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RELATIONSHIPS BETWEEN THE MINERAL COMPOSITION OF FLOWERS AND LEAVES IN THREE PEACH CULTIVARS

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Abstract

Peach leaves function as the main organ for mineral accumulation and redistribution, reflecting soil conditions and cultivar characteristics, while the mineral composition of flowers provides an earlier indication of the tree's nutritional status. The present study examines the cultivars Cresthaven, Glohaven, and Redhaven using data on essential nutrients (N, P, K, Ca, Mg, and Fe) in flowers and leaves. Calculated elemental ratios reveal differences in nutritional balance and potential productivity among the cultivars. Principal Component Analysis (PCA) was performed, identifying variable correlation relationships between nutrient contents in flowers and leaves. Moderate to strong correlations were observed at 60 DAFB, particularly for P, Mg, Ca, and Fe, indicating coordinated physiological roles during early vegetative growth. The study provides a scientifically grounded basis for improving nutrient management strategies based on the individual needs of plants rather than a uniform approach.

Key words*: peach, nutrient management strategies.*

INTRODUCTION

Plant tissue analysis is a fundamental tool for diagnosing nutritional status, with leaf analysis traditionally considered the standard method in fruit-growing practice. In recent years, the classical diagnostic approach has expanded through the inclusion of different plant organs and the monitoring of nutrient dynamics during individual phenological stages. It has been established that flower analysis can serve as a complementary method to leaf analysis, particularly for early diagnosis at the beginning of the growing season (Gui et al., 2014; Martinez et al., 2003). Under conditions of pronounced nutrient deficiency or excess, this approach allows timely correction of fertilization before irreversible losses in yield and quality occur.

Studies on apple ('Gala') have demonstrated significant correlations between nutrient contents in buds, flowers, and leaves, creating opportunities for early assessment of nutritional status and optimization of fertilization practices (Mota et al., 2022). Similarly, in almond, flower analysis at the beginning of the growing season has been shown to predict the dynamics of macro- and micronutrients in leaves and fruits throughout the season (Bouranis et al., 2001).

Contemporary research emphasizes the importance of phenology-oriented diagnostics and integrated nutrient management strategies. Monitoring the seasonal dynamics of individual elements, including micronutrients, reveals pronounced variations associated with growth intensity and reproductive development (Kozin et al., 2025). Review publications highlight the necessity of applying the "4R" principles (right source, right rate, right time, and right place) and combining different diagnostic methods to increase the precision and sustainability of nutrient management (Muneer et al., 2024). The practical effectiveness of this approach has been confirmed in various fruit crops, where optimized fertilization rates significantly influence the mineral composition of leaves, as well as yield and fruit quality (Al-Saif, 2026; Ferreira et al., 2025; Wang et al., 2025).

Research in this field also emphasizes the integration of physiological, biochemical, and statistical approaches for a better understanding of growth, adaptability, and productivity in plant species. Methods such as Principal Component Analysis (PCA) are widely used to reveal complex relationships among studied traits, both in the context of physiological and nutritional analyses (Bolat et al., 2026) and in the synthesis of phenological and genetic variation (Nicolás-

Almansa et al., 2026; Osorio et al., 2026). The present study fits within this contemporary scientific framework by applying PCA for an integrated evaluation of mineral nutrition and physiological responses with an applied nutritional and diagnostic perspective.

The study aims to analyze the relationships between the contents of chemical elements in flowers and leaves of three peach cultivars in order to provide scientifically justified recommendations for nutrient application in peach production and to optimize production outcomes.

MATERIALS AND METHODS

The experiment was conducted during the period 2023-2024 in a fruit-bearing peach orchard including the cultivars Cresthaven, Glohaven, and Redhaven. Samples for mineral composition analysis were collected from 15 trees of each cultivar, with each tree considered as a separate replication. Flower samples were collected at the phenological stage "Full Bloom" (FB - more than 75% of flowers open), with 110 whole flowers taken from each tree. Leaf samples were collected at 60 and 120 days after full bloom (DAFB) from the middle part of one-year-old shoots.

The content of the main nutrient elements in flowers and leaves was determined as follows: nitrogen (N) by the Kjeldahl method; potassium (K) by flame photometry; phosphorus (P) and iron (Fe) by spectrophotometry; and calcium (Ca) and magnesium (Mg) by complexometric titration.

Principal Component Analysis (PCA) was applied in the study to examine the correlation relationships between chemical elements in flowers and leaves of the three cultivars. The results of the analysis indicate which elements have the greatest significance for the overall mineral pattern of the plants in the experiment. Principal Component Analysis is widely used in economic and agroeconomic research (Keranova et al., 2022; Masheva & Uzunhalieva, 2025; Sharma et al., 2025; Amir et al., 2026; Khadici et al., 2026).

To evaluate the relationships between the contents of chemical elements in flowers and leaves of the studied peach cultivars, Spearman's rank correlation coefficient (ρ) was used. A standardized interpretation scale was applied: ρ = 0.00–0.19 (very weak correlation, indicating no relationship between variables); ρ = 0.20-0.39 (weak correlation); ρ = 0.40-0.59 (moderate correlation); ρ = 0.60-0.79 (strong correlation); and ρ = 0.80-1.00 (very strong correlation). The correlation analysis was applied in a cross-comparison between the element contents in flowers and the different elements in leaves analyzed on the 60th and 120th day after flowering, in order to identify potential physiological and nutritional interactions relevant to mineral nutrition management in peach.Principal Component Analysis was calculated using the following formula: $PC1 = a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_4 \cdot X_4$, where a_1, a_2, a_3, and a_4 represent the factor loadings (the importance of the indicators), and X_1, X_2, X_3, and X_4 are the standardized variables (the chemical elements in the present study). The principal components are arranged according to the explained variance - PC1 explains the largest proportion, PC2 the next most important, and so on. In physiological analysis, the variance aims to demonstrate the importance of the chemical elements for the overall plant model.

RESULTS AND DISCUSSIONS

The obtained results indicate that mineral nutrition in peach is a dynamic process strongly dependent on the phenological stage and the agroecological conditions during the respective year.teractions between nutrient elements change both over time (FB, 60 and 120 DAFB) and between years, which corresponds to contemporary concepts of variable nutritional status in fruit crops under the influence of climatic factors, agricultural practices, and physiological activity (Cai et al., 2023).

In 2023, the correlation analysis between elements in flowers and those in leaves at 60 DAFB for the cultivar *Cresthaven* demonstrated the presence of several moderate and strong relationships between elements in flowers and leaves, indicating that flower analysis may serve as an early indicator of the subsequent mineral status of vegetative organs (Figure 1). The most pronounced relationships were observed for the following element pairs: Ca (Flowers) - K (Leaves); P (Flowers) - P (Leaves); P (Flowers) - Mg (Leaves); Fe (Flowers) - Fe (Leaves). At

60 DAFB, a strong synergistic interaction between P–Fe–Mg was observed, associated with intensive growth and high photosynthetic activity, while K showed antagonistic relationships with micronutrients.

At the later stage (120 DAFB), the synergism between P–Ca–N increased, which is associated with fruit formation and ripening, while Fe showed a clearly expressed antagonism toward the main macronutrients. The interactions among the elements became more structured, indicating a redistribution of nutrients toward the fruits (Figure 2).

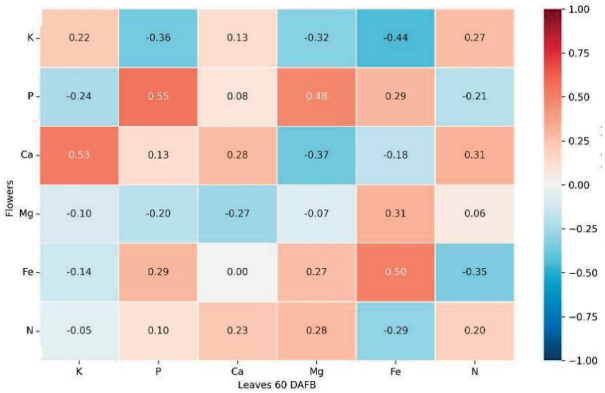

Figure 1. Correlation matrices showing the relationships between chemical elements in flowers and leaves at 60 DAFB in the cultivar 'Cresthaven' in 2023

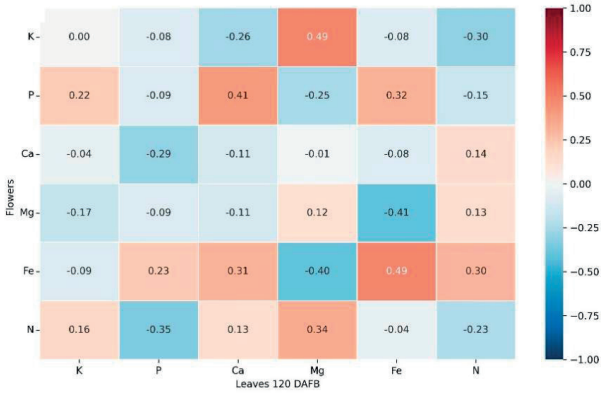

Figure 2. Correlation matrices showing the relationships between chemical elements in flowers and leaves at 120 DAFB in the cultivar 'Cresthaven' in 2023

In 2024 (60 DAFB), a strong positive correlation was established between P (Flowers) – Mg (Leaves) and N (Flowers) – Mg (Leaves), as well as a moderate relationship between Fe (Flowers) – N (Leaves), highlighting the role of magnesium in early physiological processes. A pronounced negative relationship was also recorded between Ca (Leaves) and Mg (Flowers), indicating antagonism between the two elements (Figure 3). These interactions suggest an active exchange among macroelements at the early stage of development.

At 120 DAFB, the correlation relationships weaken, with only a moderate dependence between Fe (Flowers) – N (Leaves) remaining (Figure 4). This confirms the dynamic nature of the mineral balance during different phenological phases.

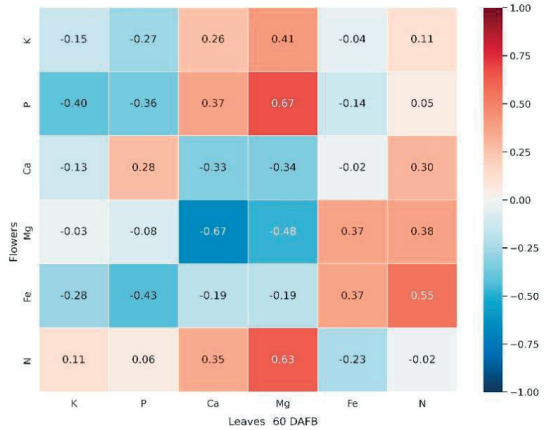

Figure 3. Correlation matrices of the relationships between chemical elements in flowers and leaves at 60 DAFB of the 'Cresthaven' cultivar in 2024

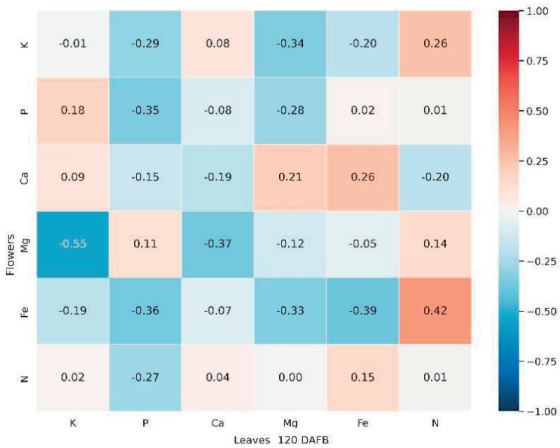

Figure 4. Correlation matrices of the relationships between chemical elements in flowers and leaves at 120 DAFB of the 'Cresthaven' cultivar in 2024

The application of a comprehensive PCA identified the leading chemical elements that describe the mineral balance of the plant.

The results are presented through a Scree plot figure, which facilitates the visualization of the significant components, and through a table describing the component loadings of the chemical elements, where a higher value indicates a greater physiological contribution (Figure 5).

The PCA results reveal a clearly structured mineral balance, in which the first two principal components (PC1 and PC2) explain the major part of the variation. Of particular interest is the fact that the leading elements change between 2023 and 2024 and also between the cultivars.

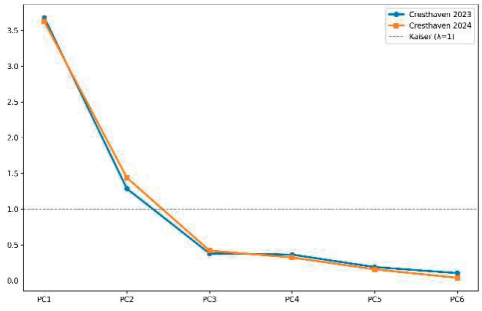

Figure 5. Eigenvalues of the principal components for 2023 and 2024

In 2023, PC1 was dominated by Fe, P, Mg, and K, whereas in 2024 a rearrangement was

observed with a stronger contribution from Ca and Mg (Table 1). In 2024, Fe showed a strong loading in the second component (PC2), indicating a change in its role within the overall elemental structure.

This reorganization of the component loadings reflects physiologically driven changes in nutrient priorities, likely influenced by climatic conditions and yield load. These two factors represent a prerequisite for strengthening the robustness of the study through the accumulation of a longer statistical data series.

Table 1. Component loadings of chemical elements for the 'Cresthaven' cultivar in 2023 and 2024

Chemical elements	2023 PC1 (%)	2023 PC2 (%)	2024 PC1 (%)	2024 PC2 (%)
K	19.32	5.18	23.26	2.43
P	19.88	2.75	19.52	5.72
Ca	18.60	16.24	23.16	4.52
Mg	19.46	7.86	**23.98**	0.36
Fe	**20.63**	0.91	1.35	**54.67**
N	2.12	**67.11**	8.75	32.23

Based on the conducted study, it was established that the application of combined fertilizers should not follow a uniform scheme throughout the entire growing season, but should instead be based on a stage-specific analysis of plant material. Flower analysis is used for early diagnosis of the mineral status and for guidance regarding initial corrective measures. Around the 60th day after full bloom (DAFB), a leaf analysis is performed, allowing targeted fertilization - either jointly in the presence of synergistic relationships between elements or sequentially in the case of antagonistic interactions.

By the 120th day after full bloom, when the correlation relationships weaken and become restructured, fertilization should be individualized and limited to the correction of specific deficiencies, with the aim of maintaining the mineral balance, rather than through general combined applications.

The correlation relationships between elements in flowers and leaves in the 'Glohaven' cultivar do not follow a common pattern but vary over time. In 2023, the correlation analysis at 60 DAFB revealed moderate relationships between K (Flowers) – Mg (Leaves), P (Flowers) – Fe (Leaves), and N (Flowers) – N (Leaves) (Figures 6 and 7).

In 2024, at 60 DAFB, moderate positive correlations were observed between Ca (Flowers) and Ca (Leaves), as well as between N (Leaves) and Mg (Flowers), while Fe (Leaves) showed a strong negative relationship with K (Flowers). At the second sampling date (120 DAFB), the correlations weakened, with Ca showing more pronounced negative relationships with N and P (Figures 8 and 9). This suggests that as leaf development progresses, the interactions among nutrient elements change.

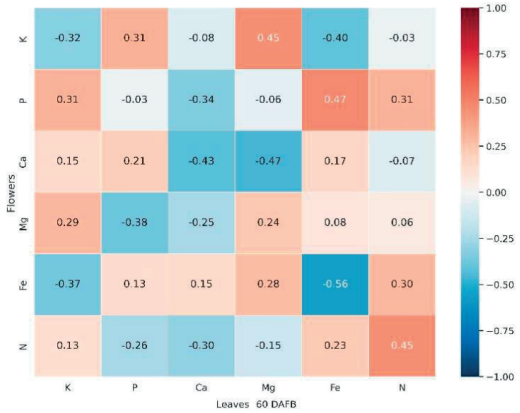

Figure 6. Correlation matrices of the relationships between chemical elements in flowers and leaves at 60 DAFB for the 'Glohaven' cultivar in 2023

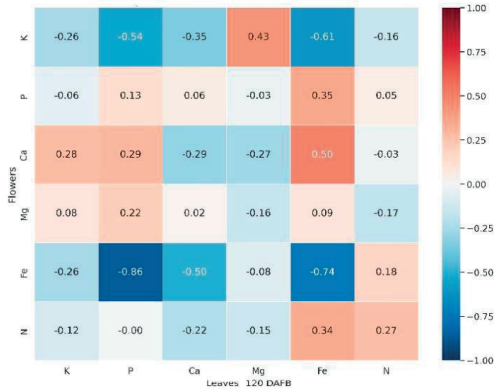

Figure 7. Correlation matrices of the relationships between chemical elements in flowers and leaves at 120 DAFB for the 'Glohaven' cultivar in 2023

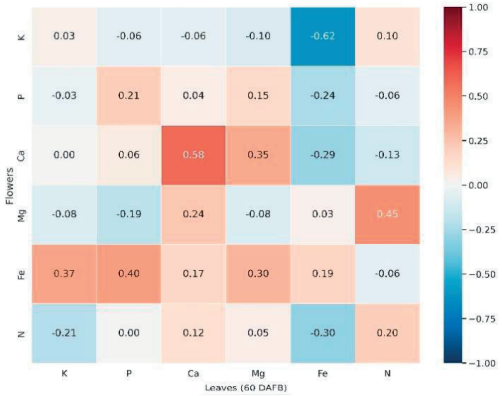

Figure 8. Correlation matrices of the relationships between chemical elements in flowers and leaves at 60 DAFB for the 'Glohaven' cultivar in 2024

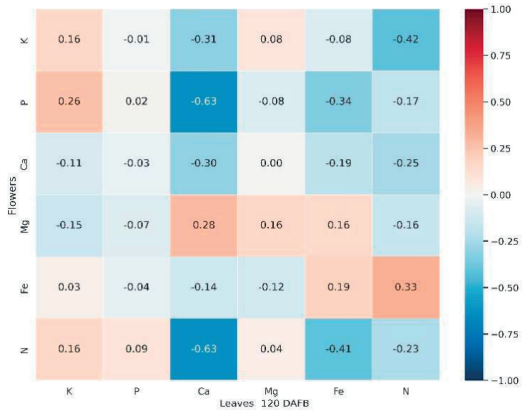

Figure 9. Correlation matrices of the relationships between chemical elements in flowers and leaves at 120 DAFB for the 'Glohaven' cultivar in 2024

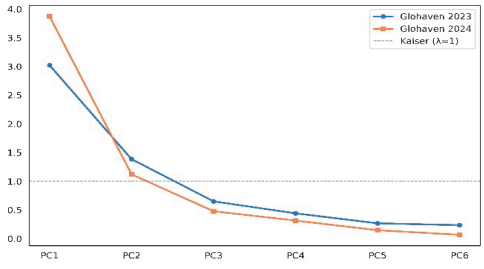

Figure 10. Eigenvalues of the principal components for 2023 and 2024

The PCA results show that in the 'Glohaven' cultivar there is a clearly expressed structural organization of the mineral balance, with the main variation explained by a limited number of leading elements (Table 2, Figure 10). A change in the leading elements and their significance is observed between the individual years, indicating that the mineral balance in this cultivar is also dynamic. The PCA results further demonstrate that the mineral balance in 'Glohaven' is determined by a small number of key elements, although their relative importance varies between years.

In 2023, Fe and Mg showed high loadings in PC1, whereas in 2024 Fe strongly dominated in the second component (PC2). This confirms the need for an adaptive rather than a uniform approach in the management of mineral nutrition.

Table 2. Component loadings of chemical elements for the 'Glohaven' cultivar in 2023 and 2024

Chemical elements	2023 PC1 (%)	2023 PC2 (%)	2024 PC1 (%)	2024 PC2 (%)
K	0.32	**57.84**	20.40	8.08
P	21.00	2.21	**23.08**	3.19
Ca	14.32	22.24	16.28	0.98
Mg	**22.62**	0.02	17.63	7.78
Fe	**25.74**	0.84	1.39	**78.90**
N	16.01	16.86	21.22	1.07

For the 'Redhaven' cultivar, the applied correlation analysis between elements in flowers and those in leaves in 2023 revealed a strong correlation between Ca (Flowers) – Mg (Leaves) at 60 DAFB, which was not maintained during the second sampling and analysis period of leaf samples (120 DAFB) (Figures 11 and 12).

At 120 DAFB, strong positive correlations were observed between P and Mg, as well as between Fe and Mg, indicating a synchronization in the accumulation of these elements in the leaves. At the same time, Ca exhibited clearly negative relationships with K and N, which may suggest antagonistic interactions. Overall, a clear separation was observed between groups of elements with positive internal relationships and those showing opposing trends (Figure 12).

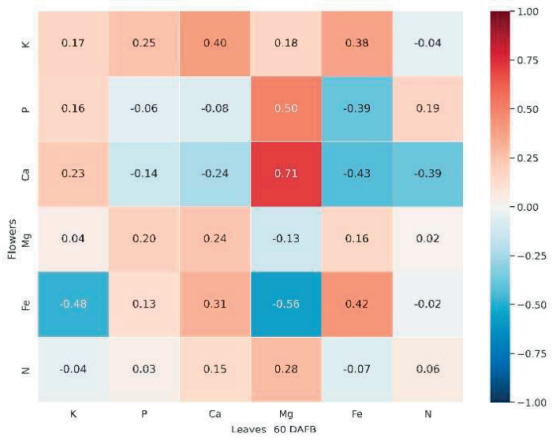

Figure 11. Correlation matrices of the relationships between chemical elements in flowers and leaves at 60 DAFB for the 'Redhaven' cultivar in 2023.

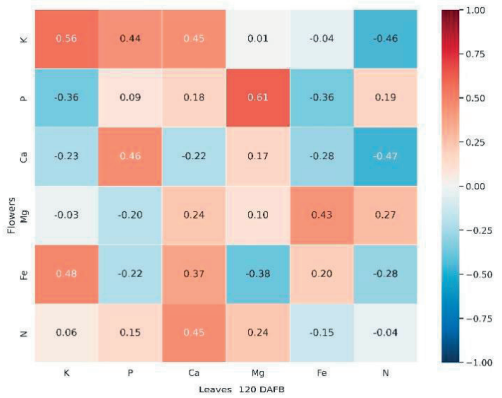

Figure 12. Correlation matrices of the relationships between chemical elements in flowers and leaves at 120 DAFB for the 'Redhaven' cultivar in 2023

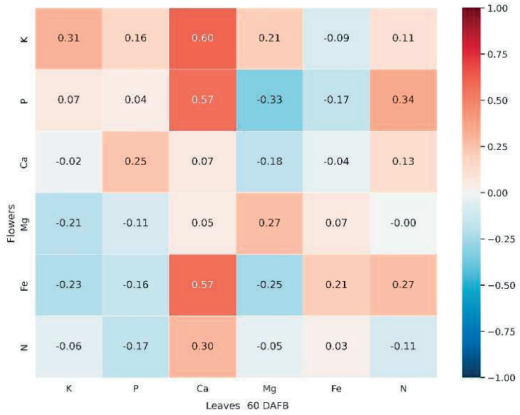

Figure 13. Correlation matrices of the relationships between chemical elements in flowers and leaves at 60 DAFB for the 'Redhaven' cultivar in 2024.

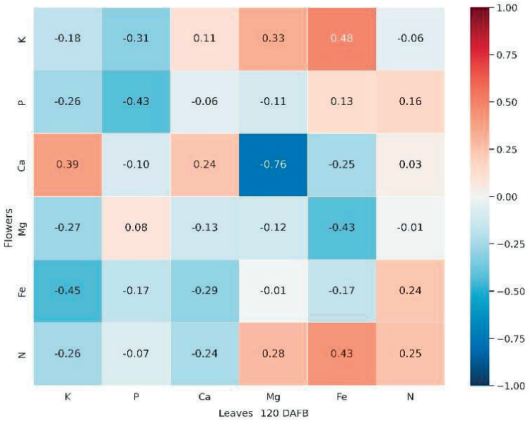

Figure 14. Correlation matrices of the relationships between chemical elements in flowers and leaves at 120 DAFB for the 'Redhaven' cultivar in 2024

For 2024, strong correlation relationships were established between K (flowers) and Ca (leaves), as well as moderate correlations between Ca (leaves) and P (flowers) and between Ca (leaves) and Fe (flowers) (Figures 13 and 14). The lack of stable relationships during the second sampling period confirms that element interactions are temporally variable and cultivar-specific.

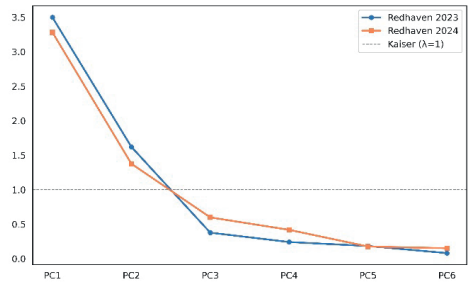

Figure 15. Eigenvalues of the principal components for 2023 and 2024

The eigenvalues and component loadings, similarly to the first two studied cultivars, do not follow a common pattern but develop dynamically, which confirms, on the one hand, the non-uniform interaction among chemical elements and, on the other, the need for an individual approach to fertilization (Figure 15). In 2024, Ca and Mg dominated in PC1, while Fe showed a high loading in PC2, indicating a functional redistribution of the role of microelements in the overall mineral structure (Table 3).

Table 3. Component loadings of chemical elements for the 'Redhaven' cultivar in 2023 and 2024

Chemical elements	2023 PC1 (%)	2023 PC2 (%)	2024 PC1 (%)	2024 PC2 (%)
K	2.09	**53.68**	19.15	1.79
P	**21.36**	0.60	14.25	29.76
Ca	18.47	13.86	**25.28**	0.06
Mg	**22.19**	3.34	**25.51**	0.61
Fe	16.32	17.22	6.64	**46.09**
N	19.55	11.29	9.17	21.70

The obtained data have direct practical significance. Early flower analysis provides an opportunity to predict potential deficiencies and to implement early corrective measures, particularly with respect to P, Mg and Fe. Leaf analysis at 60 DAFB allows more precise adjustment of fertilization during the period of active growth and yield formation.

By 120 DAFB, when correlation relationships weaken, the approach should be strictly individualized and based on specific deficiencies, rather than on combined fertilizer formulations. This corresponds to the modern principles of precision agriculture and sustainable nutrient management, where the objective is to optimize yield and fruit quality while minimizing environmental risk.

Maatallah et al. (2024) and Dascalu et al. (2024), reported results on the role of nitrogen and potassium as leading factors in individual PCA components in experimental studies on peach, demonstrating that optimal levels of N and K during fruit development and ripening increase yield and improve quality parameters (fruit mass, soluble solids content, and coloration). At the same time, excessive nitrogen application does not lead to further yield increases, highlighting the need for precise diagnostics and balanced fertilization. This corresponds with the conclusion of the present study that fertilization at 120 DAFB should be limited to the correction of specific deficiencies rather than using general combined applications.

The established relationship between Fe and N content in different years is consistent with contemporary research on leaf diagnostics applying correlation and multivariate analysis. Mertoğlu & Kırca (2025) identified significant relationships between macro- and microelements (including Fe) in leaves and fruits of apple. Modern chemometric models confirm that leaf nitrogen is a reliable indicator of the physiological and nutritional status of apple (Hou et al., 2024; Zhao et al., 2024).

The PCA analysis in the present study demonstrates a clearly structured mineral balance, with the first two principal components explaining a substantial proportion of the total variation. A similar approach is widely used in the evaluation of complex biochemical and nutritional indicators in peach and other fruit crops for the identification of leading factors and grouping of cultivars according to similarity (Nowicka et al., 2019). In this context, the changes in component loadings between 2023 and 2024 reflect not random variability but a physiologically driven reorganization of elemental interactions.

CONCLUSIONS

The mineral balance in peach is a dynamic, phenologically determined, and cultivar-specific process. The leading nutrient elements and their relative importance change between developmental stages and between years.

Early flower analysis (during flowering) may serve as a tool for predicting potential imbalances. Leaf analysis at 60 DAFB enables refinement of fertilization during the period of active growth, while at 120 DAFB the approach should be strictly individualized and focused on specific deficiencies.

The obtained results support the need for an adaptive, phenology-based management of mineral nutrition, rather than the application of uniform fertilization schemes.

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