



Calcium, Magnesium and Potassium Nutrition of Peanut as Influenced by Soil Cation Ratios

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ABSTRACT

Background: Calcareous soils derived from limestone and related parent materials are widespread in southern Türkiye, including the eastern Mediterranean region. These soils typically contain high levels of exchangeable calcium and, in many cases, substantial amounts of magnesium. In calcareous environments, nutrient behavior is strongly linked to cation proportions. Where calcium (Ca) is abundant, it may influence the relative availability of magnesium (Mg) and potassium (K) through exchange-related interactions. Therefore, concentration values alone may not fully represent plant-accessible nutrient status. For this reason, evaluating soil fertility solely on the basis of individual nutrient concentrations may overlook imbalances that affect plant nutrition. To address this issue under practical field conditions, we examined selected soil cation ratios and their relationships with Ca, Mg and K concentrations in peanut grown in the Osmaniye region, where calcareous soils are dominant.

Methods: Field sampling was carried out in peanut-growing areas of Osmaniye province. A total of 45 surface soil samples were collected, together with the youngest fully expanded peanut leaves at the full flowering stage. Soil samples were air-dried, sieved and characterized in terms of pH, electrical conductivity (EC), calcium carbonate content, organic matter and exchangeable Ca, Mg and K concentrations. Leaf samples were oven-dried, ground and subjected to wet digestion prior to determination of Ca, Mg and K using atomic absorption spectrophotometry (AAS). Base cation saturation ratios were derived from exchangeable cation data. The associations between soil properties and leaf nutrient concentrations were examined using correlation analysis and principal component analysis (PCA). Spatial variability of selected parameters was mapped by kriging interpolation within a GIS environment.

Result: The study area is dominated by soils formed from the weathering of limestone and dolomite and this geological background is reflected in their chemical composition. Exchangeable Ca and Mg levels were consistently high, resulting in elevated Ca/K and Mg/K ratios across most of the sampling area and likely restricting K uptake, thereby causing K deficiency in peanut leaves. Both correlation analysis and principal component analysis (PCA) revealed clear antagonistic relationships between K and the divalent cations, whereas Ca and Mg tended to vary in the same direction. Spatial evaluation further showed that locations with higher soil Ca/K and Mg/K ratios frequently coincided with reduced foliar K levels. This pattern suggests that the dominance of Ca and Mg, largely controlled by parent material, may influence K nutrition in the region. Overall, the results support the consideration of cation balance, in addition to individual nutrient concentrations, when developing fertilization strategies for peanut production.

Key words: Cation interactions, Osmaniye plain, Potassium deficiency, Soil health, Spatial distribution.

INTRODUCTION

The nutrient availability of soil is governed by the relationship between individual concentrations and their relative balance within the soil exchange complex. Chemical equilibria and competitive interactions influence mobility, adsorption-desorption reactions and root uptake of plant nutrients. Maintaining productivity, therefore, depends on adequate nutrient supply as well as on the balance among essential soil elements (Shibaeva *et al.*, 2023). Balanced nutrient supply depends on improved agricultural practices, effective soil management and the integration of current scientific researches into practice.

Numerous studies have evaluated soil nutrient performance and have emphasized the need for targeted assessment of specific soil functions (Singh *et al.*, 2024). Soil health assessments support more pragmatic management strategies and are associated with improved sustainability in agricultural production (Shukla *et al.*, 2024). Effective plant nutrition strategies depend on maintaining balanced nutrient supply. A central aspect of this balance

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involves sustaining appropriate nutrient ratios in soil, since these ratios affect plant nutrient uptake (Gaspar *et al.*, 2015).

The base cation saturation ratio (BCSR) concept addresses this balance by emphasizing the relative distribution of Ca, Mg and K in the exchange complex. Earlier studies have suggested saturation ranges of approximately 60-75% for Ca, 10-20% for Mg and 3-5% for K (Zalewska *et al.*, 2018; Culman *et al.*, 2021). Some authors also include sodium (Na) within this framework and describe it as Ca-Mg-K-Na saturation (Tiecher *et al.*, 2022). Supporters of the approach propose that adjusting cation proportions may enhance soil structure and nutrient use efficiency (Roy *et al.*, 2020). This discussion becomes particularly relevant in calcareous soils, where elevated Ca and Mg levels are largely determined by parent material. Under such conditions, competitive interactions with potassium may become more pronounced. Evaluating cation balance in these environments can therefore help clarify whether ratio-based interpretations offer additional insight beyond conventional soil testing approaches.

The increasing interest in the BCSR approach, particularly within organic agriculture, has led many farmers to reconsider their soil management practices. Rather than focusing solely on individual nutrient levels, attention has shifted toward maintaining a more balanced cation composition. In this context, organic amendments are frequently used to enhance base cation status and contribute to improved soil quality (Murrell and Cullen, 2014). Adjusting Ca:Mg ratios in line with BCSR principles is therefore often regarded as part of a broader effort to sustain long-term soil productivity. In the United States, institutions such as the United States

Department of Agriculture, along with regional extension services, have incorporated elements of the BCSR concept into educational programs designed to support farmer decision-making in soil management (Culman *et al.*, 2021).

Peanut (*Arachis hypogaea* L.) is widely cultivated in the Osmaniye Plain of Türkiye, a region dominated by calcareous soils. In 2024, peanut production covered 576,419 decares and reached 246,796 tons, with an average yield of 428 kg per decare (TUIK, 2024). Existing research has explored the role of base cations in plant nutrition, yet the relationship between cation ratios and peanut nutrient status has received relatively limited attention. This study evaluates Ca, Mg and K nutrition through the use of soil cation ratios in peanut-producing areas of the Osmaniye Plain. Particular attention is given to the relationship between soil cation balance and peanut nutrient status and quality. The results help clarify nutritional conditions under calcareous soils and provide insight into the practical relevance of cation ratios for regional soil management.

MATERIALS AND METHODS

Site description

The research was carried out in Osmaniye Province in the Eastern Mediterranean region of southern Türkiye (Fig 1). The province is one of the main peanut-producing areas of the country. Sampling locations were distributed across the central district and agriculturally intensive basins, including Kadirli and Düziçi. The study area lies within the

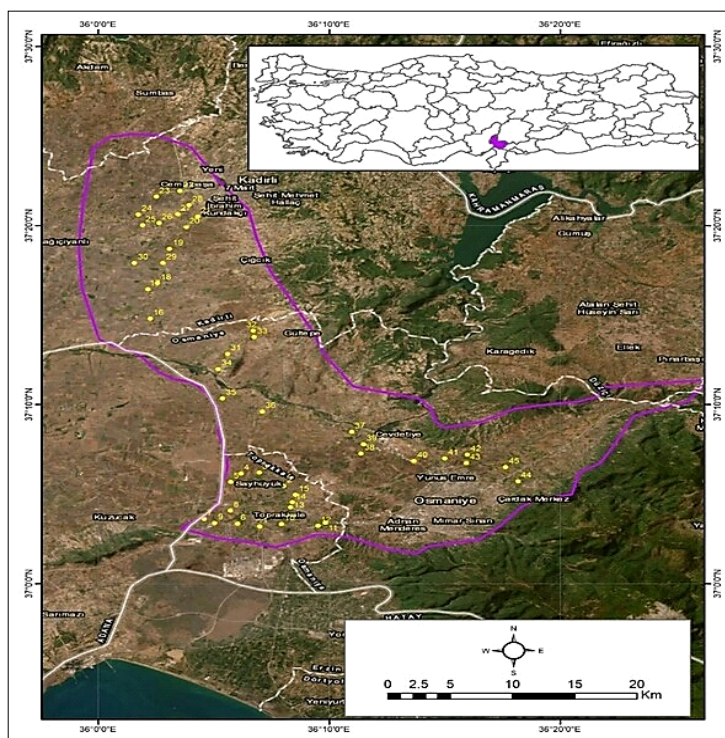


Fig 1: Map showing the geographical location of the study area and sampling sites.

alluvial plains at the eastern edge of Çukurova and extends toward the western foothills of the Amanos Mountains. The altitude of the sampled areas varies between 100 and 350 meters above sea level on average. A typical Mediterranean climate prevails in the region (Fig 1). Summers are hot and dry, while winters are mild and rainy. The average annual temperature is around 18-19°C and the total annual rainfall varies between 600-900 mm. These climatic characteristics are highly favorable for the vegetation process of plants such as peanuts (*Arachis hypogaea* L.), which require high temperatures and a certain moisture balance (Meteorological Report, 2026).

Sample collection and preparation for analysis

Soil samples were collected from agricultural fields cultivated with peanut. The geographic coordinates of each sampling location were recorded using a Magellan Explorer 610 Global Positioning System (GPS). In total, 45 soil samples were collected from the 0-20 cm soil depth. After air-drying under natural conditions, the soil samples were passed through a 2-mm sieve, prepared for analysis and stored in sealed plastic containers under cool conditions until further analysis (Richard, 1954).

Leaf samples were also collected from the same agricultural fields where soil sampling was conducted. During the full flowering stage, the youngest fully expanded leaves were collected from the main stem (Welch and Anderson, 1962). The collected leaves were first washed with a diluted HCl solution (0.1 N) and subsequently rinsed with deionized water, then oven-dried at 65°C for 48 h. The dried samples were ground, properly labeled and stored in nylon bags under cool conditions until chemical analyses were performed (Jones and Case, 1990).

Calculation of base cation saturation ratios values

Base cation saturation ratios (BCSR) were calculated based on the relative concentrations of exchangeable cations (cmolc kg⁻¹), following the method described by McLean (1977). The calculations were performed using the following equation:

$$\text{BCSR} = \frac{\text{Exchangeable cation 1 (cmol}_c \text{ kg}^{-1})}{\text{Exchangeable cation 2 (cmol}_c \text{ kg}^{-1})} \quad (\text{Equation 1})$$

Conducting soil and plant analysis

Soil pH and electrical conductivity were determined by saturation sludge (Black, 1965; Richards, 1954). Calcium carbonate (CaCO₃) content was measured using a Scheibler calcimeter (Klute, 1986), soil texture was determined by the hydrometer method (Bouyoucos, 1951) and soil organic matter content was analyzed according to the Walkley-Black method (Nelson and Sommers, 1996). Exchangeable cations were extracted with 1 N ammonium acetate as described by Helmke and Sparks (1996).

For plant analysis, 0.30 g of ground leaf samples were digested using a block digestion procedure with 0.5 mL nitric acid and 4 mL perchloric acid, following the method reported

by Jones and Case (1990). After digestion, the samples were filtered and potassium (K), calcium (Ca) and magnesium (Mg) concentrations were determined using an Agilent 240AA atomic absorption spectrophotometer (AAS).

Statistical analysis

Descriptive statistics for soil and plant parameters were computed using Microsoft Excel 2016. Principal component analysis (PCA) was conducted using JMP software (version 17) to evaluate the relationships between plant-available and total nutrient concentrations and soil cation ratios. Eigenvalues, eigenvectors and three-dimensional (3D) scatter plots were generated to facilitate interpretation of the multivariate data structure. Additionally, correlation matrices of parameters including cation ratios and concentrations in soils and plants, as well as graphical representations of the relationships among Ca, Mg and K concentrations in plant leaves, were produced using JMP 17.

Interpolation procedures for mapping studies

Spatial interpolation procedures for the Osmaniye study area were performed using Kriging methods, including Ordinary, Simple and Universal Kriging, to generate spatial distribution maps. A total of nine different interpolation models were evaluated for spatial mapping. These methods are widely applied in agricultural studies (Aytop *et al.*, 2023; Alaboz *et al.*, 2021; Neissian *et al.*, 2023; Ortel *et al.*, 2023). The most appropriate Kriging model for each parameter was selected based on Root Mean Square Error (RMSE) values. The Kriging method yielding the lowest RMSE value (Equation 2) was considered the optimal approach for the corresponding spatial map. All mapping procedures were conducted using ArcGIS software (version 10.7.1).

$$\text{RMSE} = \sqrt{\sum (Z_i - \hat{Z})^2 / n} \quad (\text{Equation 2})$$

Where,

Z_i = The predicted value.

Z = The observed value.

n = The number of samples.

RESULTS AND DISCUSSION

Soil characteristics of study field

Descriptive analysis of selected soil properties revealed that soil pH values varied from slightly alkaline to moderately alkaline (Table 1). According to the salinity criteria of Maas (1986), electrical conductivity values classified the soils as non-saline. Calcium carbonate contents varied widely, with a mean value of 22.61%. The average soil organic matter level was evaluated as moderate according to Ülgen and Yurtsever (1974).

Concentrations of exchangeable cations

Exchangeable cation concentrations in soils from the study area varied considerably, with mean concentrations of Ca (Ca-s), Mg (Mg-s) and K (K-s) of 8236, 1473 and 532 mg kg⁻¹, respectively (Table 2).

Base cation saturation ratios (BCSR) of the soils

Elemental analyses of soil samples indicated that Ca/K ratios ranged from 7.8 to 152, with a mean value of 38.5, while Ca/Mg ratios varied between 0.3 and 11.4, averaging 4.56. In addition, Mg/K ratios ranged from 1.9 to 64.6, with a mean value of 3.18 (Table 3).

Foliar concentrations of Ca, Mg and K

Foliar analyses of peanut plants revealed that Ca (Ca-p) concentrations ranged from 0.82 to 3.52%, with a mean value of 1.62%, while Mg (Mg-p) concentrations varied between 0.64 and 1.78%, averaging 1.29%. Potassium (K-p) concentrations ranged from 0.54 to 1.73%, with a mean of 0.98% (Table 4).

Effect of base soil cation ratios (BCSR) on plant nutrients

The distribution matrices of Ca-s, Mg-s and K-s concentrations and the Ca/K, Mg/K and Ca/Mg ratios in the soils of the Osmaniye region revealed a significant negative correlation between exchangeable soil Ca and K ($p < 0.01$; $r = -0.23$). Additionally, the soil Ca/K and Mg/K ratios exhibited significant negative correlations with exchangeable soil K, with correlation coefficients of -0.13

and -0.76, respectively ($p < 0.01$). Regarding plant tissue concentrations of the examined elements, plant K-p exhibited significant negative correlations with both Ca-p and Mg-p ($p < 0.01$; $r = -0.15$ and $p < 0.01$; $r = -0.59$, respectively). In contrast, a significant positive correlation was determined between plant Ca-p and Mg-p ($p < 0.01$; $r = 0.16$) (Fig 2).

Principal component analysis of the variables

Principal component analysis (PCA) performed on the cation ratios derived from available Ca, Mg and K contents of the soils collected from the Osmaniye region, along with leaf concentration data, identified three principal components with eigenvalues greater than 1. In each PCA component, variables exhibiting the highest loading values were considered representative of the cation ratios and plant concentrations. The loadings (weights) of soil and plant parameters associated with each principal component are presented in Table 5. Based on the loading criteria, the variable exhibiting the highest absolute loading value, together with other variables within approximately 10% of this value, was considered in the selection process (Andrews *et al.*, 2002). Among the six principal components,

Table 1: Soil characteristics of study field.

Osmaniye plain							
Soil parameters	N	Min	Max	Mean	SD	Skewness	Kurtosis
pH	45	7.49	8.50	8.04	0.22	0.04	-0.05
EC ($\mu\text{S}/\text{cm}$)	45	318	494	386	43.46	0.69	-0.02
Lime (%)	45	0.79	48.37	22.62	15.60	0.09	-1.36
OM %	45	0.70	3.68	2.15	0.57	-0.07	1.11

Table 2: Concentrations of exchangeable cations in study field (mg kg^{-1}).

Osmaniye plain							
Soil nutrient	N	Min	Max	Mean	SD	Skewness	Kurtosis
Ca-s	45	855.50	12625.00	8236	2333.91175	-1.039	1.318
Mg-s	45	440.00	4840.00	1473	884.99924	1.695	4.077
K-s	45	90.00	1170.00	532	268.39723	.355	-.799

Table 3: Ratios of exchangeable cations of study soils.

Osmaniye plain							
Ratio	N	Min	Max	Mean	SD	Skewness	Kurtosis
Ca/K	45	7.8	152.8	38.54	25.28	2.33	7.98
Ca/Mg	45	0.3	11.4	4.56	2.64	0.67	-0.02
Mg/K	45	1.9	64.6	12.30	11.51	2.51	8.39

Table 4: Concentrations of some macronutrients in peanut leaves from the study area.

Osmaniye plain							
Plant nutrient (%)	N	Min	Max	Mean	SD	Skewness	Kurtosis
Ca-p	45	0.82	3.52	1.62	.46496	1.614	5.38
Mg-p	45	0.64	1.78	1.29	.27882	-0.466	0.00
K-p	45	0.54	1.73	.98	.31022	0.435	-.792

PC1, PC2 and PC3, with eigenvalues of 2.53, 1.39 and 1.04, respectively, were selected. These principal components explained 42.274%, 23.230% and 17.482% of the total variance, respectively, accounting for a cumulative explained variance of 82.985% (Table 5). The eigenvectors associated with the three principal components with eigenvalues greater than 1, which cumulatively explained 82.98% of the total variance of the parameters, are presented in the table below. In PC1, Mg-p and K-p exhibited the highest loadings, indicating a strong contribution of these variables to this component. For PC2, Ca-p and Mg-p, together with the Ca/K and Mg/K ratios, showed high loadings and were identified as the main contributing variables. In PC3, Ca-p and the Ca/K and Ca/Mg ratios had the highest loadings and were the principal contributors to this component.

Based on the above-mentioned eigenvector values, examination of the three-dimensional (3D) representation of the principal components revealed contrasting directional patterns between plant K (K-p) concentrations

and those of Ca-p and Mg-p. As indicated in the eigenvector matrix, K-p exhibited negative loadings in PC1, whereas Ca-p and Mg-p were positively loaded. Similarly, in PC2, Ca-p and Mg-p showed negative loadings, while K-p was positively loaded. Taken together, plant Ca and Mg exhibited similar loading directions, in contrast to plant K, which exhibited an opposite trend. Consistent patterns were also observed in the 3D distribution matrix of these variables, reflecting their three-dimensional spatial relationships (Fig 3).

Spatial distribution model analysis of the study area

The exchangeable soil K concentration, soil Ca/Mg ratio and plant K concentration reported in Table 6 were based on normally distributed data. However, as the data for available soil Ca and Mg concentrations, soil Ca/K and Mg/K ratios and plant Ca and Mg concentrations did not meet the normality assumption, appropriate data transformations were applied and the transformed values are presented in the table.

Spatial distribution maps illustrating soil Ca, Mg and K concentrations, the Ca/Mg, Ca/K and Mg/K ratios, as well as the concentrations of these elements in peanut plants cultivated in the soils of the Osmaniye region, are presented in Fig 4. As depicted in these maps, soil Ca concentrations were consistently high across the entire study area, with markedly elevated levels recorded in the northern part of the region (Fig 4a). Soil Mg concentrations exceeded 1500 mg kg⁻¹ in more than half of both the northern and southern sections of the study area (Fig 4b). Soil K concentrations were relatively high in more than half of the study area and no signs of potassium deficiency were observed in the regional soils (Fig 4c). Across the plain, soil Ca/Mg ratios ranged between 6.6 and 11.2 (Fig 4d).

Table 5: Principal component analysis of soil Ca, Mg, K ratios and plant nutrient variables.

Variable	PC1	PC2	PC3
Ca/K	0.26	0.64	0.43
Ca/Mg	-0.47	0.20	0.44
Mg/K	0.51	0.39	-0.03
Ca-p	0.02	-0.43	0.75
Mg-p	0.46	-0.41	-0.02
K-p	-0.48	0.17	-0.21
Eigenvalue	2.53	1.39	1.01
Explained variance (%)	42.27	23.23	17.48
Cumulative variance (%)	42.27	65.50	82.99

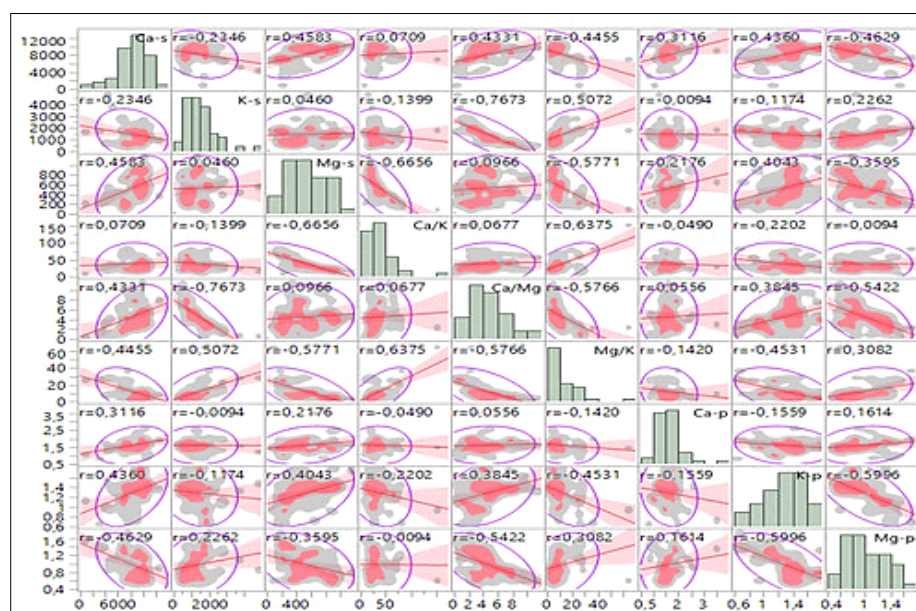


Fig 2: Scatterplot matrix for the comprehensive examination of correlations and regression lines.

The Ca/K ratio varied considerably, with values between 19.06 and 29.9 in some parts of the plain and higher values reaching 30 to 73.3 in others (Fig 4e). A similar spatial pattern was observed for the Mg/K ratio. Lower

values (2.7-11.2) were mainly observed in the eastern and northern parts of the plain, whereas higher ratios (11.3-46.8) occurred in the southern and western areas (Fig 4f).

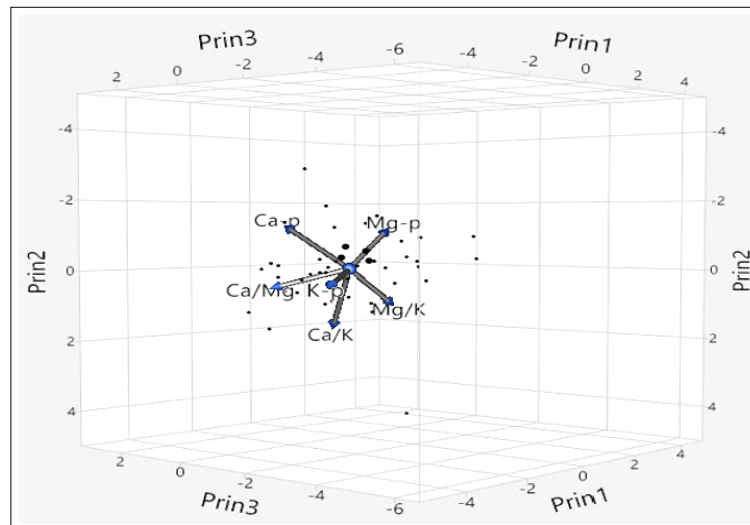


Fig 3: Scatterplot 3D dimension of six principal components.

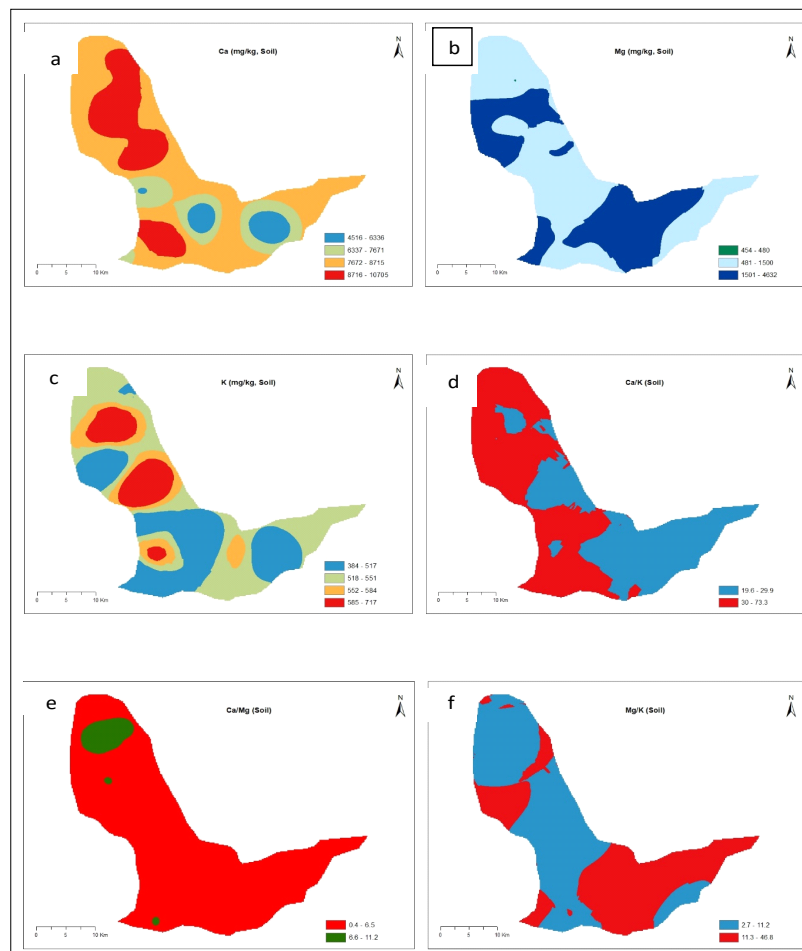


Fig 4: Spatial distribution of cation concentrations and ratios in the study area.

The spatial maps indicate that Ca concentrations in peanut leaves were above 1.26% across most of the study area (Fig 5a). K concentrations ranged from 1.20 to 1.25% in the southern and western parts of the region, with higher values (>1.33%) in the north (Fig 5b). Conversely, plant Mg concentrations exhibited a distinct spatial pattern, with lower values (0.7-0.8%) predominating in the northern areas and higher concentrations (0.9-1.3%) observed in the central and southern regions (Fig 5c).

A detailed assessment of the characteristic properties of the regional soils indicated that they predominantly exhibited slightly to moderately alkaline reactions, together with relatively high lime contents (Table 1). In accordance with the classification proposed by Rehm *et al.* (1996), nearly all soils in the study area were found to contain sufficient levels of potassium (Table 2). Based on the mean concentrations of Ca and Mg in the study area (Table 2), excessively high levels were identified over wide spatial extents of the region, as illustrated in Fig 4a-4b. Kalkanç *et al.* (2021) reported that the soils of the Osmaniye region are predominantly highly calcareous and contain high levels of plant-available calcium (Ca) and magnesium (Mg). The Osmaniye region is characterized by extensive agricultural lands developed on diverse parent materials, including basalt, basaltic tuff, marl, alluvial and colluvial deposits, limestone, ophiolite and serpentinite (Şimşek *et al.*, 2021). Koca (2000) also documented that the study area, located in the northern segment of the Amanos orogenic belt, is underlain by formations composed of interbedded Devonian-aged dolomitic limestone, shale, dolomitic breccia and sandstone. As inferred from the regional

geology, the elevated levels of plant-available calcium (Ca) and magnesium (Mg) in the soils are largely attributable to the mineralogical composition of the parent materials from which these soils have developed.

Evaluation of soil analyses and plant-available nutrient concentrations indicated that the Ca/K and Mg/K ratios in the soils of the study area were, on average, substantially higher than the proposed ideal cation ratios (Table 3). Additionally, the soil Ca/Mg ratio was comparatively closer to the ideal range, with a mean value of 4.56, relative to the other cation ratios (Table 3). The ideal cation ratios for Ca/K, Mg/K and Ca/Mg have been reported as 13, 2 and 6.5, respectively (Chaganti and Culman, 2017). Zalewska *et al.* (2018) reported that balanced mineral composition and suitable cation ratios were linked to higher yields. Potassium saturation above 5% was associated with increased yield, whereas excessive K accumulation reduced Mg and Ca concentrations and impaired forage quality. When K saturation declined below 4%, yield decreased in annual grass. The elevated soil Ca/K and Mg/K ratios observed here indicate a potential cation imbalance that may restrict optimal K nutrition. Attention to cation ratios may therefore help sustain yield and quality in the region.

Peanut leaves exhibited mean Ca, Mg and K concentrations of 1.62%, 1.29% and 0.98%, respectively. Reference thresholds reported by Jones *et al.* (1991) indicate that adequate foliar status is associated with K, Ca and Mg concentrations above 1.7%, 1.25% and 0.30%. A significant negative relationship was observed between Ca and K in plant tissues. Magnesium also showed a

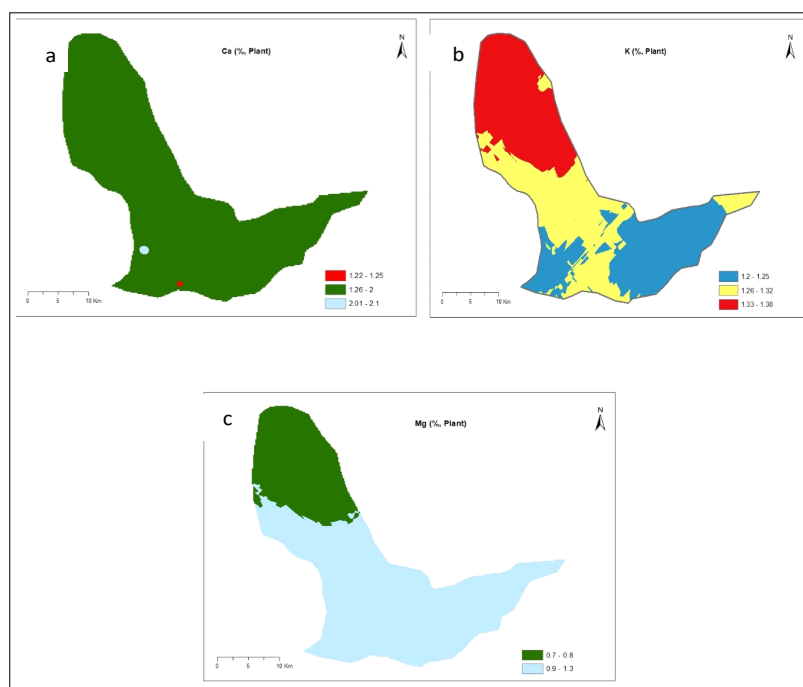


Fig 5: Spatial distribution of cation concentrations and ratios in the study area.

strong negative association with K (Fig 2). These results point to potential antagonistic interactions affecting K uptake. PCA results were consistent with these patterns. Plant Mg contributed positively to PC1, while plant K loaded negatively. In PC2, plant Ca and Mg were negatively associated, whereas plant K showed a positive loading, together with soil Ca/K and Mg/K ratios (Table 6). The 3D PCA score plot further reflects the contrasting responses of K relative to Ca and Mg (Fig 3).

Spatial distribution maps indicate a close association between soil cation balance and peanut nutrient patterns in the Osmaniye Plain (Fig 4-5). High soil Ca levels across much of the study area, particularly in the northern part, are consistent with carbonate-rich lithology and ongoing calcification processes. Likewise, Mg concentrations exceeding 1500 mg kg⁻¹ reflect the presence of dolomitic limestone and serpentine parent materials, contributing to Ca-Mg enrichment at the landscape scale. Although soil K concentrations were generally within adequate ranges, Ca/K and Mg/K ratios exceeded recommended thresholds in several parts of the plain, especially in the northern and eastern areas. Under these conditions, potassium availability appears to be influenced more by cation imbalance than by absolute soil K levels. Plant nutrient maps further show lower foliar K concentrations in locations characterized by elevated soil Ca/K and Mg/K ratios, whereas foliar Ca and Mg levels were comparatively high. These spatial trends align with the negative correlations observed in the statistical analyses and support the presence of antagonistic interactions among Ca, Mg and K. At the regional scale, K limitation therefore seems to be associated primarily with cation balance rather than with an overall shortage of soil K. From a management perspective, reliance on soil K concentrations alone may not adequately reflect nutritional constraints in peanut production. Incorporating Ca/K and Mg/K ratios into fertilization planning, particularly in calcareous environments, may provide a more reliable basis for nutrient management decisions. Nutrient interactions in soil-plant systems are complex and may shift between synergistic

and antagonistic responses depending on environmental conditions (Fageria, 2001). Elevated Ca and Mg concentrations can intensify ionic competition at exchange sites and reduce K uptake (Hannan, 2011; Wacal *et al.*, 2019). For instance, Pegues *et al.* (2019) reported a negative relationship between plant Ca and K following gypsum application. Similarly, Demir and Dikici (2025) observed excessive Mg accumulation and reduced K concentrations in plants grown on serpentine soils with high Mg/K ratios. Xie *et al.* (2021) further emphasized the importance of maintaining K⁺-Mg²⁺ balance, noting that imbalances in soil K/Mg ratios can restrict plant growth across species.

Potassium is fundamental to several physiological processes in plants, including stomatal regulation, nutrient transport and protein synthesis. In peanut, adequate K nutrition is associated with improvements in kernel size, test weight and overall yield performance (Nagaraju *et al.*, 2024). Previous research on legumes similarly demonstrates that potassium plays a pivotal role in regulating nutrient uptake and sustaining plant productivity. Potassium application has been shown to enhance growth, yield and nutrient acquisition in legume-based systems, including groundnut and lentil (Reddy *et al.*, 2023; Singh *et al.*, 2026). Furthermore, potassium-mediated mechanisms have been reported to improve plant performance under stress conditions, particularly in black gram (Ahmad *et al.*, 2025). In addition, improved nutrient management practices have been shown to increase nutrient uptake efficiency and crop productivity in legume systems (Balasubramanian *et al.*, 2024). Therefore, maintaining a balanced K status in the soil-plant system is critical for optimizing nutrient interactions under varying environmental conditions. Nutrient uptake reflects complex interactions among elements, which may be neutral, synergistic, or antagonistic (Rietra *et al.*, 2017). In the Osmaniye Plain, elevated Ca and Mg concentrations contributed to increased Ca/K and Mg/K ratios. Although soil K levels were generally sufficient, these imbalances were associated with comparatively low foliar K concentrations.

Table 6: RMSE values according to different interpolation models.

	Ordinary			Kriging			Universal		
	*Gau.	*Exp.	*Sph.	*Gau.	*Exp.	*Sph.	*Gau.	*Exp.	*Sph.
Ca-s	1918.445	1842.649	1879.106	1798.297	1829.593	1809.127	1918.445	1842.649	1879.106
Mg-s	728.8586	723.5433	730.5432	786.2766	708.0748	749.9119	728.8586	723.5433	730.5432
K-s	260.9544	260.4528	262.711	253.1777	253.3944	252.7346	260.9544	260.4528	262.711
Ca/Mg	24.651	24.32814	24.53957	24.501	24.4115	24.44288	24.651	24.32814	24.53957
Ca/K	1.879438	1.887025	1.894119	1.902909	1.813607	1.866923	1.879438	1.887025	1.894119
Mg/K	9.643482	9.582991	9.642381	8.594766	9.02544	8.747467	9.643482	9.582991	9.642381
Ca-p	0.4859619	0.4774118	0.480393	0.4536017	0.4548742	0.4543115	0.4859619	0.4774118	0.480393
Mg-p	0.2755067	0.2759632	0.2753566	0.2719499	0.2734088	0.2723394	0.2755067	0.2759632	0.2753566
K-p	0.2532998	0.2688671	0.2656705	0.2601609	0.2859165	0.26559	0.2532998	0.2688672	0.2656706

*Gau.: Gaussian, *Exp.: Exponential, *Sph.: Spherical.

Fertilization strategies should therefore account for cation balance in addition to soil K concentration. Where soil conditions limit nutrient transfer to plants, foliar K application may serve as a complementary approach. Direct foliar application can help reduce soil-induced antagonistic effects and mitigate K deficiency (Mikkelsen, 2017).

CONCLUSION

The results indicate a clear relationship between soil cation ratios and peanut nutrient status in the Osmaniye Plain, particularly with respect to K nutrition. High lime content and alkaline soil conditions were associated with elevated Ca and Mg levels across much of the study area, leading to increased Ca/K and Mg/K ratios. Although soil K concentrations were generally adequate, foliar analyses showed that K levels were often below sufficiency thresholds.

Correlation and principal component analyses consistently reflected negative associations between plant K and elevated Ca and Mg concentrations. Spatial patterns supported this interpretation at the regional scale. Together, these results suggest that reliance on individual soil nutrient concentrations may not fully explain nutritional limitations in calcareous environments.

Nutrient management in such soils may therefore benefit from considering Ca/K and Mg/K ratios alongside soil K levels. A cation ratio-based approach can provide additional insight into potassium constraints and may assist in refining fertilization strategies. Further field experiments evaluating different K fertilizer rates and foliar applications under high Ca and Mg conditions would help translate these observations into practical agronomic recommendations.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

All authors declare that they have no conflict of interest.

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