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Nutrient dynamics in apple: Analyzing macro and micronutrient distribution in leaves and fruits

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Abstract

Apple cultivation is a key component of sustainable agriculture, significantly contributing to global fruit production. This study aimed to analyze the macro and micronutrient contents in apple leaves and fruits and to evaluate their relations with each other. The research was conducted in Denizli, Türkiye, using the Scarlet Spur apple cultivar grafted onto MM 111 rootstock, with a planting density of 4.5 × 2.5 m. Nutrient concentrations were measured using ICP-AES and spectrophotometric techniques. The results showed that nitrogen (0.50%–0.63%) and potassium (0.10%–0.94%) were the most abundant macronutrients in fruit, whereas calcium (0.04%–0.06%) and magnesium (0.06%–0.07%) were lower. Among micronutrients, iron (7.40–9.20 ppm) and boron (98.35–115.55 ppm) were found in higher concentrations, while zinc (2.07–2.44 ppm) and copper (1.70–1.80 ppm) were relatively low. Leaf tissues exhibited higher nutrient concentrations than fruit, with nitrogen (2.41%–2.56%), potassium (1.66%–1.83%), and calcium (1.49%–1.63%) being dominant. Strong negative correlations were observed between nitrogen and calcium in fruit ($r = -0.99$), while calcium and magnesium in leaves showed a strong positive relationship ($r = 0.99$). These results suggest that proper nutrient management is essential to improve fruit quality and optimize yield. The study emphasizes the necessity of balanced fertilization strategies and highlights the potential of apples as a rich dietary source of essential minerals. Future research should focus on optimizing fertilization practices and understanding the environmental factors influencing nutrient uptake.

Keywords: Fruit quality, Nutrient uptake, Macro and micronutrients, Sustainable agriculture

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INTRODUCTION

Fruit cultivation plays a crucial role in agricultural production, being of immense economic and ecological importance. Türkiye provides ideal environment for fruit cultivation owing to it’s diverse climatic conditions and rich soil structure (Karadeniz et al., 2013; Şenyurt et al., 2015). This favorable situation has resulted in horticultural production making up a significant share of Türkiye's overall agricultural production (Kaplan, 2016; Ağaoğlu et al., 2019).

According to FAO (2023) data, global apple production reached approximately 97.3 million tons. China produces 49.6 million tons on its own, followed by the United States (5.15 million tons), Türkiye (4.60 million tons), Poland (3.89 million tons), and India (2.87 million tons). These figures reveal that the top five apple-producing countries together contribute nearly 68% of total global production. With its favorable ecological conditions and significant production potential, Türkiye is the world's third largest apple producer. It is the highest producer in Europe and Asia after China.

In modern fruit cultivation, one of the fundamental pillars of sustainable agricultural production is the strategic management of plant nutrition. This is critical for optimizing yield and quality parameters. In modern fruit production, the provision of essential nutrients in a balanced manner to support the plants vital functions is of paramount importance (Bayram & Büyük, 2021). Nutrients required by plants are classified into macronutrients and micronutrients depending on the quantities needed. Macronutrients, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S), are needed in large quantities, while micronutrients, including iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), and molybdenum (Mo), are required in trace amounts (Zincircioğlu, 2018). Each of these nutrients plays a specific role in plant metabolism, and deficiencies of these elements can lead to characteristic symptoms (Yıldız, 2012; Kacar et al., 2013). Previous studies have reported that nitrogen deficiency, which is a key component of photosynthesis, slows down vegetative growth and causes chlorosis in leaves (Şenel, 2019). Similarly, calcium deficiency, which is essential for cell wall stability and fruit quality, can lead to shortened storage life and physiological disorders (Jaime-Guerrero et al., 2024).

The nutrient requirements of apple trees are crucial for both fruit quality and yield. During their growth and development, apple trees require various macro and micronutrients, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), and zinc (Zn). Researches has shown that determining the concentrations of these nutrients in the leaves of apple trees is vital, as it affects the trees' nutritional status and consequently their yield (Erdal, 2005; Bayram & Büyük, 2021). A study conducted in apple orchards in the Isparta region revealed deficiencies in phosphorus (P), calcium (Ca), potassium (K), and manganese (Mn) in the leaves of the trees (Erdal, 2005). These deficiencies can negatively impact the health of apple trees and fruit quality.

Apple is a nutritious fruit and the nutrient content of its fruits plays an important role in terms of health (Dumanoglu et al., 2018). Apples contain various antioxidant compounds such as phenolic compounds, ascorbic acid (vitamin C), vitamin E, and β-carotene (Özel et al., 2020). These bioactive compounds are associated with positive health outcomes, including the prevention of several chronic diseases such as cancer, diabetes, and cardiovascular diseases (Nizamlıoğlu, 2022). In addition, the nutritional profile of apples is increasingly important in light of growing consumer preferences for healthier diets.

Nutrient element analyses play a pivotal role in developing fertilization programs for apple trees. These analyses help identify the specific nutrients required by the trees, thus allowing for the more effective planning of fertilization practices (Çimrin et al., 2000; Küçükyumuk & Erdal, 2014). Foliar applications of iron and zinc fertilizers have been shown to positively influence the nutrient content of both the leaves and fruits of apple trees, contributing to improved tree development (Çimrin et al., 2000; Baysall & Erdal, 2015). Furthermore, boron fertilization has been found to increase nutrient element concentrations in apples, highlighting its potential benefits in fruit production (Baysal & Erdal, 2015).

Iron and zinc are critical micronutrients in human nutrition that significantly enhance the nutritional value of apples. Despite the consumption of 20–25 mg of iron through the normal daily diet, only 1–2 mg of this iron is absorbed by the small intestine (Güleç, 2018). Therefore, the iron content and bioavailability of foods are crucial. Zinc, the second most abundant trace element in the human body after iron, is essential for the function of over 300 enzymes (Akdeniz et al., 2016). Zinc is found primarily in the bones, muscles, hair, and skin, with an estimated total body content of 2 g in adults. Adequate zinc intake is essential for maintaining a strong immune system and nervous system (Gombart et al., 2020; Marcos, 2021). Zinc plays a crucial role in human nutrition, being an essential trace element that also has significant physiological effects on both plants and animals.

The primary aim of this study is to (1) determine the levels of macro and micronutrients in the leaves and fruits of apple trees, (2) explore the relationships between these elements, and (3) provide a comprehensive analysis of the dynamics of nutrient elements in apple cultivation.

MATERIALS AND METHODS

The study was conducted in 2023 in the Çivril district of Denizli, Türkiye. The plant material consisted of the Scarlet Spur apple cultivar, grafted onto MM111 rootstock, which was planted in 2017 with a spacing of 4.5 × 2.5 m between and within rows. The research site is located at an altitude of 840 meters and features a transitional climate between the Mediterranean and Continental climates.

The formation of the abscission layer, coloration, and taste were taken into consideration as criteria for harvesting the fruits (Akkurt et al., 2024). Leaf samples were taken from the newest leaves, which had finished growing in July (Mertoğlu et al., 2024). The samples were decontaminated through sequential washing in a detergent solution, followed by tap and distilled water rinsing to remove any external contaminants. Subsequently, the samples were dried at a controlled temperature of 70°C until a constant weight was achieved. Dried samples were then homogenized by grinding to a particle size of less than 0.5 mm for uniformity in analysis. The powdered samples were subjected to acid digestion using a nitric acid (HNO_3) and perchloric acid ($HClO_4$) mixture in a 3:1 volume ratio, as described by Kacar (1972). Elemental analysis included the determination of K, Mg, Ca, Fe, Mn, Cu, and Zn, which were quantified using an inductively coupled plasma atomic emission spectrometer (ICP-AES; Varian Liberty Series II, Varian Inc., Palo Alto, CA, USA). P content was determined through the Barton reagent method using a UV/VIS spectrometer (Shimadzu 1208, Shimadzu, Kyoto, Japan) according to Barton (1948). Total nitrogen content was analyzed using the micro-Kjeldahl method (Lees, 1971).

The study was established according to the randomized plot experimental design with five replications. In this study, all statistical analyses and data visualizations were performed using RStudio (2024.12.0+467). Descriptive statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) for nutrient elements were calculated using the 'stats' and 'dplyr' packages. Pearson correlation analysis ($p<0.05$) was applied to determine relationships between elements, and the 'corrplot' package was used. Data visualizations, including box-plots, scatter plots, and density curves, were generated using the 'ggplot2' and 'GGally' packages. For data organization and manipulation, the 'tidyverse' and 'reshape2' packages were utilized (Zar, 2013).

RESULTS AND DISCUSSION

The minimum, maximum, mean, standard deviation, and coefficient of variation (C.V.%) values for the nutrients in apple fruit and leaves are presented in Table 1. Regarding the fruit, the nitrogen (N) content ranged from 0.50% to 0.63%, with a mean value of 0.58%. Phosphorus (P) content ranged from 0.08% to 0.09%, with a mean of 0.09%; potassium (K) ranged from 0.10% to 0.94%, with a mean of 0.64%; calcium (Ca) ranged from 0.04% to 0.06%, with a mean of 0.05%; and magnesium (Mg) ranged from 0.06% to 0.07%, with a mean of 0.06%. Among micronutrients, iron (Fe) ranged from 7.40 to 9.20 ppm (mean 8.57 ppm), copper (Cu) ranged from 1.70 to 1.80 ppm (mean 1.76 ppm), manganese (Mn) ranged from 2.76 to 2.97 ppm (mean 2.89 ppm), zinc (Zn) ranged from 2.07 to 2.44 ppm (mean 2.24 ppm), and boron (B) ranged from 98.35 to 115.55 ppm (mean 104.97 ppm). The highest coefficient of variation was observed for K (%73.31), while the lowest for Cu (%3.12).

In the apple leaves, the macronutrient nitrogen content ranged from 2.41% to 2.56%, with a mean of 2.50%. Phosphorus content ranged from 0.21% to 0.22%, with a mean of 0.21%; potassium ranged from 1.66% to 1.83%, with a mean of 1.74%; calcium ranged from 1.49% to 1.63%, with a mean of 1.58%; and magnesium ranged from 0.50% to 0.60%, with a mean of 0.57%. Among micronutrients, iron content ranged from 79.00 to 110.50 ppm (mean 92.67 ppm), copper ranged from 8.40 to 9.40 ppm (mean 8.97 ppm), manganese ranged from 38.30 to 44.70 ppm (mean 41.93 ppm), zinc ranged from 16.30 to 20.00 ppm (mean 17.97 ppm), and boron ranged from 81.80 to 108.40 ppm (mean 97.60 ppm). The highest coefficient of variation was observed for Fe (%17.44), and the lowest for P (%2.71).

We detected was higher than the values reported by Ahmed et al. (2024) in the fruit, the potassium content for the Golden and Starking apple cultivars (0.39% and 0.57%, respectively). Our phosphorus content was in agreement with their findings (Golden: 0.09%, Starking: 0.10%). However, our calcium content was significantly lower than their reported value of 0.12% for both cultivars. Similarly, our magnesium content was higher than the values reported for Golden (0.03%) and Starking (0.03%).

Regarding micronutrients, our iron content was higher than the values reported by Ahmed et al. (2024) for Golden (4.80 ppm) and Starking (7.80 ppm). Our copper content was similar to the values in the literature (Golden: 1.91 ppm, Starking: 2.73 ppm), while our manganese content was higher than their findings (Golden: 0.96 ppm, Starking: 2.13 ppm). Our zinc content was lower than the literature values (Golden: 6.76 ppm, Starking: 7.35 ppm), but boron was significantly higher than the reported values (Golden: 6.74 ppm, Starking: 6.66 ppm).

The nitrogen content we detected was higher than the values reported in the literature (0.1-0.3%) (Kurešová et al., 2019; Yıldız et al., 2022). The nutrient element contents in the leaf samples were generally consistent with the ranges reported by Özel et al. (2020) and Sas-Paszt et al. (2014).

Nava et al. (2018) was reported that the coefficients of variation for nutrient elements can differ due to environmental factors. Similarly, in our study, the highest variation coefficient in the fruit was found for potassium, and in the leaves for iron. These differences can be attributed to the mobility of nutrient elements within the plant and their sensitivity to environmental factors. These variations could be influenced by cultivar characteristics, ecological conditions, soil composition, and cultivation techniques (Nemeskéri et al., 2015). The notably high levels of nitrogen, potassium, magnesium, and boron in the fruit, and the low calcium and zinc levels, may be linked to regional soil characteristics and fertilization programs (Richardson et al., 2021). These differences can also be attributed to factors such as the soil nutrient content, irrigation water, harvest time, location, temperature, light intensity, and fruit types, as well as the different parts of the fruit. The high variation coefficients for potassium in the fruit (%73.31) and iron in the leaves (%17.44) suggest that these elements' contents are more influenced by environmental factors.

Figure 1 illustrates the correlations between nutrient elements in apple fruit. Upon examining statistically significant relationships ($p<0.05$), several noteworthy correlations were identified: a very strong negative correlation between N and Ca ($r=-0.99$), a perfect positive correlation between N and Fe ($r=1.00$), a very strong negative correlation between P and K ($r=-0.99$), a very strong negative correlation between P and Cu ($r=-0.99$), a perfect positive correlation between K and Cu ($r=1.00$), and a very strong negative correlation between Fe and Ca ($r=-0.99$). These findings indicate that in the fruit, N changes inversely with Ca and directly with Fe, while P exhibits an inverse relationship with both K and Cu, K has a direct relationship with Cu, and Fe changes inversely with Ca. However, no statistically significant correlations were observed between other element pairs.

Table 1. Descriptive Statistics for Macro and Micro minerals in Apple Fruits and Leaves

Plant part	Variable	Min.	Max.	Mean	StDev	C.V. %
Fruit	N (%)	0.500	0.630	0.583	0.07	12.40
	P (%)	0.081	0.094	0.086	0.01	8.14
	K (%)	0.100	0.944	0.637	0.47	73.31
	Ca (%)	0.040	0.063	0.049	0.01	25.69
	Mg (%)	0.055	0.066	0.060	0.01	9.28
	Fe (ppm)	7.400	9.200	8.567	1.01	11.81
	Cu (ppm)	1.700	1.800	1.763	0.06	3.12
	Mn (ppm)	2.760	2.970	2.893	0.12	4.01
	Zn (ppm)	2.070	2.440	2.237	0.19	8.39
	B (ppm)	98.350	115.550	104.967	9.26	8.82
Leaf	N (%)	2.410	2.560	2.503	0.08	3.25
	P (%)	0.210	0.220	0.213	0.01	2.71
	K (%)	1.660	1.830	1.740	0.09	4.91
	Ca (%)	1.490	1.630	1.580	0.08	4.94
	Mg (%)	0.500	0.600	0.567	0.06	10.19
	Fe (ppm)	79.000	110.500	92.667	16.16	17.44
	Cu (ppm)	8.400	9.400	8.967	0.51	5.72
	Mn (ppm)	38.300	44.700	41.933	3.29	7.84
	Zn (ppm)	16.300	20.000	17.967	1.88	10.45
	B (ppm)	81.800	108.400	97.600	13.99	14.33

When analyzing the correlations of nutrient elements in apple leaves, the only statistically significant ($p<0.05$) relationship was found to be a very strong positive correlation ($r=0.99$) between Mg and Ca. This indicates that the concentrations of Mg and Ca in the leaves tend to increase or decrease together. Although no other relationships were statistically significant, strong positive correlations were found between B and Ca ($r=0.990$), B and Mg ($r=0.98$), Cu and Mg ($r=0.96$), Cu and K ($r=0.95$), Zn and P ($r=0.94$), Cu and Ca ($r=0.94$), Zn and Mn ($r=0.92$), and Mn and N ($r=0.915$). Furthermore, a negative correlation was identified between Fe and N ($r=-0.98$), but it was not statistically significant at the 0.05 level.

In previous studies, correlations between nutrient elements have been observed that align with some of our findings. For instance, Nava et al. (2018) reported a positive correlation between Ca and Mg in Fuji apples, which is consistent with the very strong positive correlation found between Mg and Ca in our leaf tissue samples. Bozkurt et al. (2001) also identified a high correlation ($r=0.80$) between Ca and Mg in apple leaves from the Van region. In a study on apricot (Çelik, 2019), a positive relationship between Fe and Ca and K was reported. Similarly, Ceylan et al. (2004) observed a negative correlation ($r=-0.59$) between N and K in kiwi fruit leaves, whereas this relationship was not statistically significant in our study.

Moreover, in a study by Çelik (2019) on apricot leaves, a positive correlation between K and Cu minerals was identified, which also aligns with some of the findings in our study. A further comparative study on different fruit species (Golden apple, Starking apple, pear, and quince) revealed a significant and strong positive relationship between P and Mg ($p<0.05$, $r>0.70$) (Ahmed et al., 2024). In the same study, significant and strong positive correlations were also found between Fe and B, which differs from the relationships observed in our study. These variations might stem from differences in the fruit species being studied, as each type of fruit has distinct mechanisms for nutrient uptake and transport.

The contrasts between these studies and ours highlight the complex nature of nutrient element interactions and suggest that these relationships are not universal but vary depending on factors such as fruit species, variety, ecological conditions, and even the specific plant part (leaf versus fruit). The discrepancies in nutrient element correlations across studies indicate that the mechanisms governing nutrient dynamics are influenced by a combination of genetic, environmental, and physiological factors. As such, further research is necessary to fully understand the intricacies of these interactions and their implications for plant nutrition.

Based on the findings of this study and those of previous research, it is evident that the relationships between nutrient elements can vary significantly depending on fruit types, varieties, environmental conditions, and plant parts. Therefore, when designing plant nutrition programs or conducting agricultural research, it is crucial to consider these diverse factors. Adapting nutrient management strategies to specific conditions will ultimately lead to efficiency and sustainability in agricultural practices, improving both crop yield and quality.

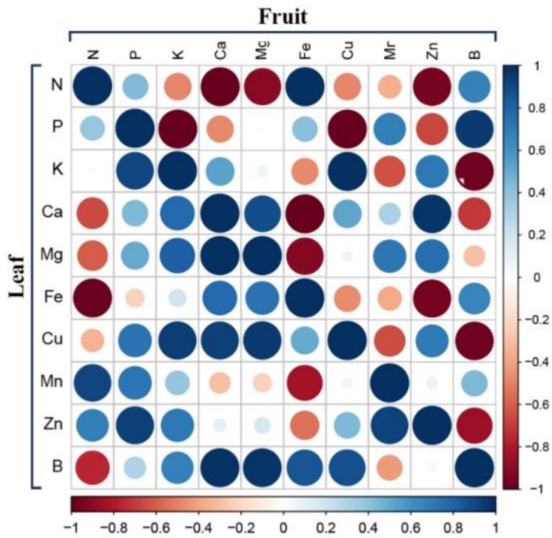

Figure 1. Correlation Analysis of Macro and Micro Minerals in Fruit and Leaf

The distribution of macro nutrient contents in apple fruit and leaf samples is presented in Figure 2. Upon analyzing the figure, it becomes evident that nitrogen (N) exhibits the highest concentration, ranging from approximately 1.5% to 2.5%, with a broad distribution. Following nitrogen, potassium (K) shows a concentration range of 1% to 1.8%, also demonstrating a relatively wide distribution. Calcium (Ca) is distributed between 0.5% and 1.5%, while magnesium (Mg) content varies from 0.2% to 0.6%. The element with the lowest concentration is phosphorus (P), which has a narrow distribution between 0.1% and 0.2%. Outlier values are represented by the points seen in the box-plot.

The findings from the study by Ahmed et al. (2024) report potassium content in the Golden and Starking apple varieties as ranging from 3585-3930 mg/kg and 3533-5671 mg/kg, respectively. This observed variation may be attributed to factors such as sampling time, variety characteristics, and the analytical methods used. Additionally, Nour et al. (2010) highlighted the substantial variation in nutrient element contents across different apple varieties, reinforcing the influence of these factors on the results.

This variability in nutrient content across different apple varieties emphasizes the need to consider a wide range of environmental and genetic factors when interpreting nutrient analysis results. Furthermore, such differences might indicate that localized soil properties, climate conditions, and agricultural practices play a significant role in shaping the nutrient composition of apple fruits.

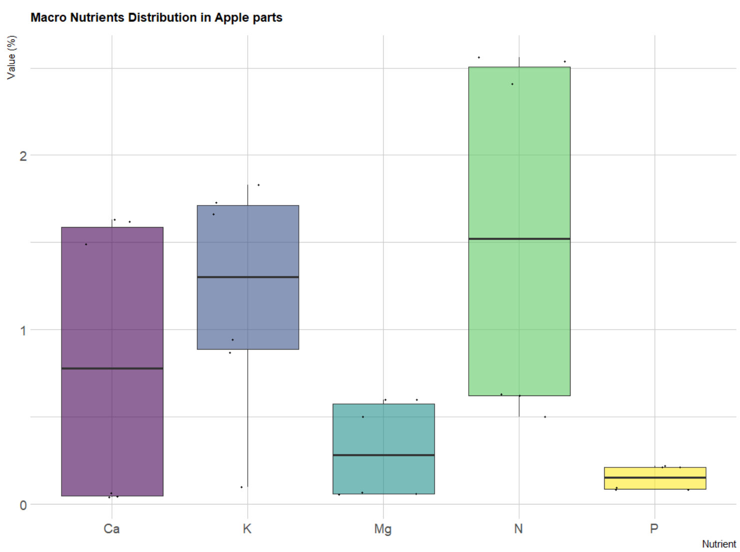

Figure 2. Distribution of Macro Minerals (Ca, K, Mg, N, P) in Apple Fruit and Leaves (%).

The distribution of micronutrient contents in apple fruit and leaf samples is illustrated in Figure 3. Upon examining the distribution of micronutrients, it is apparent that boron (B) exhibits the highest concentration, ranging from 80 to 120 ppm. This is closely followed by iron (Fe), which shows a broad distribution spanning from approximately 10 to 90 ppm. Manganese (Mn) content fluctuates between 5 and 45 ppm, while zinc (Zn) is found to range from 5 to 20 ppm. Copper (Cu) displays the lowest concentration, ranging between 1 and 10 ppm. In the box-plot graph, the points represent outliers. Notably, the distribution of boron and iron stands out for its broader spread compared to the other elements. The findings for zinc and copper in our study largely align with those reported by Ahmed et al. (2024) (Zn: 6.76-22.85 ppm, Cu: 1.91-11.80 ppm), suggesting that the transport and accumulation of these elements in the plant may be relatively stable. Habte et al. (2017) also suggested that the distribution of elements in fruits is strongly influenced by genetic structure and physiological processes.

In their research, Nava et al. (2018) found that leaf tissues contained higher concentrations of nutrients than fruit tissues in Fuji apples, a result that aligns with our findings. In our study, we observed that the concentrations of both macro and micronutrients in leaf tissues were significantly higher than those in fruit tissues.

When comparing the distribution of nutrient elements in both the fruit and leaf samples, it is evident that the leaves generally exhibit higher concentrations. This is likely due to the fact that leaves play a crucial role in storing nutrients essential for photosynthesis and various metabolic processes (Radojčin et al., 2021). Furthermore, Ahmed et al. (2024) reported that element distribution varies across different parts of the fruit (skin, flesh, seeds), with the highest accumulation generally occurring in the seeds.

While the distribution of nutrient elements in apple fruit and leaves in our study partially aligns with the literature, we also identified some key differences. These variations may be attributed to factors such as cultivar-specific traits, growing conditions, soil composition, climate variables, and differences in analytical methods. It is important to note that environmental factors, including soil fertility, irrigation, and timing of harvest, can significantly influence the nutrient content in both fruit and leaf tissues. Therefore, understanding the underlying causes of these discrepancies can facilitate the optimization agricultural practices and improve nutrient management strategies for apple cultivation.

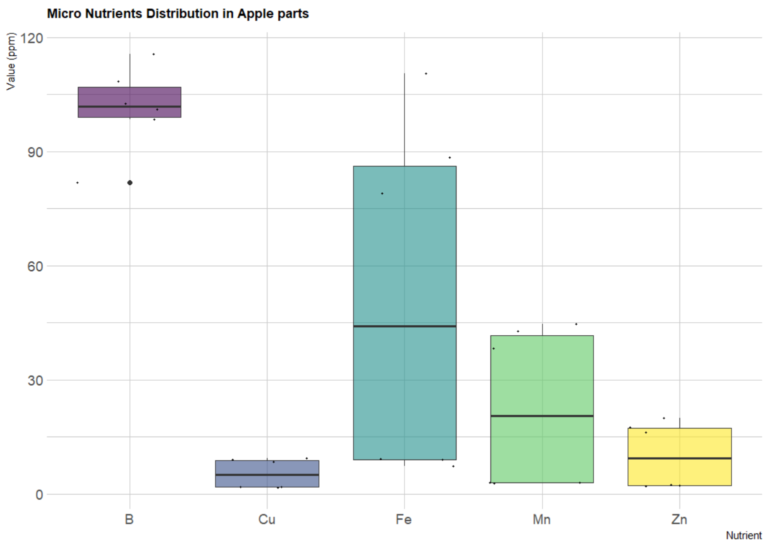

Figure 3. Distribution of Micro Minerals (B, Cu, Fe, Mn, Zn) in Apple Fruit and Leaves (ppm).

The bivariate distribution plots and density curves illustrating the relationships between nutrient elements in apple fruit and leaf tissues are presented in Figure 4. As depicted in the figure, the scatter plots for the relationships between macroelements show not only the individual distributions of each element (on the diagonal) but also the correlations between them. Nitrogen (N) exhibits a broad distribution ranging from 0.5% to 2.5%, whereas phosphorus (P) has a more concentrated distribution, ranging from 0.08% to 0.20%. Potassium (K) shows variability between 0.5% and 1.5%, calcium (Ca) is distributed between 0% and 1.5%, and magnesium (Mg) spans from 0.2% to 0.6%. Of particular note are the pronounced relationships between nitrogen (N) and calcium (Ca), as well as between phosphorus (P) and potassium (K). In the scatter plots, blue points represent leaf samples, while red points represent fruit samples. The density curves on the diagonal highlight the distribution characteristics of each element, providing further insight into their concentration patterns within the tissues. These visualizations underscore the variability and associations of macroelements, which are key for understanding nutrient dynamics in apples.

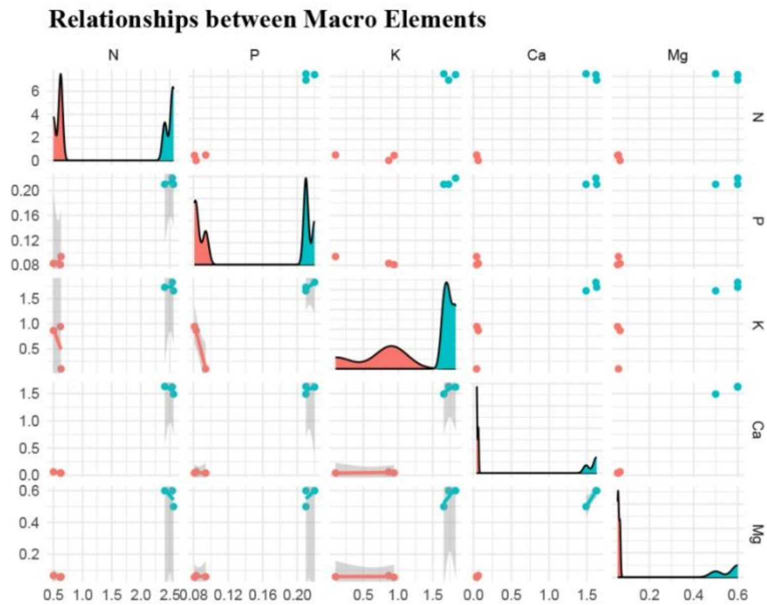

Figure 4. Bivariate Relations and Distributions of Macro Minerals in Tissues.

The bivariate relationships between micronutrient elements in apple fruit and leaf tissues are presented in Figure 5. These distribution plots illustrate the relationships between the micronutrients, with Fe ranging from 30-90 ppm, Cu from 2.5-7.5 ppm, Mn from 10-40 ppm, Zn from 5-20 ppm, and B spanning 90-110 ppm. It is of particular note is the clear linear trend observed in the relationships of B with other elements, indicating a consistent correlation pattern across samples. A negative correlation is observed between Fe and both Cu and Mn, suggesting that as one of these elements increases, the other tends to decrease. Conversely, a positive correlation between Zn and B is observed, implying that higher concentrations of one are associated with higher levels of the other. The blue points in the plots represent leaf samples, while the red points represent fruit samples, allowing for a clear distinction between tissue types. The density plots along the diagonal provide additional insight into the distribution characteristics of each micronutrient, showing how the concentration of each element varies within the dataset. Notably, the distribution of the B element displays a bimodal (dual-peak) pattern, suggesting that there may be two distinct subpopulations or environmental factors influencing its distribution. These results underline the complex interactions between micronutrients in apples and the potential for varying nutrient dynamics between different tissues.

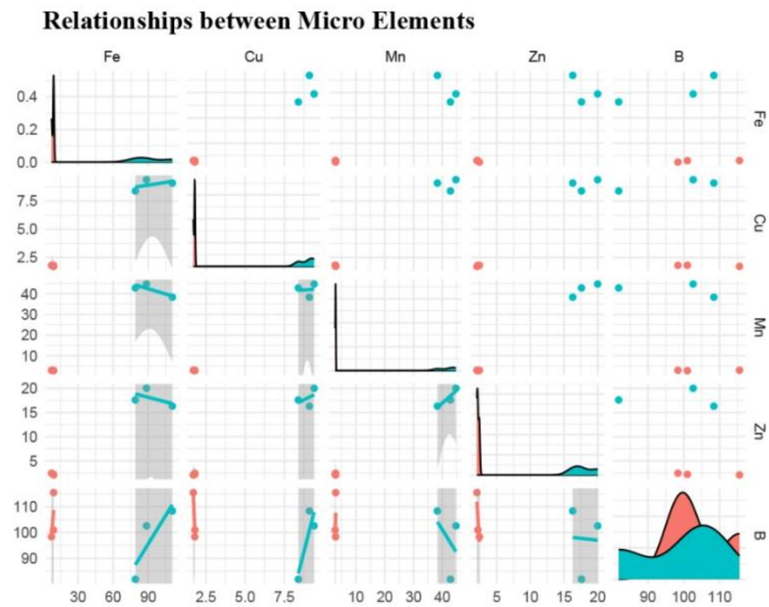

Figure 5. Bivariate Relations and Distributions of Micro Minerals in Tissues.

CONCLUSION

This study provides crucial insights into the distribution and interactions of macro and micronutrients in apple trees, emphasizing their impact on fruit quality and yield. The findings revealed significant variations in nutrient content between leaves and fruits, with leaf tissues generally exhibiting higher concentrations. Notably, nitrogen levels in fruit ranged from 0.50% to 0.63%, while in leaves, they were significantly higher (2.41%–2.56%). Potassium, essential for fruit quality, showed a wide variation in fruit (0.10%–0.94%) compared to leaves (1.66%–1.83%). A concerning observation was the relatively low calcium (0.04%–0.06%) and zinc (2.07–2.44 ppm) levels in fruit, which may negatively affect storage life and disease resistance. The strong negative correlation between nitrogen and calcium ($r = -0.99$) indicates a potential imbalance that could impact fruit firmness and shelf life. These results underscore the importance of precise nutrient management to maintain optimal fruit quality and maximize productivity. Appropriate fertilization programs should be implemented based on regular soil and leaf analyses to balance apples' low calcium and zinc levels to harvest high-quality fruits and manage post-harvest period according to different ecologies.

Compliance with Ethical Standards

Peer-review

Externally peer-reviewed.

Declaration of Interests

The authors declare that they have no conflict of interest.

Author contribution

The contribution of the authors to the present study is equal. All the authors read and approved the final manuscript. All the authors verify that the text, figures, and tables are original and that they have not been published before.

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