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**ORIGINAL PAPER**

# Assessment of Ca, Mg, and K nutrition in cotton through the base cation saturation ratio approach in southern Turkey*

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**Abstract**

Soil nutrient balance is a critical factor for ensuring optimal plant nutrition, yet fertilization strategies based solely on individual nutrient concentrations often overlook interactions among elements. This study evaluated cotton nutrition in the Ceyhan and Asagi Seyhan Plains of the Adana region, one of Türkiye's major cotton-producing areas, using the Base Cation Saturation Ratio (BCSR) approach. In this context, soil and cotton leaf samples were collected from 98 agricultural fields representing the region. The exchangeable concentrations of calcium (Ca), magnesium (Mg), and potassium (K) were determined in soil samples, while the foliar concentrations of these elements were measured in cotton plants. Soil analyses revealed elevated Ca and Mg levels, whereas K remained comparatively low. Accordingly, the mean soil cation ratios were 38.39 for Ca/K, 10.24 for Mg/K, and 4.14 for Ca/Mg, indicating a pronounced imbalance in the soil cation composition relative to the ideal cation balance. Foliar analyses revealed a significant negative correlation between K concentration and both Ca and Mg, whereas plant Ca and Mg concentrations were positively correlated. Principal component analysis (PCA) further supported these relationships, showing positive loadings of plant Ca and Mg and negative loadings of K on the first principal component. Spatial distribution maps confirmed that areas with elevated soil Ca/K and Mg/K ratios were associated with reduced foliar K concentrations. Moreover, concurrent increases in soil Ca and Mg were found to intensify potassium deficiency in cotton plants. Overall, the results demonstrate that elevated Ca and Mg levels in soils and plant tissues are closely linked to reduced K nutrition in cotton across both plains. These findings emphasize the importance of incorporating cation balance and nutrient interactions into soil fertility assessments to avoid underestimation of potassium limitations.

**Keywords:** foliar analysis, potassium deficiency, nutrient interaction, soil balancing, spatial distribution maps

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# INTRODUCTION

Supplying essential nutrients to growing plants at optimal levels has been shown to enhance crop productivity by improving nutrient uptake and use efficiency, which supports more effective plant growth and yield (Tang 2025). Balanced plant nutrition is among the most critical factors to address in this context. In recent years, numerous studies have been conducted to assess nutrient performance in agricultural fields and to develop relevant indicators (Quemada et al. 2020). Targeted assessment of specific soil functions represents a more pragmatic strategy for managing soil health (Vogel et al. 2019). In this context, various approaches exist for determination of nutrient concentrations in soils. As noted by Chaganti and Culman (2017), soil test results are usually interpreted through three main approaches used to determine fertilizer needs: Sufficiency Level of Available Nutrients (SLAN), Buildup and Maintenance, and Base Cation Saturation Ratio (BCSR). Among these, the SLAN approach evaluates each nutrient in the soil individually and determines its adequacy based on specific threshold values, whereas the Buildup and Maintenance method recommends applying nutrients in amounts equivalent to those removed through crop harvest (Chaganti and Culman 2017). An alternative approach, known as the BCSR approach, functions as a soil management strategy that seeks to achieve ideal ratios of exchangeable cations (Chaganti et al. 2021). In comparison with SLAN, BCSR, also known as mineral balance, proposes that maintaining appropriate ratios among soil cations is essential for optimal plant growth, and that imbalances may restrict plant growth (Gaspar, Laboski 2016).

Currently, the BCSR approach is being developed and spread by leading agricultural consultants and various soil testing organizations associated with the Agri-Climate Rural Environment Scheme (ACRES) (Ingram 2007). These organizations focus on the management of soil calcium (Ca) and magnesium (Mg) levels and generally advocate for the application of high-Ca lime and gypsum to enhance soil Ca base saturation levels (Culman et al. 2021). Theoretically, soil balancing emphasizes the critical role of Ca in both crop growth and the physical and chemical properties of the soil. Practitioners recommend balancing calcium levels with Mg and potassium (K) levels to achieve ratios considered to optimize soil health and nutrient availability (Brock et al. 2021).

According to Kopittke and Menzies (2007), ideal soil should have 65% Ca, 10% Mg, 5% K, and 20% H in its cation exchange sites. Consistently, Zalewska et al. (2017) observed the highest yield values in ryegrass at cation saturation levels close to those mentioned above. Additionally, it was observed that when K saturation exceeded 5%, potassium accumulation occurred in the plant, accompanied by a decrease in the concentrations of Ca and Mg. Haby et al. (1990) reported that high levels of K fertilization can

lead to a decrease in Mg uptake. Yang et al. (2024) have stated that balancing exchangeable cations improves nutrient availability in the soil and reduces the effects of competition among Ca, Mg, and K cations. The term 'soil balancing' has been a subject of considerable debate and discussion among farmers, consultants, and researchers. It may hold different meanings for different individuals, and its implementation by consultants and farmers can vary to some extent (Brock et al. 2021).

While there are studies examining the effects of basic cations on plant nutrition, there is a lack of sufficient data concerning the relationship between cotton nutrition and cation ratios. Some producers and agricultural consultants apply this approach to guide soil and crop management. However, there is an absence of clear understanding regarding the relationship between soil balancing and nutrient interactions, and this subject deserves further exploration (Chaganti, Culman 2017). According to the International Cotton Advisory Committee (ICAC), cotton was cultivated on 31.3 million hectares worldwide in the 2023/24 season (Ruiz 2024). In Turkey, cotton planting areas decreased by 16% compared to the previous season, reaching 478,000 hectares, and 2.1 million tons of seed cotton were produced (TUIK 2024). This study examines the Ca, Mg, and K nutrition of cotton in the Asagi Seyhan and Ceyhan Plains of Adana, one of Turkey's major cotton-producing regions, with a focus on soil cation ratios.

## MATERIALS AND METHODS

### Site description

The study area covers cotton farming areas in the Asagi Seyhan and Ceyhan Plains, located within the boundaries of Adana Province in Turkey's Mediterranean Region (Figure 1). The areas without cotton cultivation in the Ceyhan and Asagi Seyhan Plains were excluded from the study area. The area sampled in the Ceyhan Plain is approximately 19,510 ha, whereas in the Asagi Seyhan Plain, it covers 45,466 hectares. The long-term (1929-2023) annual average rainfall of the region within the study area boundaries is 668.3 mm, while the annual average temp. is 19.3°C. The region has a Mediterranean climate. In the Ceyhan Plain, 27,024 ha of soils are classified as Entisols, 26,945 ha as Vertisols, 14,458 ha as Inceptisols, and the remaining soils are Mollisols (Turgut et al. 2021). The majority of the soils in the study area of the Asagi Seyhan Plain are classified as Entisols and Inceptisols (Dinc et al. 1995).

### Sample collection and preparation for analysis

The samples were collected from agricultural fields where cotton (*Gossypium hirsutum* L.) is grown. The location data of the samples were recorded

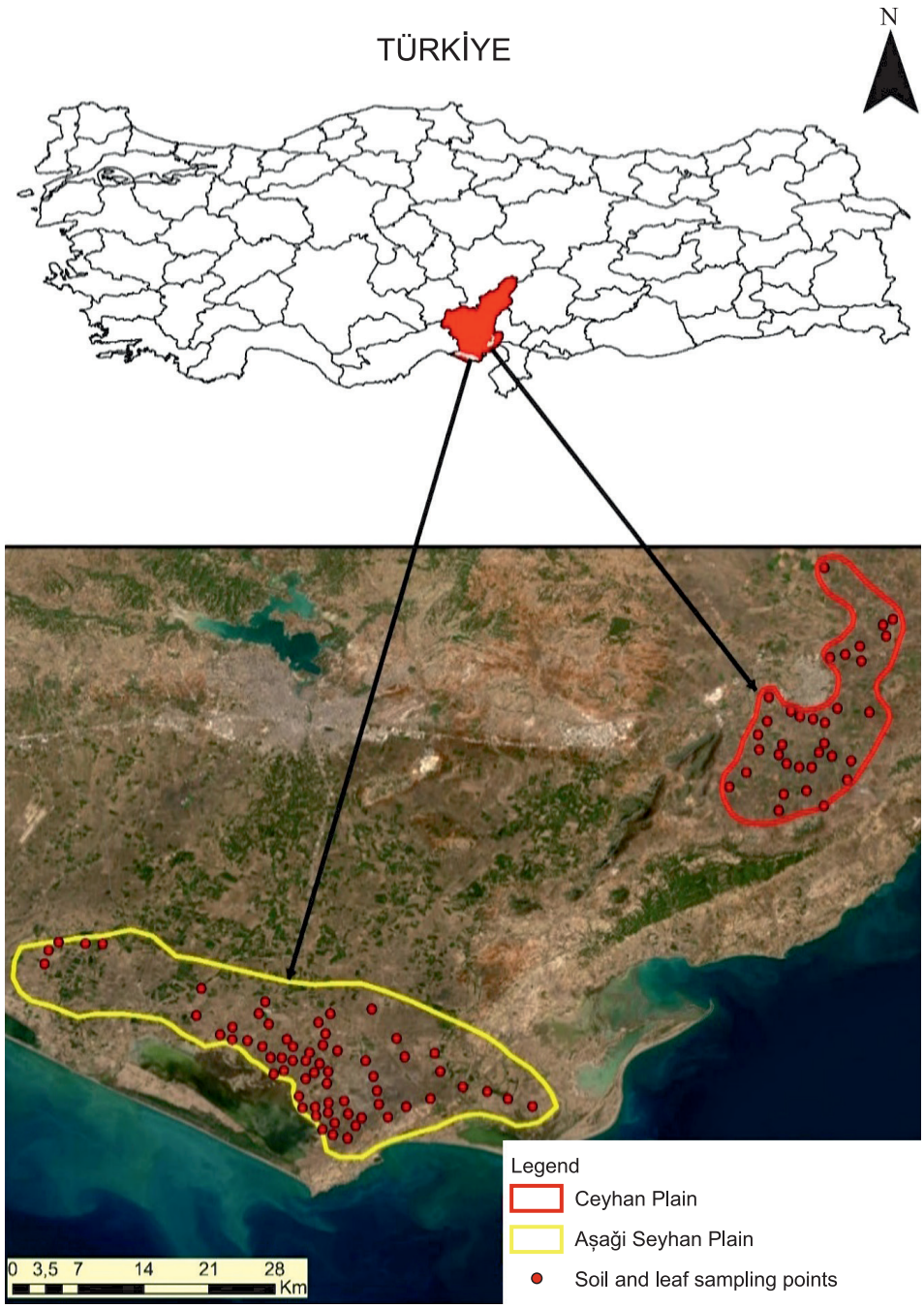



Fig. 1. Map of the study area and sampling points

using a Magellan Explorist 610 GPS (Geographical Positioning System). Accordingly, a total of 98 samples were collected from a depth of 0/20 cm. After being air-dried under natural conditions, the soil samples were sieved through a 2 mm mesh and prepared for analysis, then stored in sealed plastic containers in a cool environment (Richard 1954).

Leaf samples were also collected from the agricultural fields where soil samples were taken. During the flowering stage, newly matured youngest leaves on the main stem were collected (Samuels et al. 1959). The collected leaves were first washed with a diluted HCl (0.1 N) solution and then with distilled water in the laboratory and were left to dry in an oven at 65°C for 48 hours. The dried samples were ground and stored in labeled nylon bags in the refrigerator until analysis (Jones, Case 1990).

**Conducting of soil and plant analyses**

In the soils of the study area, pH and electrical conductivity were determined using the saturation sludge method (Black 1965, Richard 1954), lime content was measured with the Scheibler calcimeter (Klute 1986), texture was analyzed using the hydrometer method (Bouyoucos 1951), organic matter was assessed according to the Walkley-Black method (Nelson, Sommers 1996), and exchangeable cations were determined using 1N ammonium acetate as reported by Helmke and Sparks (1996).

A 0.30 g sample of leaf tissue was taken, and the block digestion procedure described by Jones and Case (1990) was followed using 0.5 ml nitric acid and 2 ml hydrogen peroxide, with subsequent digestion in a pressure microwave oven. After the digestion process, the samples were filtered, and K, Ca, and Mg concentrations were determined using an Agilent 5100 ICP-OES device.

**Calculation of BCSR values**

Basic cation saturation ratios (Ca/Mg, Ca/K, and Mg/K) were calculated by determining the relative proportions of individual cation concentrations (in cmolc $kg^{-1}$), as outlined by McLean (1972).

**Statistical analyses**

Descriptive statistics for the soil and plant analysis parameters were determined using the SPSS IBM 23.0 software. The relationships between the exchangeable and total concentrations of plant nutrients and the cation ratios in the soil were analyzed using principal component analysis (PCA) in JMP 17 software, and eigenvalues, eigenvectors, and 3D scatterplot views of the parameters were obtained. Correlation matrices for the parameters including cation ratios and concentrations in soil and plants as well as graphs for Ca, Mg, and K in plant leaves were also plotted using JMP 17.

### Interpolation procedures for mapping studies

Interpolation of a specific section of the Ceyhan and Asagi Seyhan Plains was carried out using the Kriging method (Ordinary, Simple, and Universal), and spatial distribution maps were created. For spatial distribution maps, 9 different interpolation models were used. These methods are frequently employed in agricultural studies (Alaboz et al. 2021, Aytop et al. 2023, Neissian et al. 2023, Ortel et al. 2023). The Root Mean Square Error (RMSE) values were used to determine the most suitable method among the Kriging techniques for the relevant parameters. The Kriging method that provided the lowest RMSE (Equation 1) value was identified as the most suitable method for the respective mapping parameter. All mapping processes were conducted using ArcGIS 10.7.1 software.

$$RMSE= \sqrt{(\sum(Zi-Z)^2/n)} \qquad \text{equation 1}$$

where: Zi – predicted value,
Z – measured value,
n – denotes the number of samples.

## RESULTS

### Soil characteristics of study field

The descriptive data for some characteristic properties of the soils taken from the study area are provided in Table 1. It is observed that the soil pH ranges over a wide spectrum from slightly acidic to slightly alkaline. It has been determined that 72% of the soils in the area exhibit slight alkalinity. Additionally, 20% of the soils show a neutral reaction, while 7% exhibit a moderately alkaline reaction (Saglam 2012). When examining the electrical conductivity values, it was determined that 90% of the soils are non-saline and 10% exhibit slight salinity, according to Maas (1986) classification. The lime content varies over a wide range, with the average value being

Table 1

Soil characteristics of study field

| Asagi Seyhan and Ceyhan Plains | | | | | | | |
|---|---|---|---|---|---|---|---|
| Soil Parameters | N | min | max | mean | SD | skewness | kurtosis |
| pH | 98 | 6.43 | 8.05 | 7.50 | 0.26 | -1.12 | 3.69 |
| EC (dS $m^{-1}$) | 98 | 0.13 | 2.86 | 1.15 | 0.65 | 0.41 | 0.03 |
| Lime (%) | 98 | 1.37 | 36.41 | 21.61 | 5.43 | -0.11 | 1.53 |
| OM (%) | 98 | 0.87 | 3.25 | 2.06 | 0.51 | -0.02 | -0.43 |
| Clay (%) | 98 | 21.10 | 77.86 | 49.16 | 14.33 | -0.09 | -0.81 |
| Silt (%) | 98 | 13.42 | 72.00 | 33.90 | 10.25 | 0.45 | 1.13 |
| Sand (%) | 98 | 0.78 | 63.58 | 16.94 | 11.01 | 1.87 | 4.26 |

21.81%. It was found that 69% of the soils have a high lime content, while 24% have an extremely high lime content (Ulgen, Yurtsever 1994).

## Concentrations of exchangeable cations

The concentrations of exchangeable cations in the soils sampled from the study area are presented in Table 2. It can be observed that the soil K (K-s) concentrations vary over a wide range, with an average value of 307.44 mg $kg^{-1}$. When examining the soil Ca (Ca-s) and Mg (Mg-s) concentrations in the area, it is found that the average concentrations are 5402.56 and 880 mg $kg^{-1}$, respectively.

Table 2

Concentrations of exchangeable cations in study field (mg $kg^{-1}$)

| Asagi Seyhan and Ceyhan Plains | | | | | | | |
|---|---|---|---|---|---|---|---|
| Soil Nutrient | N | min | max | mean | SD | skewness | kurtosis |
| Ca-s | 98 | 1106 | 8132 | 5389 | 1001.47 | -0.02 | 3.27 |
| Mg-s | 98 | 322 | 1586 | 880 | 290.42 | 0.19 | -0.73 |
| K-s | 98 | 84 | 608 | 308 | 116.99 | 0.46 | -0.43 |

## Base cation saturation ratios (BCSR) of the soils

When examining the cation ratios of the soils in the study area, it was found that the Ca-s/Mg-s ratio ranged from 0.89 to 9.00, with an average value of 4.14; the Ca-s/K-s ratio ranged from 17.67 to 84.26, with an average of 38.39; and the Mg-s/K-s ratio ranged from 2.70 to 28.98, with an average of 10.24 (Table 3).

Table 3

Ratios of exchangeable cations of Ceyhan and Asagi Seyhan Plains

| Asagi Seyhan and Ceyhan Plains | | | | | | | |
|---|---|---|---|---|---|---|---|
| Ratio | N | min | max | mean | SD | skewness | kurtosis |
| Ca-s/Mg-s | 98 | 0.89 | 9.00 | 4.14 | 1.60 | 0.96 | 0.84 |
| Ca-s/K-s | 98 | 17.67 | 84.26 | 38.39 | 13.75 | 1.13 | 1.26 |
| Mg-s/K-s | 98 | 2.70 | 28.98 | 10.24 | 4.38 | 1.26 | 3.50 |

## Foliar concentrations of Ca, Mg and K

The Ca, Mg, and K concentrations in cotton leaves were found to range from 1.51% to 6.08% for plant Ca (Ca-p), with an average of 3.64%; from 0.36% to 1.47% for plant Mg (Mg-p), with an average of 0.79%; and from 0.49% to 2.29% for plant K, (K-p) with an average of 1.21% (Table 4).

Table 4

Concentrations of some macronutrients in cotton leaves from the study area

| Asagi Seyhan and Ceyhan Plains | | | | | | | |
|---|---|---|---|---|---|---|---|
| Plant nutrient (%) | N | min | max | mean | SD | skewness | kurtosis |
| Ca-p | 98 | 1.51 | 6.08 | 3.64 | 0.90968 | 0.14 | 0.23 |
| Mg-p | 98 | 0.36 | 1.47 | 0.79 | 0.20706 | 0.54 | 0.69 |
| K-p | 98 | 0.49 | 2.29 | 1.22 | 0.43091 | 0.56 | -0.31 |

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

### Scatterplot matrix of measured parameters

The distribution matrices showed that soil Ca and Mg were positively associated with K, with significant relationships observed for Ca-K ($p$<0.01, $r$=0.51) and Mg-K ($p$<0.01, $r$=0.35). Additionally, the Ca-s/K-s and Mg-s/K-s ratios varied inversely with soil K levels ($p$<0.01, -0.79 and $p$<0.01; -0.627, respectively). On the other hand, when examining the concentrations of the mentioned elements in plant tissue, K-p is found to have a negative relationship with both Ca-p and Mg-p ($p$<0.01; -0.36, and $p$<0.01; -0.46, respectively). Increases in plant Ca concentrations were accompanied by corresponding increases in Mg levels ($p$<0.01; 0.39) – Figure 2. Assessment of the interac-

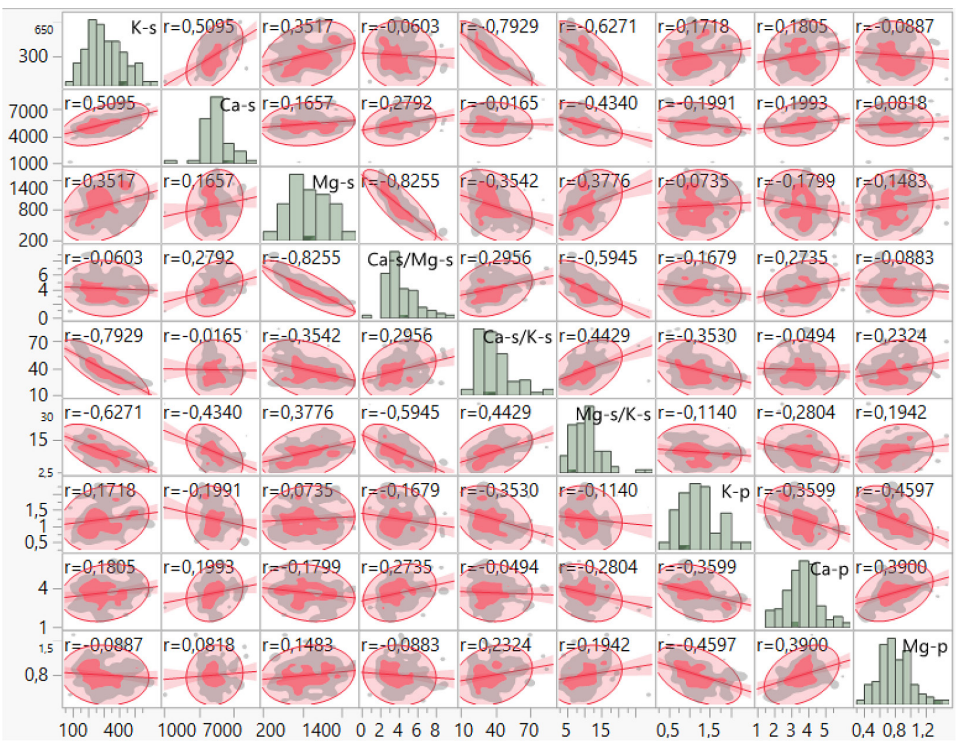



Fig. 2. Scatterplot matrix for the comprehensive examination of correlations and regression lines

tions among soil and plant nutrient concentrations and their elemental ratios revealed that the Ca-s/K-s and Mg-s/K-s ratios were inversely associated with plant potassium concentration (K-p). In addition, both plant calcium (Ca-p) and magnesium (Mg-p) levels showed significant negative relationships with K-p (Figure 2).

**Principle componential analyses of the variables**

Principal Component Analysis (PCA) was performed using soil cation ratios derived from Ca, Mg, and K concentrations, together with the corresponding specific foliar nutrient concentrations. Three principal components with eigenvalues greater than 1 were retained, collectively explaining approximately 83% of the total variance. The three-dimensional PCA scatterplot (Figure 3) illustrates the relationships among soil cation ratios and

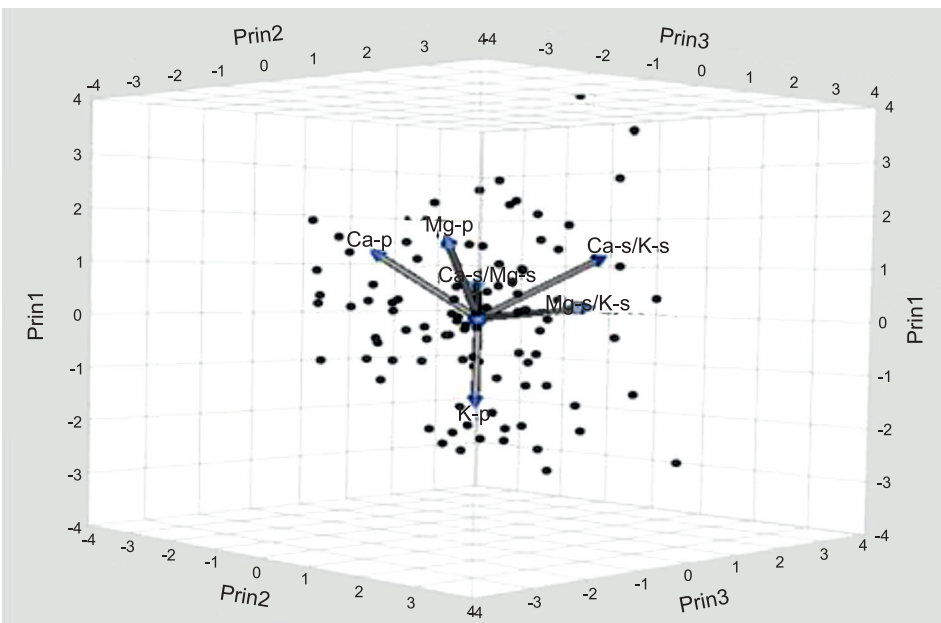



Fig. 3. Scatterplot 3D dimension of six principal components

foliar nutrient concentrations. In the first principal component, Ca-p and Mg-p are positioned in the positive loading space, whereas K-p is located in the opposite direction, indicating an inverse relationship between plant potassium concentration and calcium-magnesium accumulation. This opposing trend is consistently reflected in the 3D distribution of the principal components, indicating the antagonistic interaction between plant K and Ca-Mg nutrition in cotton.

## Spatial distribution model analysis of the study area

Nine different Kriging interpolation methods were employed to generate spatial distribution maps for the Ca, Mg, and K contents in the soils of Ceyhan and Asagi Seyhan Plains, as well as for the element ratios and the Ca, Mg, and K percentages in the leaves. The interpolation models with the lowest RMSE values were selected to determine the most accurate distribution maps (Table 5).

Table 5

Cross-validation of the data obtained from the study area according to Kriging models and RMSE values

| | Ceyhan Plain | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ordinary | | | simple | | | universal | | |
| | Gau | Exp | Sph | Gau | Exp | Sph | Gau | Exp | Sph |
| Ca-s | 1.0660 | 1.0314 | 1.0756 | 1.0918 | **0.9864** | 1.0673 | 1.0669 | 1.0317 | 1.0751 |
| Mg-s | 1.1200 | 1.1949 | 1.1285 | **1.0034** | 1.0000 | 1.0035 | 1.1208 | 1.1949 | 1.1280 |
| K-s | 1.1369 | 0.8958 | 1.0787 | 1.5090 | **0.8713** | 1.2172 | 1.1369 | 0.8958 | 1.0785 |
| Ca-s/Mg-s | 1.0383 | 1.0392 | 1.0500 | 0.9578 | 0.9578 | **0.9571** | 1.0386 | 1.0392 | 1.0500 |
| Ca-s/K-s | 1.1452 | 1.1424 | 1.1416 | 1.0647 | 1.0129 | **1.0501** | 1.1452 | 1.1424 | 1.1416 |
| Mg-s/K-s | **0.9594** | 0.9670 | 0.9713 | 1.0726 | 1.0614 | 1.0789 | 0.9594 | 0.9670 | 0.9713 |
| Ca-p | 0.5939 | 0.6219 | 0.6093 | 0.6738 | 0.6690 | 0.6736 | **0.5939** | 0.6219 | 0.6093 |
| Mg-p | **0.21966** | 0.2203 | 0.2185 | 0.2134 | 0.2143 | 0.2130 | 0.21967 | 0.2203 | 0.2185 |
| K-p | 0.3456 | 0.3467 | 0.3445 | 0.3264 | 0.3305 | **0.3209** | 0.3456 | 0.3467 | 0.3445 |
| | Asagi Seyhan Plain | | | | | | | | |
| Ca-s | 1.0673 | 1.0542 | 1.0723 | 0.9939 | 0.9936 | **0.9935** | 1.0684 | 1.0517 | 1.0795 |
| Mg-s | 0.9642 | 0.9775 | 0.9567 | 0.9346 | 0.9319 | **0.9261** | 0.9642 | 0.9706 | 0.9567 |
| K-s | 1.0635 | 1.0675 | 1.0675 | **0.9832** | 0.9847 | 0.9846 | 1.0626 | 1.0623 | 1.0698 |
| Ca-s/Mg-s | 0.9846 | 1.0011 | 0.9883 | 0.9138 | 0.9245 | **0.9014** | 0.9828 | 1.0010 | 0.9883 |
| Ca-s/K-s | 1.0981 | 1.0952 | 1.0784 | 1.0188 | **1.0114** | 1.0125 | 1.0982 | 1.0957 | 1.0782 |
| Mg-s/K-s | 1.0198 | 1.0270 | 1.0173 | 1.0030 | 1.0040 | **1.0021** | 1.0198 | 1.0215 | 1.0148 |
| Ca-p | 0.9245 | 0.9182 | 0.9271 | 0.8702 | 0.8718 | **0.8685** | 0.9241 | 0.9185 | 0.9271 |
| Mg-p | 0.1978 | 0.1974 | 0.1986 | **0.1936** | 0.1947 | 0.1940 | 0.1979 | 0.1974 | 0.1986 |
| K-p | 0.4374 | 0.4483 | 0.4421 | **0.4205** | 0.4311 | 0.4209 | 0.4374 | 0.4483 | 0.4421 |

Figure 4 shows the spatial distribution maps of the Ca, Mg, and K contents of the soils in the Ceyhan Plain (Figure 4*a*), the ratios between the elements (Figure 4*b*), and the percentages of Ca-p, Mg-p, and K-p in cotton leaves (Figure 4*c*). Upon examining the map, it can be observed that the Ca-s concentration is high across the entire study area. This is an expected result, as the parent materials of the plains have high lime contents (Dinc et al.

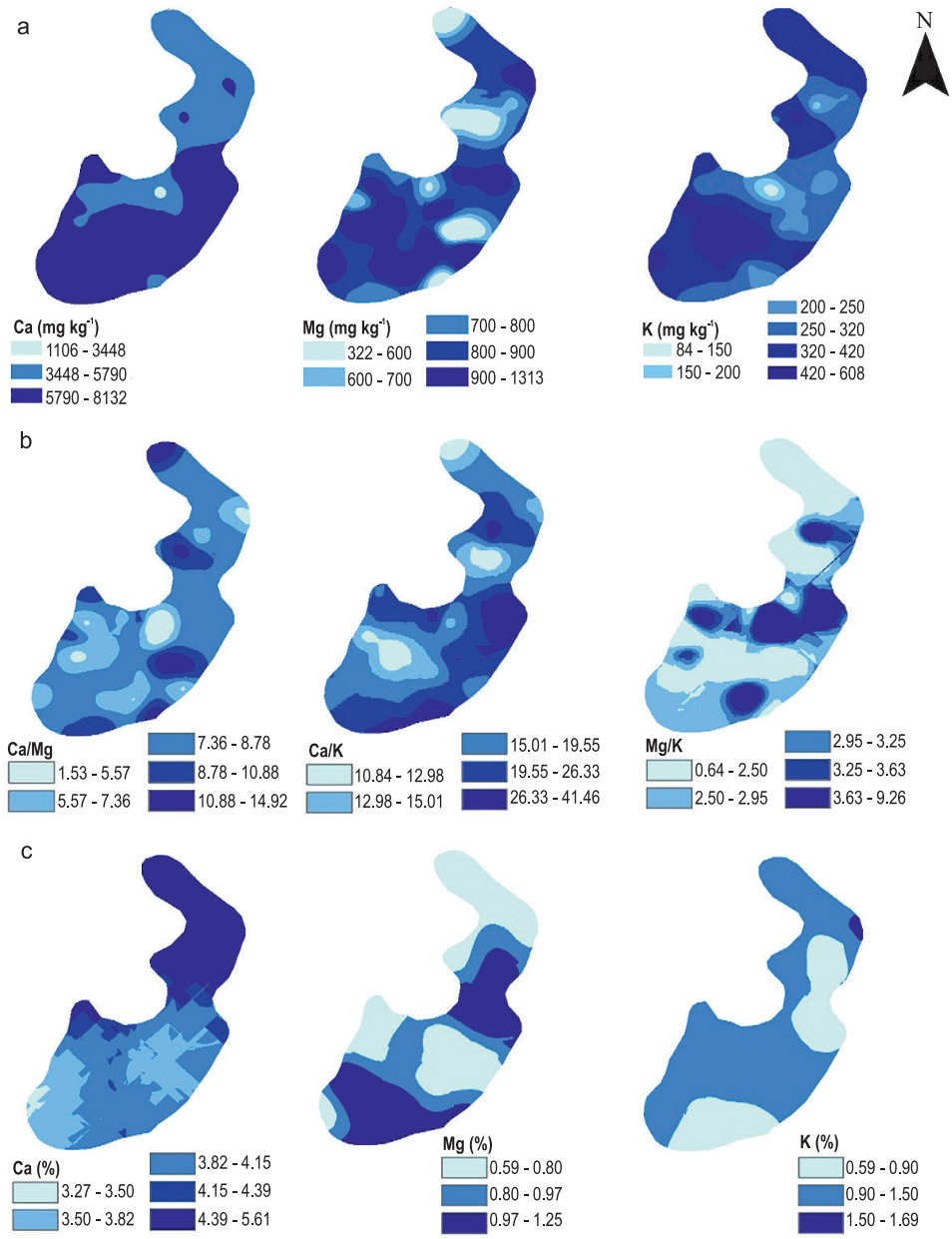



Fig. 4. Spatial distribution maps for the Ceyhan Plain showing (*a*) Ca, Mg, and K concentrations in soils, (*b*) soil cation ratios, and (*c*) concentrations of the corresponding cations in cotton leaves

1995). Particularly in the southern part of the region, the Ca concentration was found to be higher than 5790 mg $kg^{-1}$. The Mg-s content of the area was also determined to be high, especially in the southern regions. The K-s con-

centration in the soils of the Ceyhan Plain, however, was low in a small area of the central part, while it was at medium to high levels in the other sections of the plain (Figure 4*a*). The Ca/Mg ratio in the plain ranged between 7.36 and 8.78, while the Ca/K ratio ranged from 15.01 to 41.70. The Mg/K ratio in the plain, on the other hand, was observed to range between 0.64 and 2.95, particularly in the central parts of the study area (Figure 4*b*). Furthermore, as indicated by the spatial distribution maps, Ca-p concentrations across the entire Ceyhan Basin exceeded sufficiency levels and even increased to excessive levels toward the northern part of the basin. Similarly, Mg-p concentrations were sufficient throughout the basin, with more than half of the area exhibiting excessive levels. In contrast, evaluation of K-p values revealed widespread potassium deficiency within the basin, particularly in areas where soil Mg levels increased concurrently with Ca, in which K-p concentrations were observed to be extremely low.

The Ca, Mg, and K concentrations of the soils in the Asagi Seyhan Plain (Figure 5*d*), the ratios of these elements to each other (Figure 5*e*), and the Ca-p, Mg-p, and K-p contents in cotton leaves (Figure 5*f*) are illustrated in the map below. The Ca-s content of the soils in the Asagi Seyhan Plain is higher than 4807 mg $kg^{-1}$, according to the spatial distribution map. The Mg-s concentration was found to be higher than 900 mg $kg^{-1}$, particularly in the northeastern and southwestern parts of the study area. Across

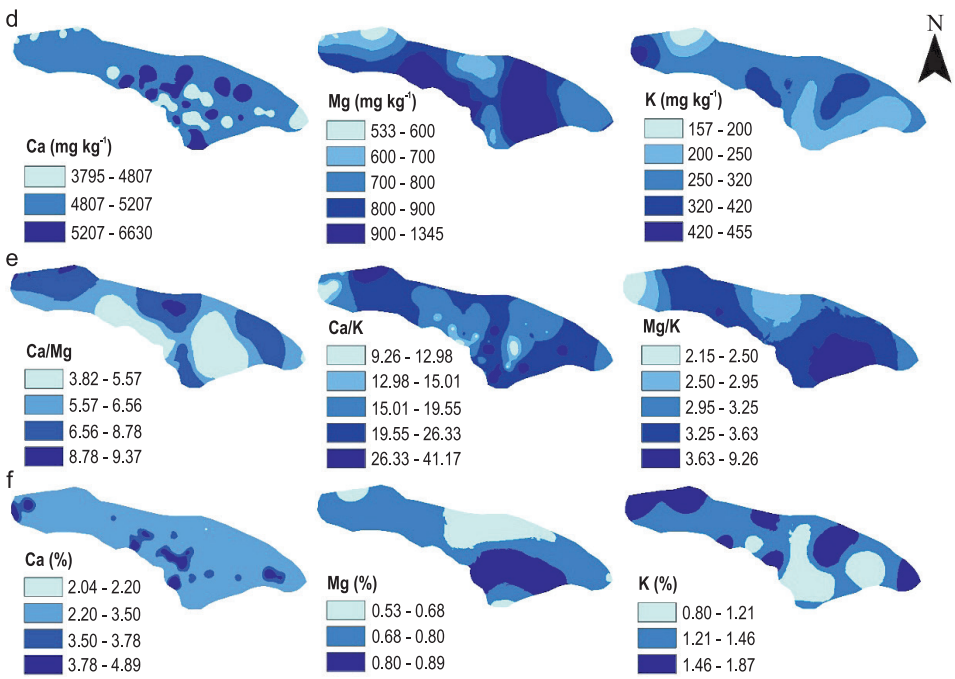



Fig. 5. Spatial distribution maps for the Asagi Seyhan Plain showing (*d*) Ca, Mg, and K concentrations in soils, (*e*) soil cation ratios, and (*f*) concentrations of the corresponding cations in cotton leaves

the entire study area, the K-s concentration is observed to be around 250-320 mg $kg^{-1}$. The spatial distribution maps of the Ca/Mg, Ca/K, and Mg/K ratios in the soils of the Asagi Seyhan Plain study area are presented in Figure 3*e*. The Ca/Mg ratio ranged from 3.82 to 9.37, the Ca/K ratio from 9.26 to 41.17, and the Mg/K ratio from 2.15 to 9.26. As indicated by the spatial distribution maps, Ca-p concentrations across the entire Asagi Seyhan Basin were above the established sufficiency levels. Similarly, Mg-p concentrations were fully sufficient throughout the basin and increased to excessive levels in the southern parts of the plain. In contrast, evaluation of K-p values showed that although potassium concentrations were sufficient in some areas, K deficiency predominated across the basin. Notably, extremely low K-p concentrations were observed in the southern sectors, where soil Mg levels increased concurrently with Ca, indicating a strong spatial association between elevated Ca-p and Mg-p status and reduced potassium nutrition.

## DISCUSSION

Assessment of soil properties in the study area reveals that most samples demonstrate a slightly alkaline reaction accompanied by high lime levels (Table 1). According to the threshold defined by Rehm et al. (1996), only 1% of the soils were classified as potassium-deficient, while the remainder exhibited adequate to high levels of K. Furthermore, based on the classification approach outlined by Loue (1968), calcium concentrations were found to be high in 99% of the soils across the region. The magnesium concentrations in the region's soils were found to be sufficient in 8% of the area, while 92% of the soils exhibit excessive levels of Mg (FAO 1980) – Table 2. Considering the mean values obtained, Ca-p and Mg-p levels in cotton leaves were within or above the sufficiency thresholds, whereas the average K-p concentration fell below the recommended range (Jones et al. 1990), indicating a potential limitation in K nutrition that may constrain optimal growth and physiological functioning under the prevailing soil cation conditions (Table 4). Potassium deficiency reduces photosynthesis and impairs the translocation of assimilates, limiting carbon allocation to growing tissues (Tränkner et al. 2018, Kusaka et al. 2021, Gu et al. 2024). Potassium is also essential for leaf expansion and cellular elongation in growing tissues (Halaji et al. 2023), and adequate potassium supply has been associated with enhanced water use efficiency in cotton under water-limited conditions (Yang et al. 2025). In this context, sufficient potassium nutrition improves stomatal regulation and plant water relations, thereby supporting sustained photosynthetic activity under drought stress (Zahoor et al. 2017, Zhu et al. 2022). Potassium deficiency in cotton can manifest at different crop growth stages, including persistent deficits throughout the season and transient shortages during high-demand periods such as boll development, when K demand is elevated

and uptake may not meet plant needs (Kommineni et al. 2024, Singh et al. 2024). In recent years, potassium (K) deficiencies have been increasingly reported in intensively managed cotton production systems in major cotton-growing regions, including China and other Asia–Pacific areas, despite regular fertilizer inputs, suggesting that high yield demand and soil nutrient imbalances can constrain effective K nutrition (Oosterhuis et al. 2013, Zhao et al. 2020, Shao et al. 2023).

Assessment of cation saturation ratios in the soils showed that the Ca-s/K-s and Mg-s/K-s ratios exceeded recommended levels, whereas the Ca-s/Mg-s ratio conformed to the ideal range (Table 3). The ideal cation ratios for Ca/K, Mg/K, and Ca/Mg are reported by researchers to be 13, 2, and 6.5, respectively (Kopittke, Menzies 2007). The high concentrations of Ca and Mg in the region's soils are clearly observed in the spatial distribution maps. Additionally, the soil potassium levels are found to be within adequate ranges. However, in both plains, a substantial proportion of the soils exhibits Ca-s/K-s cation ratios that considerably surpass the ideal values. On the other hand, in the Ceyhan Plain, the Mg-s/K-s ratio is below the ideal values in nearly half of the area, whereas in the Asagi Seyhan Plain, most of the soils exhibit Mg-s/K-s ratios above the ideal ones. In terms of the Ca-s/Mg-s ratio, the Ceyhan Plain exhibits a significant amount close to the ideal values, while a considerable portion of the Asagi Seyhan Plain falls below the ideal values (Figures 4*b*, 5*e*). The Mesozoic-aged limestones and dolomites, which are common in the Central and Eastern Taurus Mountains, are distributed in the northern and generally eastern parts of the Adana region (Yetis 2017). Dolomitization reactions represent diagenetic processes in which pre-existing limestone is chemically altered through interaction with magnesium-rich fluids, resulting in replacement by dolomite; recent studies document these mechanisms through geochemical and petrographic evidence in carbonate systems, and dolomite theoretically exhibits a 1:1 equivalent ratio of Ca and Mg on a $cmol_e\ kg^{-1}$ basis (Takamoto 2021, Liu et al. 2025). This condition is consistent with the soil Ca/Mg ratios being close to the ideal cation ratios in the region. Additionally, the fact that the Ca-s/K-s and Mg-s/K-s ratios exceed the ideal cation ratios is thought to be related to the significant presence of dolomites in the region from a geological perspective. In addition, the fact that the Ca-s/K-s and Mg-s/K-s ratios exceed the ideal cation values is thought to be related to the substantial presence of dolomites in the region from a geological standpoint.

Multivariate examination of soil and plant nutrient concentrations and elemental ratios revealed negative correlations between the Ca-s/K-s and Mg-s/K-s ratios and plant potassium concentration (K-p). Furthermore, both plant calcium (Ca-p) and magnesium (Mg-p) concentrations demonstrated a significant negative correlation with K-p (Figure 2). Foliar analyses from both the Ceyhan and Asagi Seyhan Plains revealed similar nutrient status patterns in cotton leaves. In both basins, Ca-p and Mg-p concentra-

tions were generally sufficient and frequently exceeded optimal levels. In contrast, potassium deficiency was widespread, with K-p concentrations commonly falling below the sufficiency threshold of 1.5% (Jones et al. 1990). Overall, a general pattern was observed in both basins, suggesting that extremely low K-p concentrations were associated with concurrently elevated Ca-p and Mg-p levels (Figures 4*c* and 5*f*).

The principal component analysis (PCA) of the relationships between cation ratios and foliar elemental concentrations revealed that Ca-p and Mg-p had positive loadings on PCA1, while K-p exhibited a negative loading (Figure 3). Principal Component Analysis (PCA) is a multivariate statistical method used to reduce the dimensionality of a dataset by identifying the underlying components, which are linear combinations of the original variables that explain the maximum possible variance of all the variables (Greenacre et al. 2022). The PCA analysis conducted in this study reveals a significant correlation between the increase in plant Ca and Mg concentrations and the reduction in K levels, as evidenced by both the PCA1 and the 3D distribution plots of the principal components (Figure 3). The graphs illustrating the binary combinations of leaf Ca-p, Mg-p, and K-p concentrations within these relationships are presented below. The analysis indicates a significant decline in potassium levels concomitant with an increase in both leaf calcium and magnesium contents. Furthermore, a positive correlation is observed between the increase in leaf calcium concentrations and the elevation of magnesium concentrations (Figures 6 *a*, *b*, *c*). The coexistence of multiple nutrients in soils and within the plant internal environment leads to interactions that influence nutrient uptake, assimilation, and metabolic activity, and these interactions may be antagonistic or synergistic depending on nutrient form, source, and availability (Fan et al. 2021, Kumar et al. 2021). Elevated concentrations of calcium (Ca) and magnesium (Mg) in soils can induce ionic competition, leading to the displacement of potassium (K) from soil colloids, which consequently contributes to potassium deficiency in plants (Hannan 2011, Wacal et al. 2019, Demir, Dikici 2025).

The relationships between Ca-p, Mg-p, and K-p in cotton leaves are presented in the graph below (Figure 7). Upon examining the charts illustrating the variation of Ca-p and K-p across different ranges of Mg-p, it is observed that as Mg-p concentrations exceed 0.73%, the decline in K-p concentrations becomes more pronounced. This suggests that the antagonistic effect of increasing Mg concentrations on plant potassium uptake is intensified in the presence of already high levels of calcium. Interactions among Ca, Mg, and K are widely recognized in plant nutrition because these cations compete for adsorption sites in soils and for uptake sites in plant roots. Consequently, an excessive supply of one cation may suppress the uptake of others and lead to nutrient imbalances in plants (Rietra et al. 2017, Xie et al. 2021). Several studies have also shown that imbalanced proportions of exchangeable base cations in soil can negatively affect potassium uptake and plant nutrient

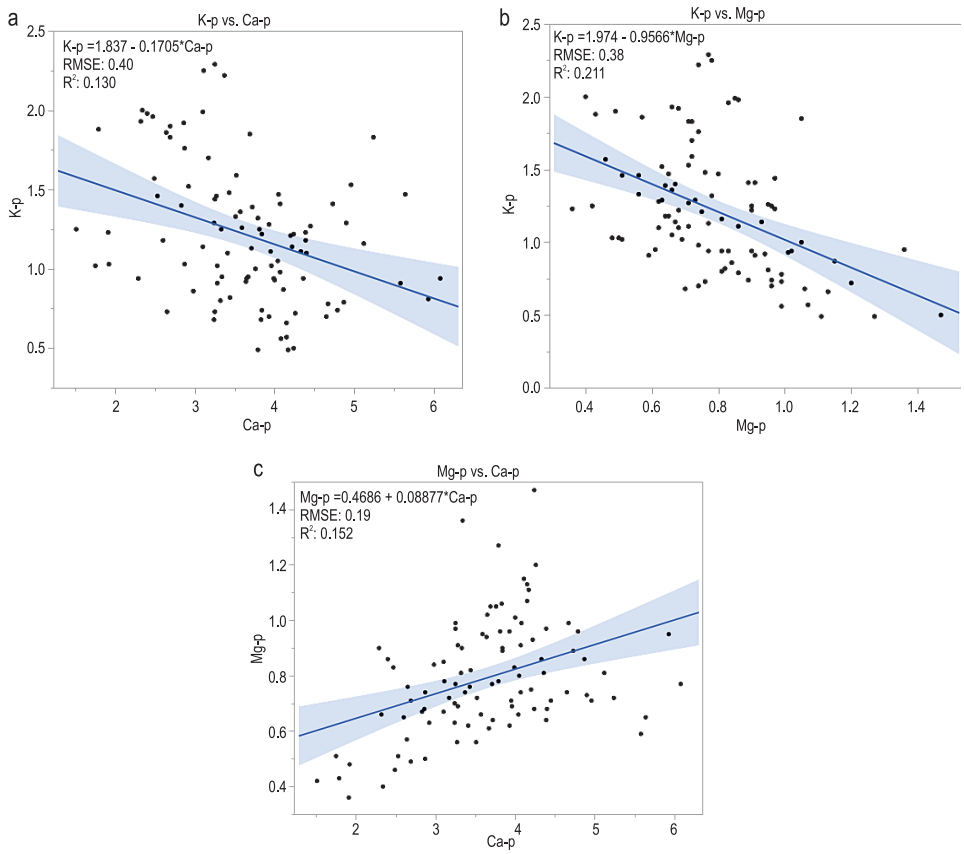



Fig. 6. Graphical illustration of the decline in K levels in response to increasing concentrations of foliar Ca – *a*, depiction of the negative correlation between foliar concentrations of Mg and K – *b*, graphical representation of the direct relationship between Ca and Mg concentrations in leaf tissues – *c*

status, emphasizing the importance of maintaining balanced Ca-Mg-K interactions in soil fertility management (Qu et al. 2023, Yang et al. 2024).

To achieve high yields while minimizing nutrient losses, it is essential to apply limiting nutrients in balanced proportions and to adjust fertilization practices according to soil chemical conditions and crop nutrient requirements, as supported by recent studies demonstrating improvements in nutrient use efficiency and crop productivity under balanced fertilization strategies (Zhang et al. 2025, Xing et al. 2025). In addition, sustainable nutrient management approaches, including organic amendments and the use of potassium-solubilizing bacteria, have been reported to enhance potassium availability and improve nutrient uptake by promoting mineral weathering and biological mobilization processes in soil (Yıldırım 2016, Saltalı, Yakupoglu et al. 2022, Yang et al. 2024, Akkaya et al. 2025). Since nutrient interactions have been investigated for only a limited range of crops,

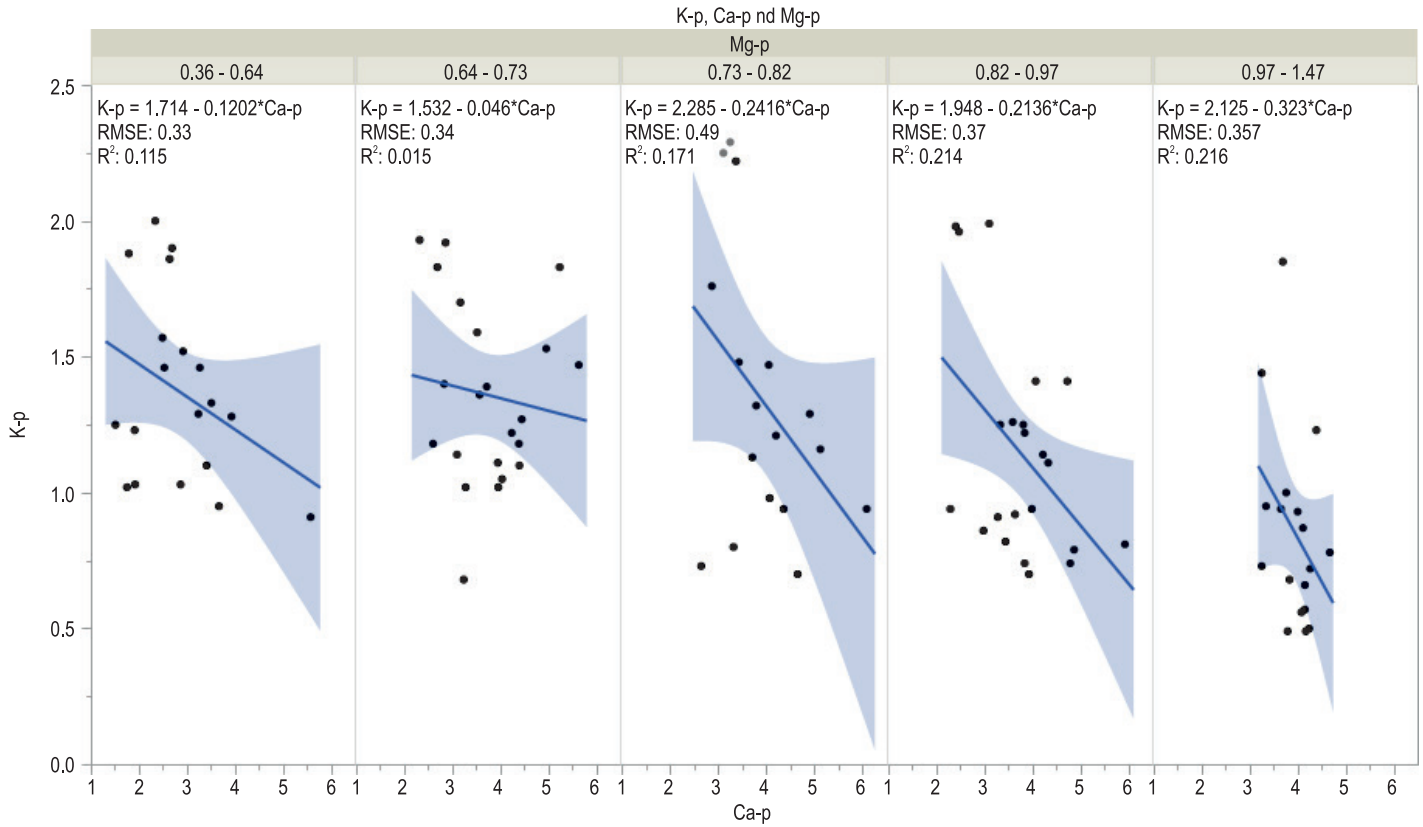



Fig. 7. Variations in K-p concentrations in response to increased foliar Ca content across different foliar Mg levels

nutrients, soil types, and climatic conditions, current knowledge remains largely general and cannot be directly applied to other production systems (Rietra et al. 2017). Consequently, further large-scale field studies are needed to improve our understanding of nutrient interactions and their implications for nutrient availability, plant uptake, and crop productivity under diverse soil and environmental conditions.

## CONCLUSIONS

Soils of the Asagi Seyhan and Ceyhan Plains did not show considerable deficiencies of Ca, Mg, or K. However, foliar analyses of cotton leaves revealed elevated concentrations of Ca and Mg, whereas potassium levels were below sufficiency thresholds, with some areas showing critically low values.

The findings indicate that in both plains, increases in plant calcium (Ca) and magnesium (Mg) concentrations are associated with a concurrent decrease in potassium (K) levels in cotton leaves. This relationship is clearly illustrated by the scatterplot matrix used to examine correlations and regression lines, as well as by the three-dimensional PCA scatter plot. Furthermore, regions with high concentrations of both Ca and Mg in plants exhibit more pronounced potassium deficiencies, as demonstrated by the spatial distribution maps and the interactions among the plant nutrients.

While there are several approaches to evaluating the sufficiency of nutrients in soil, it has been concluded that assessments based solely on individual elements may be inadequate for evaluating plant nutrition, particularly when ideal cation ratios are exceeded. In such cases, the Base Cation Saturation Ratio (BCSR) approach can serve as an additional tool for the comprehensive evaluation of Ca, Mg, and K levels in soil. Further field studies are required to improve our understanding of nutrient interactions and their effects on nutrient availability, plant uptake, and crop productivity across different soil and environmental conditions.

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### Author contributions

The idea of conducting this study – H. Aytop and Ö.F. Demir, soil sampling and laboratory analysis – C.H. Yilmaz and H. Aytop, written – Ö.F. Demir, H. Aytop, and C.H. Yilmaz. All the authors have read and approved the final manuscript.

## Conflicts of interest

The authors declare no conflict of interest.

## Supplementary material

The manuscript contains supplementary material available only online: https://jsite.uwm.edu.pl/articles/view/3769/

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