). Fingerprinting and tracing the sources of soils and sediments: Earth and ocean science, geoarchaeological, forensic, and human health applications. Earth-Sci. Rev. 162: 1-23.

Pietta, P.G. (2000). Flavonoids as antioxidants. J. Nat. Prod. 63(7): 1035-1042. DOI: 10.1021/np9904509.

Pojer, E., F. Mattivi, D. Johnson and C.S. Stockley (2013). The case for anthocyanin consumption to promote human health: A review. Compr. Rev. Food Sci. Food Saf. 12(5): 483-508. DOI: 10.1111/1541-4337.12024.

Poulose, S.M., D.R. Fisher, J. Larson, D.F. Bielinski, A.M. Rimando, A.N. Carey, A.G. Schauss and B. Shukitt-Hale (2012). Anthocyanin-rich açai (*Euterpe oleracea* Mart.) fruit pulp fractions attenuate inflammatory stress signaling in mouse brain BV-2 microglial cells. J. Agric. Food Chem. 60(4): 1084-1093. DOI: 10.1021/jf203989k.

Rengel, Z. (2015). Availability of Mn, Zn and Fe in the rhizosphere. J.Soil Sci.Plant Nut. 15(2): 397-409.

Richter, B., S. Gurk, D. Wagner, M. Bockmayr and M. Fischer (2019). Food authentication: Multi-elemental analysis of white asparagus for provenance discrimination. Food Chem. 286: 475-482. DOI: https://doi.org/10.1016/j.foodchem.2019.01.105.

Sáez-Plaza, P., T. Michałowski, M.J. Navas, A.G. Asuero and S. Wybraniec (2013). An overview of the kjeldahl method of nitrogen determination. Part I. Early history, chemistry of the procedure, and titrimetric finish. Cri. Rev. Anal. Chem. 43(4): 178-223. DOI: 10.1080/10408347.2012.751786.

Templ, M. and B. Templ (2021). Statistical analysis of chemical element compositions in food science: problems and possibilities. Molecules 26(19): 5752.

UNDP (2023). Journey towards sustainable development of Vietnamese dragon fruit.

Vietnam General Department of Standards Metrology and Quality (2007). Fruit and vegetable products – determination of titratable acidity. TCVN 5483 - 2007. Vietnam, Ministry of Science and Technology of Vietnam. TCVN 5483:2007.

Vietnam General Department of Standards Metrology and Quality (2015). Food additive - Ascorbic acid. TCVN 11168 : 2015. Vietnam, Ministry of Science and Technology of Vietnam. TCVN 11168 : 2015.

Vietnam General Department of Standards Metrology and Quality (1988). Canned foods - Determination of total sugar, reducing sugar and starch content. M. o. S. a. T. o. Vietnam. Vietnam, Ministry of Science and Technology of Vietnam. TCVN 4594:1988.

Yan Wang, X.Y., Linan Liu, Junmei Ma, Sufang Fan, Yan Zhang and Qiang Li (2021). Multielement principal component analysis and origin traceability of rice based on ICP-MS/MS. J. Food Qual. 2021: 12. DOI: https://doi.org/10.1155/2021/5536241.

Yasmin, A., M.J. Sumi, K. Akter, R.H.M. Rabbi, H.S. Almoallim, M.J. Ansari, A. Hossain and S. Imran (2024). Comparative analysis of nutrient composition and antioxidant activity in three dragon fruit cultivars. PeerJ 12: e17719. DOI: 10.7717/peerj.17719.