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Effects of Different Cultivation Systems and Fruit Parts on Mineral Composition: a Case Study on Kumquat

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Abstract
This study investigates the impact of open-field and greenhouse cultivation systems on the mineral composition of kumquat (*Fortunella margarita*), with particular attention to variations between fruit peel and pulp. The research utilized fruits harvested from 4-year-old plants cultivated in Muğla, Turkey. Elemental analysis of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) was conducted using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and UV/VIS spectrometry. Results indicated significantly higher mineral concentrations under greenhouse conditions, with Mg increasing from 0.86 g kg^{-1} in open-field cultivation to 1.25 g kg^{-1} in greenhouse conditions, and Fe rising from 60.83 mg kg^{-1} to 67.85 mg kg^{-1}. The peel exhibited a higher mineral density compared to the pulp, as evidenced by Fe levels of 66.74 mg kg^{-1} in the peel versus 61.94 mg kg^{-1} in the pulp. Macronutrient concentrations, including N (1.03 g kg^{-1} vs. 0.83 g kg^{-1}) and K (1.68 g kg^{-1} vs. 1.24 g kg^{-1}), were also elevated in greenhouse-grown fruits. Correlation analysis revealed strong positive relationships between K and Ca ($r = 0.77$), Mg and K ($r = 0.72$), and Mg and Ca ($r = 0.81$), emphasizing their synergistic roles in nutrient transport and photosynthetic processes. These findings underscore the efficacy of greenhouse cultivation in optimizing nutrient uptake, distribution, and fruit quality, providing critical insights for enhancing kumquat production practices.

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1. Introduction

Protected cultivation serves as a significant alternative production technique by enabling the cultivation of crops beyond their natural ecology (Shamshiri et al., 2018). Unlike natural conditions, protected cultivation accelerates early temperature increases and maintains consistently higher levels (Badji et al., 2022). This feature is particularly advantageous for cultivating tropical and subtropical crops in regions characterized by continental climates (Zhang et al., 2022).

In recent years, the increasing demand for early-season production has led to the widespread adoption of protected cultivation across diverse fruit groups, including peaches, almonds, bananas, and strawberries (Güneş and Gübbük, 2006; İmrak et al., 2009). The primary advantages of protected cultivation include early and extended harvest periods, reduced water consumption, prolonged periods of optimal growth temperatures, enhanced photosynthetic activity, safeguarded cultivation, and superior fruit quality. These benefits have significantly contributed to its global expansion. Comparative studies have demonstrated that protected cultivation, relative to open-field practices, promotes early ripening in peaches (Demiral and Ülger, 2021) and apples (İmrak et al., 2009), extends the maturation period while enhancing fruit quality in Ponkan mandarins (Lin et al., 2016), and improves yield, fruit size, and earliness in bananas (Güneş and Gübbük, 2006).

Citrus fruits constitute the most extensively cultivated fruit group globally. Renowned for their aromatic appeal, these fruits are highly valued for their diverse phytochemical profile, which imparts significant health benefits, including protective effects against atherosclerosis, osteoporosis, prostate and breast cancers, and antimicrobial properties (Guthrie and Carroll, 1998; Gao et al., 2006; Shalaby et al., 2011; Barreca et al., 2017). As a result, citrus consumption has surged in both developed and developing nations over recent years (Liu et al., 2012). Reflecting their economic and nutritional importance, citrus fruits occupy a leading position in global agricultural trade (Alquézar et al., 2017).

Although citrus fruits are traditionally of tropical origin, modern cultivation predominantly occurs under subtropical climate conditions. Different species and varieties exhibit varied responses to these ecological conditions (Iwasaki et al., 1986). For instance, kumquat a species known for its rapid growth and extended flowering period can be cultivated as far as 36° north latitude. Its resilience to brief and moderate frosts enables robust vegetative growth in subtropical climates (Chang et al., 2014; Manner et al., 2006). Combining the extended shoot development and flowering periods facilitated by subtropical conditions with the benefits of protected cultivation yields particularly favorable outcomes during periods of limited fruit diversity and market supply.

Kumquat is a highly functional fruit characterized by its diverse industrial applications and abundant bioactive compounds (Gölükcü et al., 2011; Turgut et al., 2015). However, existing literature provides limited insights into the effects of different cultivation systems on its mineral composition. This study aims to fill this gap by investigating the influence of open-field and protected cultivation systems on the mineral profile of kumquat. Furthermore, it seeks to explore the interrelationships among various properties to assess their potential for integrated consideration, offering a comprehensive perspective on optimizing kumquat production.

2. Material and Methods

2.1. Plant material

Fruits harvested from 4-year-old *Fortunella margarita* (Lour.) Swingle grafted onto Carrizo citrange located in Muğla were used as material in the study. Plants with 2 x 1 m planting distances were irrigated and fertilized using drip irrigation. All cultural practices were carried out routinely. The formation of coloration and taste were considered criteria for fruit harvesting.

2.2. Environmental conditions

Maximum temperatures were recorded in August, with values reaching 33.7 °C under open-field and 51.12 °C in the greenhouse. The minimum temperature was observed in February under open-field (6.8 °C) and in January within the greenhouse (6.2 °C). The average temperature was slightly higher in open-field (10.5 °C) compared to the greenhouse (10.2 °C). Relative humidity levels were generally higher in open-field than in the greenhouse. The lowest humidity under open-field was recorded in September (64.9%), while the highest value was observed in November (80.4%). Under the greenhouse, humidity reached its lowest in July (41.59%) and peaked in November (65.30%). Rainfall data revealed that January was the wettest month under open field, with a total precipitation of 406.3 mm (Anonymous, 2024).

2.3. Methods

2.3.1. Sample preparation

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.

2.3.2. Chemical 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 elemental composition of the leaves was evaluated against established threshold values as reported by Marchal (1987). This systematic approach ensured the precision and reliability of the mineral and nutrient quantification for subsequent interpretation and comparison.

2.3.3. Statistical analysis

The study was established according to the randomized plot experimental design with 36 replications (Zar, 2013). Minitab-21 (Minitab Inc., State College, Pennsylvania, USA) package program was used in the analysis.

3. Results and Discussion

The Table 1 summarizes nutrient concentrations (N, P, K, Ca, Mg, Cu, Mn, Fe, Zn) in fruits under different cultivation systems (greenhouse and open field) and their partitioning between fruit peel and pulp. ANOVA results assess the statistical significance of cultivation system (YS), fruit part (MK), and their interaction (YS × MK) on nutrient content.

In the context of macronutrients, no statistically significant impact of cultivation systems was observed on the concentrations of N, P, K, and Ca, while Mg was significantly influenced. Notably, all macronutrient levels were slightly elevated under protected cultivation compared to open-field conditions. Specifically, the concentrations of N, P, K, Ca, and Mg were measured at 0.83 g kg^{-1}, 1.11 g kg^{-1}, 1.24 g kg^{-1}, 2.48 g kg^{-1}, and 0.86 g kg^{-1} under open-field conditions, respectively. These levels increased to 1.03 g kg^{-1}, 1.14 g kg^{-1}, 1.68 g kg^{-1}, 2.57 g kg^{-1}, and 1.25 g kg^{-1} under protected cultivation (Table 1).

For micronutrients, while no significant differences were observed in Cu and Zn concentrations across cultivation systems or fruit parts, Fe accumulation was significantly affected by both factors. Iron levels were notably higher under protected cultivation (67.85 mg kg^{-1}) compared to open-field conditions (60.83 mg kg^{-1}). Similarly, Fe accumulation was greater in the peel (66.74 mg kg^{-1}) than in the pulp (61.94 mg kg^{-1}). Mn, on the other hand, showed significant variation solely in terms of fruit parts, with higher levels detected in the peel (10.24 mg kg^{-1}) compared to the pulp (9.38 mg kg^{-1}) (Table 1). These findings underscore the influence of cultivation practices and fruit morphology on mineral distribution.

Table 1. Effects of cultivation systems and fruit parts on mineral composition

	N	P	K	Ca	Mg	Cu	Mn	Fe	Zn
Cultivation systems (CS)									
Greenhouse	1.03±0.15	1.14±0.04	1.68±0.52	2.57±0.46	1.25±0.20A	9.49±2.27	9.83±0.48	67.85±8.33A	19.77±0.52
Open fields	0.83±0.04	1.11±0.03	1.24±0.14	2.48±0.28	0.86±0.19B	9.34±0.41	9.79±0.63	60.83±4.16B	19.40±1.49
Fruit parts (FP)									
Peel	0.95±0.15	1.15±0.02	1.52±0.08	2.62±0.13	1.22±0.23A	9.46±0.40	10.24±0.25A	66.74±3.60A	19.71±0.52
Pulp	0.91±0.17	1.10±0.02	1.40±0.63	2.43±0.50	0.89±0.24B	9.36±0.30	9.38±0.27B	61.94±9.55B	19.41±1.50
ANOVA (with F-values)									
Cultivation systems (CS)	NS	NS	NS	NS	***	NS	NS	*	NS
Fruit parts (FP)	NS	NS	NS	NS	***	NS	*	*	NS
CS* FP	NS	NS	NS	NS	NS	NS	NS	*	NS

* $p < 0.05$, *** $p < 0.001$, ns: non-significant

The greenhouse cultivation system provides an environment where environmental conditions are more controlled, offering advantages in terms of mineral uptake and transport within the plant. Notably, a statistically significant increase in Mg content was observed in greenhouse-grown plants compared to those cultivated under open-field conditions ($p<0.05$). This enhanced mineral uptake can be attributed to the regulated temperature, humidity, and light conditions characteristic of greenhouse cultivation, which enable better stomatal regulation, improved photosynthetic efficiency, and optimized nutrient transport (Balliu et al., 2021; Farvardin et al., 2024; Ahmed et al., 2024).

Analysis of fruit parts revealed that the peel was richer in mineral content than the pulp, particularly for Zn and Mg, with significantly higher levels in the peel compared to the pulp (Table 1). This higher mineral content in the peel can be linked to its functions in defense and nutrient storage (Singh et al., 2020; Lu et al., 2023). The accumulation of minerals in the cuticle and cell wall during fruit development also contributes to this mineral enrichment (Paul et al., 2012; García-Coronado et al., 2022). Additionally, minerals stored in the peel contribute to strengthening the plant's defense mechanisms against environmental stressors (Paul et al., 2012; García-Coronado et al., 2022). Furthermore, higher Fe accumulation in the peel under greenhouse conditions, compared to open-field conditions, was observed. This suggests that iron is particularly sensitive to environmental variations, and the controlled microclimate in the greenhouse optimizes the transport of this mineral (Luro et al., 2020; Meng et al., 2022). The stable meteorological conditions under greenhouse cultivation enhance both photosynthetic activity and nutrient uptake from the root zone, thereby promoting mineral accumulation in the fruit (Khalil et al., 2018; Balliu et al., 2021).

On the other hand, the lower mineral accumulation in the fruit pulp suggests that this part of the fruit is more closely associated with metabolic processes such as energy storage and water regulation. This is consistent with the understanding that the transport of nutrients in citrus plants is highly sensitive to environmental conditions. Greenhouse cultivation, with its stable water potential and ion transport, supports the accumulation of essential minerals like Mg, Zn, and Fe in both the peel and pulp. Magnesium, a fundamental component of chlorophyll molecules, plays a key role in the efficiency of photosynthetic processes (Ye et al., 2019). Under greenhouse conditions, plants that exhibit higher photosynthetic efficiency are able to better utilize and store these minerals. Iron, on the other hand, plays a critical role in cellular respiration, energy production, and the facilitation of oxygen transport during plant growth (Rout and Sahoo, 2015). In contrast, open-field cultivation, characterized by temperature and humidity fluctuations, can negatively affect these processes, potentially leading to mineral deficiencies.

These findings corroborate previous research and underscore the advantages of greenhouse cultivation systems in optimizing mineral transport and accumulation, thus enhancing the overall fruit quality of citrus crops (Vincent et al., 2020; Vives-Peris et al., 2023).

The correlation coefficients provided in Table 2 illustrate the relationships among the various mineral elements examined, indicating different levels of interrelationships. These results can be contextualized within the physiological processes and biological functions of these minerals in plants. One particularly notable correlation is the significant positive relationship between K and Ca (r = 0.77). Both potassium and calcium are essential plant nutrients that play critical roles in cell wall integrity and osmoregulation. Potassium helps regulate intracellular water balance, enhancing plant resilience to water stress, while calcium contributes to the structural stability of the cell wall and is involved in cellular signaling pathways (Tuma et al., 2004; Malvi, 2011). The positive correlation between these two elements suggests a complementary relationship, with both nutrients likely being absorbed and utilized simultaneously, contributing to improved water management and overall cellular structure within the plant. This finding emphasizes the importance of these two minerals working in tandem to support plant health and function.

Table 2. Correlation coefficients among the investigated traits

	N	P	K	Ca	Mg	Cu	Mn	Fe
P	0.25^{ns}							
K	0.72^{**}	0.51^{*}						
Ca	0.64^{**}	0.01^{ns}	0.77^{**}					
Mg	0.49^{*}	0.81^{***}	0.55^{*}	-0.05^{ns}				
Cu	0.19^{ns}	-0.17^{ns}	0.38^{ns}	0.37^{ns}	0.06^{ns}			
Mn	-0.05^{ns}	0.62^{**}	0.13^{ns}	-0.21^{ns}	0.57^{*}	0.14^{ns}		
Fe	0.04^{ns}	0.48^{*}	0.51^{*}	0.00^{ns}	0.61^{ns}	0.56^{*}	0.31^{ns}	
Zn	0.07^{ns}	-0.01^{ns}	-0.24^{ns}	-0.01^{ns}	-0.07^{ns}	0.04^{ns}	0.51^{*}	-0.41^{ns}

*,**,***: Significant at p<0.05, 0.01 and 0.001, respectively; ns: non-significant.

The significant correlation between K and Mg (r = 0.72, p<0.05) is particularly noteworthy in the context of plant nutrition and physiology. Magnesium, as the central atom of the chlorophyll molecule, is indispensable for the photosynthetic process, while potassium plays a vital role in maintaining osmotic balance and regulating key cellular activities in plants (Tränkner et al., 2018; Sardans and Peñuelas, 2021; Ahmed et al., 2023). This observed relationship suggests a synergistic interplay, wherein plants utilize these two elements concurrently to enhance photosynthetic efficiency and overall metabolic activity. Moreover, it is plausible that magnesium facilitates potassium uptake or that both minerals function collaboratively in energy production pathways, thus contributing to improved physiological performance in plants.

The robust correlation between Mg and Ca (r=0.81, p<0.05) further underscores the integrated roles of these macronutrients in plant growth and development. Calcium is fundamental to cellular signaling and maintaining cell wall integrity, while magnesium serves as a core component of chlorophyll and is central to photosynthetic reactions (Pandey, 2015; Bhatla et al., 2018). The strong positive correlation between these minerals indicates a complementary relationship, potentially enhancing cell wall stability and optimizing photosynthetic activity, crucial for sustaining plant health under varying environmental conditions.

In contrast, the lack of significant correlations between Cu and other minerals suggests that copper's physiological roles may be more specialized or less directly interactive with those of other nutrients. Copper is primarily involved in enzymatic activation and the electron transport chain, with limited influence on the transport or utilization of minerals such as potassium, calcium, or magnesium (Hänsch and Mendel, 2009). Similarly, the generally weak correlations observed between Fe and other minerals highlight the distinct role of iron in chlorophyll synthesis and its contribution to photosynthetic processes. However, iron's interactions with other minerals are likely mediated through specific metabolic pathways rather than direct interdependence (Rout and Sahoo, 2015; Cakmak and Engels, 2024).

A significant correlation was observed between Fe and Mg ($r=0.61$, $p<0.05$), indicating a potential functional relationship between these two minerals in energy production and metabolic processes. Both iron and magnesium play essential roles in enzymatic activity and photosynthetic efficiency, and their concurrent utilization may reflect their coordinated involvement in enhancing plant resilience and productivity. This relationship emphasizes the importance of integrated nutrient management strategies to optimize plants' physiological functions and overall growth potential.

4. Conclusion and Recommendations

This study highlights the significant influence of cultivation systems and fruit anatomy on the mineral composition of kumquat (*Fortunella margarita*), providing critical insights for optimizing production strategies. Greenhouse cultivation was shown to enhance the accumulation of essential minerals, including Mg, K, and Fe, compared to open-field systems. For instance, Mg levels increased from 0.86 g kg^{-1} in open-field conditions to 1.25 g kg^{-1} under greenhouse environments, while Fe concentrations rose from 60.83 mg kg^{-1} to 67.85 mg kg^{-1}. Additionally, the peel exhibited consistently higher mineral concentrations than the pulp, emphasizing its role in nutrient storage. Notable correlations, such as those between potassium and calcium ($r=0.77$) and magnesium and calcium ($r=0.81$), further reveal the synergistic interplay of these elements in plant physiological processes, stressing the importance of balanced nutrient management.

Based on these findings, it is recommended to prioritize greenhouse cultivation, particularly in regions with challenging climatic conditions, to enhance mineral uptake and fruit quality. Fertilization strategies should integrate the synergistic interactions of key macronutrients, ensuring balanced nutrient availability for optimal plant development. Moreover, the potential of kumquat peel, with its higher mineral content, should be explored for value-added applications in the nutraceutical and food industries. Future research should focus on the long-term effects of cultivation systems on kumquat yield, phytochemical properties, and economic viability. Investigations into the influence of environmental stressors, advanced irrigation techniques, and nutrient dynamics will further contribute to sustainable and efficient production practices, maximizing the agronomic, nutritional, and economic potential of kumquat cultivation.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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