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Mineral composition of Azorean bananas (*Musa acuminata*) across volcanic soils and implications for micronutrient intake

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ABSTRACT

The Azores archipelago has young, nutrient-rich volcanic soils that support mineral accumulation in crops. This study assessed the elemental composition of unripe Azorean bananas (*Musa acuminata* Colla) cultivated across six volcanic complexes on São Miguel Island (Sete Cidades, Picos, Fogo, Furnas, Povoação, and Nordeste) and evaluated their potential contribution to mitigating micronutrient deficiencies. Banana samples were collected from representative orchards, morphologically characterized, oven-dried, homogenized, and analyzed for K, Mg, Co, Cu, Fe, Mn, Se, and Zn using inductively coupled plasma mass spectrometry (ICP-MS). Mineral concentrations varied significantly among volcanic complexes. Nordeste bananas showed the highest concentrations of Mg, K, and Zn; Furnas had elevated Mn and Co; Fogo and Nordeste had the highest Fe; and Sete Cidades had the lowest concentrations overall. Compared with bananas from other regions, Azorean bananas were particularly rich in K, Mn, and Zn, while Mg concentrations were comparable. A 100 g portion can meaningfully contribute to daily Mg and K intake, although Mn intake in infants may require moderation. This study provides region-specific data that strengthens food composition databases and supports more accurate dietary exposure assessments, underscoring the importance of site-specific research for public health and sustainable agriculture.

1. Introduction

The "Banana dos Açores" (Protected Geographical Indication, PGI/IGP) is a distinctive banana produced in the Autonomous Region of the Azores, Portugal. The PGI designation formally recognizes fruit of *Musa acuminata* Colla, Dwarf Cavendish' (locally known as Pequena-anã), cultivated exclusively within the Azorean archipelago under regulated production conditions. The product may be marketed fresh or processed (e.g., flour, jams, dehydrated slices, fried chips, or dried fruit) (DGADR, 2025; Governo dos Açores, 2025). Beyond its economic relevance, banana cultivation forms part of the Azorean cultural landscape and represents the most extensive fruit crop on São Miguel, the largest island of the Azorean archipelago (102.34 ha) (SREA - Governo dos Açores, 2019). The distinctive characteristics of the "Banana dos Açores" are closely associated with the edaphoclimatic conditions of the archipelago (DGADR, 2025b). The Azores experience a temperate maritime climate marked by mild temperatures, low annual thermal amplitudes, high relative humidity, evenly distributed precipitation, absence of frost (Silva et al., 2025; Raposeiro et al., 2024), and soils, from volcanic origin, that are naturally enriched with essential elements (Doelsch et al., 2006; Marques et al., 2017, 2019; Aiuppa et al., 2000; Parelho et al., 2014).

São Miguel Island, the largest and most agriculturally productive island in the archipelago, is of particular importance. The geological diversity of São Miguel is reflected in the type of soil, which can be divided into two main groups according to the geochemical composition of the parent rocks (basaltic and trachytic) (Linhares et al., 2019; 2021). These volcanic soils exhibit distinctive geochemical properties, often characterized by elevated concentrations of essential elements such as iron (Fe), manganese (Mn), cobalt (Co), and zinc (Zn) (Linhares et al., 2019; 2021). Despite certain physical and chemical constraints, they are generally well-drained, rich in organic matter, and possess significant natural nutrient reserves (Parelho, 2014). The combination of mild Atlantic climatic conditions and active nutrient cycling enhances soil

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biological activity, making Azorean soils valuable for sustainable agriculture and relevant for environmental and public health research (Amaral et al., 2006).

Volcanic soils enriched in essential and trace elements may influence the mineral composition of crops cultivated in them. Adequate dietary intake of essential minerals is fundamental for normal physiological function, whereas deficiencies remain a major global public health concern (English et al., 2025). For example, Fe deficiency is the leading cause of nutritional anemia (Kolarš et al., 2025; Miller, 2013), Zn deficiency impairs immune function (Schulz and Rink, 2025; Male et al., 2024), selenium (Se) deficiency compromises antioxidant defense, and inadequate vitamin B12 availability (Li et al., 2024; Mu et al., 2023), for which Co is an essential component, is associated with hematological disorders (Agrawal et al., 2024). Collectively, dietary mineral deficiencies affect approximately two billion people worldwide, a condition known as hidden hunger (WHO, 2006; Singh et al., 2020; Yilmaz & Yilmaz, 2025). Hidden hunger is defined as a chronic deficiency of essential vitamins and minerals that may not immediately manifest as overt starvation but results in reduced energy levels, impaired cognitive development, weakened immunity, and increased susceptibility to disease (Yilmaz and Yilmaz, 2025; Arora and Mishra, 2025; Lowe, 2021). Children under five years of age are especially susceptible, as insufficient micronutrient intake contributes to stunting, wasting, impaired cognitive development, and long-term reductions in learning capacity and productivity (Elegbeleye et al., 2025; Biesalski, 2014).

Bananas are widely recognized for their high potassium (K) content, which supports muscle function, nerve signaling, and blood pressure regulation (Kumari et al., 2023). They also provide magnesium (Mg), dietary fiber, natural sugars, and bioactive compounds such as tryptophan, a precursor of serotonin associated with mood regulation (Kumar et al., 2012). Because bananas are consumed worldwide by all age groups, including infants and children, even moderate differences in mineral composition resulting from local geochemical conditions may have meaningful nutritional implications. As one of the most important locally produced fruits, *Banana dos Açores* contributes to regional food availability and has the potential to represent a sustainable source of essential dietary minerals, reinforcing its relevance within local food and nutrition systems. Accurate, region-specific food composition data are essential for nutritional surveillance, dietary exposure assessment, and the development of evidence-based dietary recommendations. However, food composition databases generally do not account for geographical variability in mineral composition resulting from differences in soil geochemistry. Consequently, characterizing the mineral composition of foods produced under distinct geological conditions is important to improve the accuracy of dietary intake assessments and to better understand their nutritional value. Despite the economic and nutritional importance of “Banana dos Açores”, little information is available regarding its mineral composition or the extent to which the geochemical variability of São Miguel Island soils influences the accumulation of essential dietary minerals in the fruit. Consequently, its potential contribution to human dietary mineral intake remains poorly characterized.

Among the elements quantified by the analytical laboratory, the present study focused on eight essential dietary minerals (K, Mg, Co, Cu, Fe, Mn, Se, and Zn). These elements were selected because they are essential for human nutrition, have established Dietary Reference Values (DRVs) defined by the European Food Safety Authority (EFSA), and are widely recognized for their physiological importance, with several being associated with nutritional deficiencies of public health concern. Furthermore, their concentrations were determined in both soil and banana samples, enabling the assessment of soil-to-plant transfer and their potential dietary contribution.

However, nutrient concentrations in crops can vary according to soil composition, geochemical background, and local environmental conditions. On São Miguel Island, six distinct volcanic complexes are recognized, each with different geological histories and lithological characteristics, which may influence soil elemental composition and, consequently, plant mineral uptake. Therefore, the objectives of this study were to:(i) characterize the concentrations of major dietary minerals (K and Mg) and trace dietary minerals (Co, Cu, Fe, Mn, Se and Zn) in unripe *Musa acuminata* Colla cultivated across the six volcanic complexes of São Miguel Island; (ii) evaluate the influence of geological setting on the spatial variability of these minerals; (iii) assess soil-to-plant transfer through Transfer Factors; and (iv) estimate the potential contribution of "Banana dos Açores" to human dietary mineral intake using EFSA Dietary Reference Values.

2. Material and methods

2.1. Study area

São Miguel is the largest (744 km^2) and most populated (≈137,300 inhabitants) island of the Azores archipelago, located approximately 1300 km west of mainland Portugal (Fig. 1a, b). The island comprises seven volcanic systems, including three active central volcanoes (Sete Cidades, Fogo, and Furnas), two active fissure systems (Picos and Congro), and two older inactive systems (Povoação and Nordeste) that have not erupted for more than 10,000 years (Pacheco et al., 2013; Gaspar et al., 2015). In the present study, six volcanic complexes were considered, as the Congro fissure system was grouped with Furnas due to their close spatial association, shared eruptive history, and similar trachytic lithology and soil-forming processes.

Volcanic activity over the last 5000 years has been dominated by explosive trachytic eruptions from central volcanoes, producing extensive pyroclastic deposits, whereas the Picos and Congro fissure systems are characterized by basaltic lava flows and scoria cones. This geological diversity results in contrasting soil types with distinct mineralogical compositions and nutrient availability. Basaltic soils, derived from mafic parent materials rich in Fe and Mg, are generally darker, more fertile, and enriched in nutrients such as calcium (Ca), K, and Mg, but may also contain elevated concentrations of elements such as chromium (Cr) and nickel (Ni) (Alloway, 2013; Tucker, 2010). In contrast, trachytic soils originate from silica-rich felsic rocks and tend to be lighter, more acidic, and less fertile, with potentially higher concentrations of elements such as arsenic (As) and lead (Pb) (Kabata-Pendias, 2011). On São Miguel, the Picos and Nordeste complexes are predominantly basaltic, whereas Sete Cidades, Fogo, Furnas/Congro, and Povoação are mainly trachytic (Nunes et al., 2020).

2.2. Topsoil and banana sampling

Topsoil and banana samples were collected from the same orchard sites to allow direct comparison between topsoil elemental composition and banana mineral content (Fig. 1b). At each location, topsoil sampling was conducted following the Geochemical Mapping of Agricultural and Grazing Land Soils (GEMAS) field protocol (GEMAS, 2008). Five sampling areas were defined at equal distances across each orchard. Within each area, a composite soil sample was obtained from five subsites arranged in a square pattern, with four sampling points at the vertices and one at the center. Surface topsoil cores (0–10 cm depth) were collected after removal of surface litter using a manual spiral auger. Soil samples were separated into two subsamples: one was used to determine the soil physicochemical properties and the other was sieved down to 2 mm and oven-dried (at 60 °C until constant weight) prior to chemical analysis.

Unripe bananas (*Musa acuminata* Colla) were collected from the same orchards with the plantation’s areas ranging from 0.05 to 2.26 ha. To ensure representative sampling, nine bananas were harvested from different plants in each orchard, comprising three fruits from the northern sector, three from the southern sector, and three from the central area of each plantation. Immediately after collecting, bananas were transported to the laboratory, weighed with and without peel, and morphologically characterized. Fruits were sliced transversely (2–3 mm

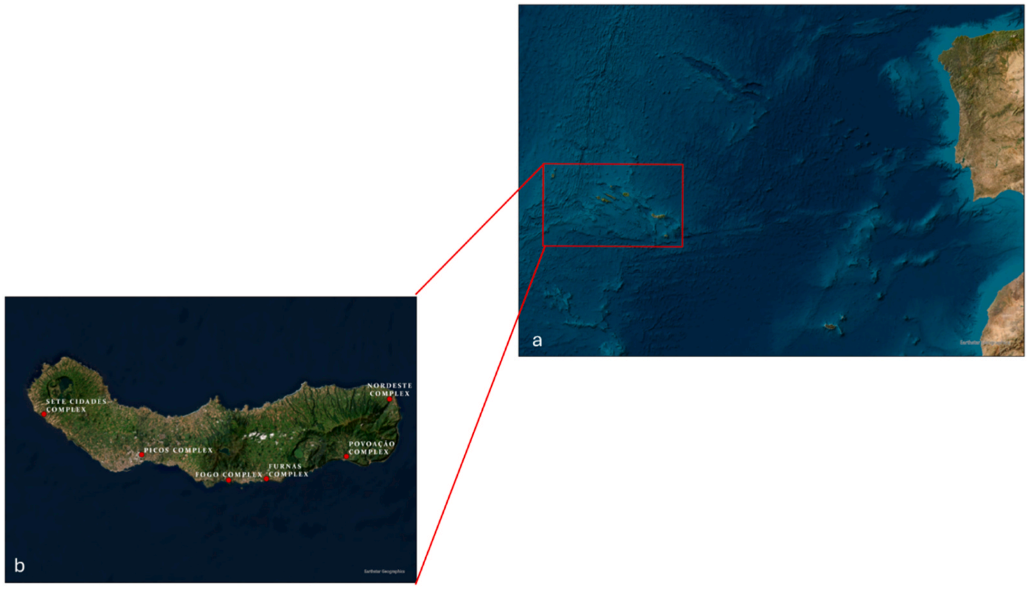

Fig. 1. (a) Location map of the Azores archipelago and (b) Sao Miguel Island. The places represented on the map correspond to the six studied sites (Sete Cidades, Picos, Fogo, Furnas, Povoação and Nordeste).

thickness) using a ceramic knife to obtain homogeneous subsamples. The slices were oven-dried at 80 °C until constant weight (approximately 80 h, to ensure no moisture was still left), ground to a fine powder using a ceramic mortar to minimize contamination and stored in airtight containers under dry conditions until analysis. After the drying process, the bananas were weighed again to determine the dry weight. Moisture content was determined gravimetrically from fresh and dry weights. Bananas were harvested at the mature green stage, corresponding to the standard commercial harvest stage for *Banana dos Açores*. Sampling fruit at the same physiological maturity ensured consistency among sites and minimized variability associated with ripening.

During farm visits, a structured questionnaire was administered to producers to document fertilization practices, pesticide application, and general agricultural management. The questionnaire was used to provide contextual information on orchard management practices and to support the interpretation of the mineral composition results; it was not intended for quantitative statistical analyses. The questionnaire template is provided as Supplementary Questionnaire S1.

2.3. *Elemental analysis of soil and banana samples*

Elemental analyses of topsoil and banana samples were performed by Activation Laboratories Ltd. (Ontario, Canada) using validated digestion and quality-control procedures appropriate for environmental and food matrices.

Elemental analyses of topsoil and banana samples were performed by Activation Laboratories Ltd. (Ontario, Canada) using validated analytical procedures appropriate for environmental and food matrices.

Topsoil samples were analyzed using the UT-1M analytical package, comprising aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP-MS). Quality control included procedural blanks, duplicate samples, and multiple geological certified reference materials (OREAS 903, 77b, 72b, 683, 681, 247, 601c, 931, 750, 45 h, 625, and 611b), with measured values in good agreement with the certified values. Although 65 elements were determined in the analytical package, the present study focused on eight essential dietary minerals (K, Mg, Co, Cu, Fe, Mn, Se, and Zn). These elements were selected because they are essential for human nutrition, have established EFSA Dietary Reference Values (DRVs), and were quantified in both soil and banana samples, allowing assessment of soil-to-plant transfer and potential dietary contribution.

Banana samples (250 ± 25 mg) were digested by microwave-assisted acid digestion using nitric acid and hydrogen peroxide and analyzed using Agilent 7850 ICP-MS following the laboratory's QOP Hydrogeo Rev. 6.6 procedure. Analytical quality control included method blanks, reagent blanks, duplicate analyses, and calibration verification using a certified multi-element ICP-MS standard solution (IV-STOCK-1643).

For statistical calculations, concentrations below the lower detection limit were considered equal to that limit. Further details regarding analytical methods and quality-assurance procedures are available from Activation Laboratories Ltd (https://actlabs.com/).

2.4. *Transfer factor calculation*

The transfer of elements from topsoil to dried banana fruit was evaluated using the Transfer Factor (TF), which is widely applied to assess the transfer of elements from soil to plants and to estimate potential human exposure through food consumption (Cui et al., 2004; Kabata-Pendias, 2011; Mirecki et al., 2015). The TF was calculated as the ratio between the concentration of each element in banana fruit and its corresponding concentration in topsoil from the same sampling site according to the following equation:

$$TF = \frac{C_{\text{banana}}}{C_{\text{soil}}}$$

where C_{banana} represents the concentration of the element in banana fruit (mg/kg) and C_{soil} represents the concentration of the element in topsoil (mg/kg).

TF values greater than 1 indicate preferential accumulation in plant tissues, whereas values lower than 1 indicate limited transfer from soil to plant (Kabata-Pendias, 2011).

2.5. *Dietary intake assessment*

The nutritional contribution of bananas to mineral intake was evaluated by comparing measured mineral concentrations with Dietary Reference Values (DRV) established by the European Food Safety Authority, 2017). DRVs for K, Mg, Co, Cu, Fe, Mn, Se, and Zn were selected according to age group and physiological condition, including infants, children, adolescents, adults, and pregnant and lactating women.

Elemental concentrations were standardized to a 100 g edible portion to facilitate comparison with international food composition databases and published nutritional studies, where nutrient composition is conventionally reported per 100 g of edible food (FAO/INFOODS, 2012). The percentage contribution of a 100 g portion to the DRV for each mineral was calculated for each age group using the following equation:

$$\text{Contribution to DRV }(\%) = \frac{\text{Mineral content in 100 g of banana}}{\text{DRV}} \times 100$$

Separate dietary contribution assessments were performed for bananas produced in the Fogo, Furnas, and Nordeste volcanic complexes due to their higher production relevance and/or distinctive mineral profiles. Because actual banana consumption varies according to age and dietary habits, additional interpretation for infants was performed using recommended serving sizes (15–30 g) based on the Portuguese National Food Guidelines (Direção-Geral da Saúde, 2019). This approach enabled comparison of the nutritional relevance of bananas across age groups and production areas, as well as identification of minerals with potentially beneficial or excessive dietary contributions.

2.6. Statistical analysis

The normality of the data was assessed prior to statistical analysis. Physicochemical parameters of the topsoils, including pH and electrical conductivity (EC), satisfied the assumptions of normality and were analyzed using one-way analysis of variance (1-way ANOVA), followed by Tukey's post hoc test for pairwise comparisons.

In contrast, elemental concentrations exhibited mixed distribution patterns across elements and matrices, with some variables not meeting normality assumptions in either topsoils or bananas. Non-parametric statistical tests were applied for non-normal data, using the Mann–Whitney *U* test for pairwise comparisons and the Kruskal–Wallis test for multiple group comparisons; when data meet the assumptions of normality, they were analyzed using 1-way ANOVA, followed by Tukey's post hoc test for pairwise comparisons.

Statistical significance was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 29.0 for Windows.

3. Results

3.1. Soil characterization

The physicochemical properties and elemental concentrations of topsoils from the six study sites are presented in Table 1. Soil pH values did not differ significantly among sites ($p = 0.331$). In contrast, electrical conductivity (EC) showed significant spatial variability ($p < 0.001$), with the highest values observed in Furnas (137.1 ± 4.98 μS/cm), and the lowest values recorded in Povoação (59.0 ± 5.51 μS/cm).

Among the analyzed elements, K and Se did not show significant differences among the study sites ($p = 0.271$ and $p = 0.421$, respectively). In contrast, all remaining elements exhibited significant spatial variability. Among the analyzed elements, Fe concentrations were highest in Nordeste and lowest in Sete Cidades, whereas Mg concentrations were highest in Picos and lowest in Povoação and Furnas. The highest Co concentrations in topsoil were recorded in Nordeste, whereas the lowest values occurred in Povoação and Furnas. Topsoil Cu concentrations were highest in Picos and Nordeste and lowest in Povoação. The Mn concentrations peaked in Nordeste and Picos, although values were significantly higher in Nordeste, and were lowest in Sete Cidades. Higher Zn concentrations were observed in Picos and Nordeste, although they were significantly higher in Nordeste, whereas the lowest concentrations were found in Sete Cidades.

3.2. Banana characterization

The morphological characteristics, fresh weight, dry weight, and moisture content of the banana samples collected from the six volcanic complexes are presented in Supplementary Table S2. Although some variation in fruit characteristics was observed among sampling sites, all samples corresponded to unripe *Musa acuminata* Colla collected and processed under the same protocol. Mineral concentrations in banana tissues were subsequently determined on a dry weight basis. The mineral concentrations in *Musa acuminata* Colla varied among the six study sites (Table 2). No significant differences were observed for K, Co, Se, and Zn among sampling locations ($p > 0.05$). Still, K was the most abundant element in banana fruit across all sites, with mean concentrations ranging from 15108 ± 277.3 mg/kg′dry weight in Nordeste to 16526 ± 279.6 mg/kg′dry weight in Furnas.

In contrast, Fe, Mg, Cu and Mn exhibited significant site-dependent variability. Significant differences in Fe concentrations were observed among sites ($p = 0.022$), with the highest values observed in Furnas (13.4 ± 0.12 mg/kg′dry weigh) and Sete Cidades (13.0 ± 0.96 mg/kg′dry weigh), and the lowest in Povoação (9.3 ± 0.15 mg/kg′dry weigh). Differences in Mg concentrations were significant, with higher values observed with significantly higher at all sites compared to Sete Cidades ($p < 0.001$), reaching maximum values in Nordeste (1401.33 ± 32.20 mg/kg′dry weigh).

Significant variation was also observed for Cu concentrations ($p = 0.007$), with higher levels recorded in Picos (3.37 ± 0.12 mg/kg′dry weigh), Povoação (3.27 ± 0.21 mg/kg′dry weigh), and Furnas (3.13 ± 0.09 mg/kg′dry weigh), and the lowest concentration observed in Sete Cidades (2.10 ± 0.20 mg/kg′dry weigh). Pronounced spatial variability was observed for Mn ($p < 0.001$), with the highest concentrations detected in Furnas (11.4 ± 0.81 mg/kg′dry weigh) and Fogo

Table 1
Soil physicochemical properties for the six sampling sites in São Miguel Island (mean ± SE).

	Sete cidades	Picos	Fogo	Furnas	Povoação	Nordeste	*p*-value[a]
pH	6.22 ± 0.12	6.04 ± 0.15	6.04 ± 0.05	5.83 ± 0.10	6.03 ± 0.13	6.1 ± 0.09	0.331
EC (μS/cm)	119.0 ± 11.40^{a}	63.8 ± 1.67^{b}	66.3 ± 7.80^{b}	137.1 ± 4.98^{c}	59.0 ± 5.51^{b}	98.7 ± 9.39^{d}	< 0.001
Macroelements (%)							
Fe	0.12 ± 0.10^{a}	2.65 ± 0.17^{b}	2.01 ± 0.26^{b,c}	1.33 ± 0.23^{c}	1.20 ± 0.13^{c}	4.26 ± 0.83^{d}	< 0.001
K	0.26 ± 0.03	0.23 ± 0.03	0.20 ± 0.04	0.24 ± 0.03	0.23 ± 0.04	0.14 ± 0.02	0.271
Mg	0.15 ± 0.01^{a}	0.34 ± 0.05^{b}	0.20 ± 0,04^{c}	0.09 ± 0,0006^{d}	0,09 ± 0,02^{d}	0.20 ± 0.02^{e}	< 0.001
Microelements (ppm)							
Co	2.88 ± 0.28^{a}	9.47 ± 1.19^{b}	4.56 ± 1.23^{c}	1.87 ± 0.38^{d}	1.46 ± 0.26^{d}	17.3 ± 4.42^{e}	< 0.001
Cu	6.46 ± 1.49^{a}	31.90 ± 5.55^{b}	13.87 ± 5.11^{b,c,d}	7.57 ± 0.93^{c}	4.14 ± 0.98^{d}	23.2 ± 4.39^{e}	< 0.001
Mn	690.3 ± 82.50^{a}	1495 ± 72.01^{b}	1050 ± 113.90^{c}	819.29 ± 221.28^{c}	877.2 ± 123.54^{c}	1752.5 ± 163.01^{d}	< 0.001
Se	2.89 ± 0.61	2.0 ± 0.00	3.4 ± 1.40	2.71 ± 0.57	2.20 ± 0.20	3.75 ± 1.18	0.421
Zn	72.94 ± 9.73^{a}	146.8 ± 14.60^{b}	94.7 ± 14.64^{c,d}	89.69 ± 10.51^{c}	77.24 ± 12.67^{c}	142.5 ± 9.84^{d}	0.002

[a] *p*-value: One-way ANOVA followed by Tukey's test was used for normally distributed variables, while the Mann–Whitney U test was used for non-normal variables. For pH, EC and each element, different letters indicate significant differences among sites.

Table 2
Element concentrations (mean ± SE) in *Musa acuminata* Colla of dietary minerals (Cu, Fe, K, Mg, Mn and Zn in mg/kg/DW and Co and Se in μg/kg/ DW) from six studied sites in São Miguel Island.

	Sete cidades	Picos	Fogo	Furnas	Povoação	Nordeste	*p*-value[a]
Dietary minerals							
Cu	2.10 ± 0.20[a]	3.37 ± 0.12[b]	2.87 ± 0.39[ac]	3.13 ± 0.09[bc]	3.27 ± 0.21[b]	2.40 ± 0.10[ac]	0.007
Fe	13.0 ± 0.96[ab]	10.9 ± 1.21[bc]	12.8 ± 0.98[bc]	13.4 ± 0.12[a]	9.3 ± 0.15[bc]	12.0 ± 0.41[bc]	0.022
K	15701 ± 814.8	16306 ± 250.5	15867 ± 444.8	16526 ± 279.6	16392 ± 253.3	15108 ± 277.3	0.262
Mg	1051.67 ± 32.79[a]	1298.33 ± 250.55[b]	1300.67 ± 34.20[b]	1282.33 ± 20.41[b]	1327.67 ± 46.70[b]	1401.33 ± 32.20[b]	< 0.001
Mn	5.20 ± 1.25[a]	3.63 ± 1.06[b]	8.9 ± 0.80 [cd]	11.4 ± 0.81[c]	7.30 ± 0.83[d]	6.77 ± 0.27[ad]	< 0.001
Zn	8.00 ± 0.50	9.27 ± 0.75	9.13 ± 0.60	10.1 ± 0.15	7.87 ± 0.48	8.85 ± 0.25	0.066
Co	0.002*	0.002*	0.002*	0.002*	0.002*	0.002*	0.416
Se	0.01*	0.02 ± 0.01	0.013 ± 0.003	0.01*	0.01*	0.013 ± 0.003	0.636

* Concentrations below the lower detection limit were considered equal to that limit.
[a] *p*-value: One-way ANOVA followed by Tukey's test was used for normally distributed variables, while the Mann–Whitney *U* test was used for non-normal variables. For each element, different letters indicate significant differences among sites.

(8.9 ± 0.80 mg/kg/dry weigh), while the lowest values occurred in Picos (3.63 ± 1.06 mg/kg/dry weigh).

3.3. Transfer factors from soil to plant

Transfer factors varied markedly among elements and sites. Potassium showed the highest TF values across all locations (6.04–10.79), indicating strong soil–plant transfer, particularly at Nordeste. Mg exhibited moderate transfer (0.38–1.48), with the highest values observed in Furnas and Povoação. In contrast, Fe, Co, Mn, Se and Zn showed consistently low TF values (<0.12), suggesting limited translocation from soil to banana fruit. For Cu, intermediate TF values (0.10–0.79), with enhanced accumulation at Povoação. Detailed TF values for each element and site are provided in Table 3.

3.4. Dietary intake assessment

Based on EFSA Dietary Reference Values, the contribution of 100 g of *Musa acuminata* to mineral intake differed markedly between infants and adults (Table 4). For infants (<1 year), banana consumption accounted for substantial proportions of the DRVs for Mg (41–53%) and K (57–61%) across all sites. Notably, Mn contributions greatly exceeded the DRV for infants at all locations, reaching 345% in Fogo, 598% in Nordeste, and up to 834% in Furnas. In contrast, contributions of Zn remained below 10%, while Fe, Co, Cu and Se contributed marginally to infant DRVs.

For adults (>18 years), contributions were considerably lower. The contribution of Mg and K reached up to 13% of the DRV, while that of Mn ranged from 4% to 10%, depending on the site. Contributions of Zn remained below 2% across all locations. For all other age groups and physiological conditions considered, none of the evaluated elements exceeded 100% of the EFSA DRVs (Supplementary Table S3).

4. Discussion

Understanding the relationship between soil geochemistry and the mineral composition of edible crops is essential for assessing both their nutritional value and the potential dietary exposure of populations consuming locally produced foods. In this study, we focused on eight essential nutrients: K, Mg, Co, Cu, Fe, Mn, Se, and Zn because of their critical roles in human health and the widespread prevalence of deficiencies. Micronutrient deficiencies remain a major public health concern, particularly among children and other vulnerable populations. Globally, nearly 60% of people experience Fe deficiency, over 30% suffer from Zn deficiency, and 15% from Se deficiency, collectively affecting approximately 2 billion individuals, or one-quarter of the world's population (Singh et al., 2020). By examining the soil-to-crop transfer of these nutrients, our findings provide insights into the environmental and dietary factors influencing micronutrient availability, which can inform strategies to mitigate deficiencies and improve nutritional outcomes.

Table 3
Transfer factors (TF) of elements from topsoil to banana fruit at the six sites in the São Miguel Island.

	Sete cidades	Picos	Fogo	Furnas	Povoação	Nordeste
Fe	0.011	0.000	0.001	0.001	0.001	0.000
K	**6.039**	**7.090**	**7.934**	**6.886**	**7.127**	**10.791**
Mg	0.701	0.382	0.650	**1.425**	**1.475**	0.701
Co	0.001	0.000	0.000	0.001	0.001	0.000
Cu	0.325	0.106	0.207	0.413	0.790	0.103
Mn	0.008	0.002	0.008	0.014	0.008	0.004
Se	0.003	0.010	0.004	0.004	0.005	0.003
Zn	0.110	0.063	0.096	0.113	0.102	0.062

The pronounced spatial variability observed in soil physicochemical properties and elemental concentrations may reflect the heterogeneous volcanic geology and contrasting geochemical settings of São Miguel Island (Widom et al., 1997). Although soil pH values were relatively uniform across sites, electrical conductivity differed significantly and may be associated with variations in parent material, soil age, and weathering intensity (Kirana et al., 2024; Rodríguez-Pérez et al., 2011). The relatively uniform concentrations of potassium and selenium suggest a consistent distribution across the island's volcanic complexes, which may reflect their common incorporation into volcanic parent materials and their behavior during soil formation. Volcanic soils often show uniform selenium content due to sorption onto Fe/Al oxides, while potassium is abundant in minerals such as feldspars, micas, and volcanic glass can remain broadly distributed during weathering and soil development (Tolu et al., 2014; Portela et al., 2019), which is consistent with our observations.

In contrast, the significant variability observed for Fe, Mg, Co, Cu, Mn and Zn may reflect differences in lithology and soil-forming processes that characterize the distinct volcanic complexes. Higher Fe and Mn concentrations in soils from Nordeste and Picos are consistent with the basaltic nature of these regions, which are typically enriched in ferromagnesian minerals. Conversely, lower concentrations in Sete Cidades are consistent the more evolved, trachytic parent materials (Neall, 2006; Pimentel et al., 2016; Porreca et al., 2018). These patterns align with previous studies reporting pronounced geochemical contrasts between basaltic and trachytic soils on volcanic islands (Kabata-Pendias, 2011; Linhares et al., 2019).

Despite pronounced differences in soil elemental concentrations, banana fruit showed more constrained variability, particularly for K, Co, Se, and Zn.

Across all sampling sites, K was the most abundant mineral in banana fruit, with a mean concentration of 434.47 mg/100 g fresh weight. This value was higher than those reported for *Musa acuminata* from the USA (326 mg/100 g), Madeira, Portugal (430 mg/100 g), Angola (329 mg/ 100 g), and Colombia (328 mg/100 g) (FAO/INFOODS, n.d.). However,

Table 4
Contribution (%) of 100 g of *Musa acuminata* to Dietary Reference Values (DRV) for selected minerals in infants (<1 year) and adults (>18 years).

	Infants (<1 year)								Adults (>18 years)							
Site	Cu	Fe	K	Mg	Mn	Zn	Co	Se	Cu	Fe	K	Mg	Mn	Zn	Co	Se
Fogo	20	3	60	41	345	8	0	**4**	6	2	13	10	4	2	0	1
Furnas	20	3	57	41	834	9	4	**2**	6	2	12	10	10	2	2	0
Nordeste	18	3	61	53	598	9	0	3	5	3	13	13	7	2	0	1

comparisons among studies should be interpreted with caution because mineral concentrations may be influenced by several factors, including cultivar, environmental and soil conditions, agronomic practices, analytical methodologies, and fruit maturity at harvest. In the present study, all bananas were harvested at the commercially mature green stage, ensuring that samples were collected at the same physiological stage and minimizing variability associated with ripening. Although ripening is accompanied by substantial biochemical changes affecting carbohydrates, organic acids, and texture (Maduwanthi and Marapana, 2019), the available evidence indicates that mineral composition is comparatively less affected. Previous studies have reported that changes in mineral concentrations during ripening are generally small or inconsistent among elements (Adeyemi and Oladiji, 2009), while more recent work found no significant differences in mineral concentrations between mature green and ripe bananas across multiple cultivars (Cooper et al., 2025).

Bananas are consistently identified as potassium-rich fruits, with mineral analyses frequently reporting higher K concentrations than other essential elements in fruit tissues (Hardisson et al., 2001; Sarma et al., 2021; Zou et al., 2022). The study by Hardisson *et al.* on Tenerife bananas similarly identified K as the dominant mineral element, followed by Mg, while elements such as Fe, Cu, Mn, and Zn occurred at substantially lower concentrations. Our results for *Musa acuminata* from six Azorean sites corroborate this pattern.

The predominance of K (15108–16526 mg/kg/ dry weight) in banana tissues is consistent with its essential physiological role exceeding Mg concentrations (1051–1401 mg/kg′ dry weigh) by more than an order of magnitude and greatly surpassing Fe, Zn, Mn and Cu levels. Plant nutrition studies further confirm that K is crucial for plant growth, root development, and fruit quality (Xu et al., 2019). From a nutritional perspective, K intake is associated with cardiovascular health benefits (Chatterjee et al., 2025; Frassetto et al., 2023), emphasizing the value of Azorean bananas as a reliable dietary source of this essential nutrient.

However, the studied elements showed variable concentrations in banana fruits across the different sampling sites, indicating that soil geochemistry alone does not fully explain plant mineral uptake. Although edaphic conditions play an important role in nutrient availability, other agronomic factors may also contribute to the observed differences between soil and fruit elemental composition. One relevant factor is fertilizer management. Information obtained through the farm management questionnaire indicated that plantations in Furnas and Fogo differed from the remaining sites with respect to fertilization and pesticide management. Furnas received YaraMila® fertilizer, whereas Fogo applied a generic NPK formulation twice yearly. In contrast, no fertilizers or agrochemicals were reported at the remaining locations. Although these differences may have contributed to the observed variation in mineral concentrations, the fertilizers were not chemically characterized, and their mineral inputs were not quantified. Consequently, the influence of fertilization practices cannot be distinguished from the effects of local soil geochemistry and should be regarded as a potential contributing factor rather than a demonstrated cause.

Nevertheless, the spatial variability observed in this study also reflects the broader geochemical heterogeneity of São Miguel Island. This uneven distribution of essential elements across São Miguel volcanic complexes has previously been documented in soil and pasture systems, where higher overall nutrient concentrations were reported in basaltic compared with trachytic soils, with corresponding differences in plant tissue composition (Linhares et al., 2019). Similar patterns were described in Tenerife, where spatial differences in banana mineral content were attributed to variations in volcanic parent materials (Hardisson et al., 2001). Collectively, these findings suggest that mineral accumulation in bananas results from the combined influence of lithology, soil-forming processes, and site-specific agronomic management. While K appears to be consistently accumulated at high levels regardless of substrate type, the concentrations of other essential minerals such as Fe, Mg, Cu and Mn are more sensitive to variations in volcanic parent material and inputs from fertilizers and/or pesticides. This interaction between the geogenic origin of the elements and agricultural practices has important implications for crop nutritional quality and for the dietary mineral intake of populations that consume food produced locally.

Building on the observed associations between soil lithology, geochemistry, and banana mineral composition, the TF analysis provides additional insight into the transfer of essential minerals from soil to fruit. The high TF values observed for K (>1) are consistent with its role as an essential element that is actively absorbed by roots and efficiently translocated to developing fruits through specialized transport systems (Lahav, Turner, 1989; Marschner, 2012), Consequently, K exhibited consistently high TF values regardless of soil type, reflecting both its high mobility within plants and its fundamental physiological functions. Moderate TF values were observed for Mg, which is consistent with its more tightly regulated uptake and redistribution due to its role in chlorophyll structure, photosynthesis, and enzyme activation (Ahmed et al., 2023; Papadakis et al., 2023). The results indicate that the *Banana dos Açores* samples evaluated in this study constitute an important dietary source of K and Mg.

In contrast, Fe, Mn, Co, Se, and Zn displayed consistently low TF values, indicating limited accumulation in banana fruit despite variations in soil concentrations. This pattern is consistent with the strong physiological regulation of mineral uptake and the generally lower mobility of these elements in soils, particularly for Fe and Zn, whose availability is strongly influenced by soil physicochemical conditions (Kabata-Pendias, 2011; Alloway, 2013). Overall, the TF values obtained in this study are comparable to those reported for agricultural crops, where K typically exhibits the highest transfer efficiency, Mg moderate transfer, and trace elements substantially lower TF values owing to tighter physiological regulation (Mirecki et al., 2015).

Although these are essential dietary minerals, they are required only in trace amounts, and excessive intake may pose health risks. Notably, the standardized assessment based on a 100 g edible portion indicated that Mn intake would exceed the EFSA Dietary Reference Values (DRVs) for infants. However, this scenario is not representative of typical infant consumption, as a 100 g serving considerably exceeds the portion sizes recommended during complementary feeding. Current feeding guidelines recommend introducing fruit in small servings of approximately 20–30 g, gradually increasing to 40–50 g as the child grows, with banana consumed as part of a varied complementary diet rather than as a single 100 g portion (HSE, 2023). Consequently, Mn intake under realistic consumption scenarios would be substantially lower than the standardized estimates presented in this study. Nevertheless, because infants have relatively low Mn dietary reference values, bananas remain an important dietary source of this element. Although the estimated Mn intake decreases in proportion to serving size, excessive and prolonged Mn exposure during early infancy has been associated with potential neurodevelopmental effects, including impaired cognitive and motor development (Coetzee et al., 2016; Zoni & Lucchini, 2013). Therefore, these findings should not be interpreted as a food safety concern but rather as reinforcing the importance of age-appropriate portion sizes and dietary diversity during complementary feeding.

These findings underscore the importance of integrating soil geochemistry, soil-to-plant transfer, and dietary intake assessment to provide a comprehensive evaluation of the nutritional value of locally produced foods. Although the observed patterns were associated with differences in volcanic geology and soil geochemistry, the mineral composition of edible tissues is also strongly influenced by plant physiological mechanisms regulating nutrient uptake and translocation. Consequently, food composition data should be interpreted considering both environmental factors and biological controls, together with age-specific consumption patterns, to achieve more realistic dietary exposure assessments.

Nevertheless, several limitations of this study should be acknowledged. First, although the sampling strategy encompassed all six volcanic complexes of São Miguel Island and captured the main basaltic and trachytic geochemical environments, the study was restricted to a single island. Consequently, the observed relationships between soil geochemistry and banana mineral composition are expected to be most applicable to regions with similar geological and pedological characteristics, whereas extrapolation to other environments should be made with caution. Second, samples were collected during a single harvest period and therefore do not account for potential seasonal variation in mineral composition, which may be influenced by climatic conditions, soil moisture, and agricultural practices. Third, the study focused exclusively on *Musa acuminata* Colla cv. Dwarf Cavendish ("Pequena-anã"), the cultivar used for the Protected Geographical Indication (PGI) "Banana dos Açores". Consequently, the results may not be representative of other banana cultivars, which can differ in their capacity to accumulate minerals. Furthermore, although information on fertilization and crop management was collected through farm questionnaires, these data were used only to provide qualitative context and were not quantitatively assessed. Finally, the study evaluated total elemental concentrations and soil-to-plant transfer but did not assess mineral bioaccessibility or bioavailability. Future studies should therefore investigate seasonal variability, compare different banana cultivars, expand the geographical coverage to other volcanic islands, and incorporate bioaccessibility and bioavailability assessments to provide a more comprehensive evaluation of the nutritional value of Azorean bananas. These limitations are particularly relevant in the context of São Miguel's banana production sector, which holds considerable regional economic importance but remains largely supported by traditional practices and limited technical support grounded in scientific research. The relative scarcity of systematic agronomic, soil, and plant health studies may constrain the optimization of nutrient management strategies and productivity outcomes. Strengthening research efforts focused on soil characterization, nutrient dynamics, and cultivar health could provide evidence-based guidance to producers, ultimately enhancing crop yield, fruit quality, and economic returns while promoting more sustainable management practices.

Beyond the characterization of *Banana dos Açores*, the present findings have broader implications for agriculture, nutrition, and food composition research in volcanic regions. The observed associations between soil geochemistry and banana mineral composition highlight the importance of considering local geological conditions when evaluating the nutritional quality of crops. Region-specific food composition data can improve dietary exposure assessments, support the development of more accurate food composition databases, and contribute to evidence-based nutritional recommendations. From an agricultural perspective, understanding the influence of soil geochemistry on mineral accumulation may assist producers and policymakers in identifying cultivation areas with potentially favorable nutritional characteristics and in developing management practices that preserve soil quality while maintaining crop nutritional value. More broadly, this approach may also support the sustainable valorization of agricultural products originating from volcanic environments, contributing to regional food systems and adding value to geographically protected products such as *Banana dos Açores*. Future studies integrating agronomic practices, seasonal variation, cultivar diversity, and mineral bioaccessibility will further strengthen the application of these findings to sustainable agriculture and public health.

5. Conclusions

Within the conditions evaluated in this study, *Banana dos Açores* showed consistently high potassium concentrations and represented a meaningful dietary source of potassium and magnesium. The significant spatial variability observed for several minerals across the six volcanic complexes, together with the differences in soil elemental composition, highlights the importance of local geochemical context when characterizing the nutritional composition of crops. Importantly, this study addresses a previously limited knowledge gap for *Banana dos Açores* by linking the mineral composition of the fruit with the geochemical heterogeneity of volcanic agricultural environments, providing region-specific data that are not captured by generalized food composition datasets.

Beyond improving food composition databases, these findings demonstrate the value of incorporating geographical and geological variability into dietary intake assessment and nutrition research. Such information can support more accurate estimation of nutrient contributions from locally produced foods and may contribute to the development of region-specific dietary recommendations and, in the longer term, nutrition-sensitive and precision nutrition approaches. The observed variation in mineral accumulation also has implications for agricultural management, as knowledge of soil–plant mineral relationships may help guide site selection, soil and nutrient management, and the identification of production conditions that support desirable crop nutritional profiles. However, these applications should be considered within the scope of the present study, as mineral accumulation reflects the combined effects of geochemistry, plant physiology and agronomic practices.

The findings also support the nutritional and agricultural valorization of *Banana dos Açores* as a region-specific product with Protected Geographical Indication. Demonstrating measurable variation in its mineral composition across volcanic environments may contribute to greater consumer awareness, strengthen the scientific basis for regional food valorization, and add nutritional information to existing geographical identity and quality frameworks. More broadly, the approach adopted here may be applicable to other crops cultivated in geologically diverse or volcanic environments, where local parent material and soil characteristics may contribute to spatial differences in crop mineral composition.

The dietary assessment further illustrates the importance of considering age-specific requirements and realistic serving sizes when interpreting mineral composition data. Although the standardized 100 g assessment indicated a high potential contribution of manganese to infant dietary reference values, this scenario does not represent typical infant consumption, and the present findings should not be interpreted as evidence of a food safety concern. Instead, they emphasize the value of region-specific composition data for contextualized dietary assessment.

The study is nevertheless limited by its coverage of a single island, one harvest period, and one cultivar. Future research should therefore include multiple harvest seasons, additional banana cultivars and production areas, and other volcanic regions, together with more detailed characterization of soil properties, parent material, environmental conditions and agronomic practices. Complementary studies addressing mineral bioaccessibility and, where feasible, bioavailability would further clarify the nutritional significance of the observed elemental profiles. Such research will help determine the extent to which the associations identified here are reproducible and transferable across volcanic agricultural systems and will strengthen the evidence base for sustainable crop production, regional food valorization and nutrition-sensitive agriculture.

CRediT authorship contribution statement

Armindo Rodrigues: Writing – review & editing, Supervision, Conceptualization. **Patrícia Garcia:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Ricardo Camarinho:** Methodology, Investigation. **Tânia Vasconcelos:** Methodology, Investigation, Formal analysis. **Diana Linhares:** Writing – original draft, Formal analysis, Data curation.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used AI for the creation of the graphical abstract and for English language verification. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2026.109472.

Data availability

Data will be made available on request.

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