






The Effects of Foliar Potassium (K) and Zinc (Zn) Applications on Plant Growth and Soil Enzyme Activities in Second-crop Sunflower (*Helianthus annuus* L.)*

İkinci Ürün Ayçiçeği (*Helianthus annuus* L.) Bitkisinde Yapraktan Potasyum (K) ve Çinko (Zn) Uygulamalarının Bitki Gelişimi ve Toprak Enzim Aktiviteleri Üzerine Etkisi

Suat Cun¹ , Hakan Yıldırım² , Zemzem Fırat³ 

Received: 23.06.2025

Accepted: 03.10.2025

Published: 29.12.2025

Abstract: This study was conducted in 2024 under the ecological conditions of Şanlıurfa Province to investigate the effects of potassium (K), zinc (Zn), and their combined foliar application (K+Zn) on plant growth, yield, and soil enzyme activities. The experiment was established using the Suomi sunflower (*Helianthus annuus* L.) cultivar, following a randomized complete block design with three replications. Foliar treatments were applied twice: at the 6–8 leaf stage and before flowering. The treatments consisted of a control (distilled water only), K (0.25% K₂SO₄), Zn (0.25% ZnSO₄·7H₂O), and K+Zn (0.25% K₂SO₄ + 0.25% ZnSO₄·7H₂O), all sprayed at a rate of 20 L da⁻¹. According to the results, the K, Zn, and K+Zn applications had statistically significant effects on fresh and dry plant weight (g), flower head diameter (cm), number of seeds per head, seed yield (count), 1000-seeds weight (g), seed length (mm), kernel ratio (%), and seed yield per decare (kg da⁻¹), as well as on catalase (CAT) activity, a key biochemical indicator of soil health. The individual application of K and Zn positively affected both plant and soil parameters, while their combined application (K+Zn) yielded the most pronounced positive results. Foliar application of K, Zn, and particularly K+Zn significantly influenced sunflower growth and also had notable effects on soil enzyme activity and overall soil health.

Keywords: Sunflower, K and Zn, Plant nutrition, Soil enzymes

&

Öz: Bu çalışma, 2024 yılında Şanlıurfa ili ekolojik koşullarında, potasyum (K), çinko (Zn) ve bu iki elementin birlikte uygulanmasının (K+Zn), bitki gelişimi, verim ve toprak enzim aktiviteleri üzerindeki etkilerini araştırmak amacıyla gerçekleştirilmiştir. Denemede Suomi ayçiçeği (*Helianthus annuus* L.) çeşidi kullanılarak, tesadüf blokları deneme desenine göre üç tekerrürlü olarak kurulmuştur. Yapraktan uygulamalar, bitkinin 6–8 yapraklı döneminde ve çiçeklenme öncesinde olmak üzere iki kez yapılmış; kontrol (%0 yaprağa sadece su püskürtülmüş), K (%0.25 K₂SO₄), Zn (%0.25 ZnSO₄·7H₂O) ve K+Zn (%0.25 K₂SO₄ + %0.25 ZnSO₄·7H₂O) hazırlanarak 20 L da⁻¹ olacak şekilde yapraklara püskürtülmüştür. Çalışmanın sonuçlarına göre K, Zn ve K+Zn uygulamalarının; bitki yaş ağırlığı (g), bitki kuru ağırlığı (g), tabla çapı (cm), tabla başına tohum sayısı, tohum verimi (adet), 1000 tane ağırlığı (g), tohum uzunluğu (mm), iç oranı (%) ve dekara tohum verimi (kg da⁻¹) ile birlikte toprak sağlığının temel biyokimyasal göstergelerinden biri olan katalaz (CAT) enzim aktivitesi üzerinde istatistiksel olarak anlamlı etkiler oluşturduğunu göstermiştir. K ve Zn elementlerinin uygulanması hem bitki hem de toprak parametrelerini olumlu yönde etkilerken, birlikte uygulandıklarında (K+Zn) ise en yüksek olumlu sonuçlar elde edilmiştir. K, Zn ve K+Zn yapraktan uygulamaları, ayçiçeği bitkisi üzerinde önemli etkiler görülürken toprak enzim aktivitesi ve genel toprak sağlığı açısından da dikkate değer bulunmuştur.

Anahtar Kelimeler: Ayçiçeği, K ve Zn, Bitki besleme, Toprak enzimleri

Cite as: Cun, S., Yıldırım, H., & Fırat, Z. (2025). The effects of foliar potassium (K) and zinc (Zn) applications on plant growth and soil enzyme activities in second-crop sunflower (*Helianthus annuus* L.). International Journal of Agriculture and Wildlife Science, 11(3), 365-379, doi: 10.24180/ijaws.1725264

Plagiarism/Ethic: This article has been reviewed by at least two referees and it has been confirmed that it is plagiarism-free and complies with research and publication ethics. <https://dergipark.org.tr/tr/pub/ijaws>

Copyright © Published by Bolu Abant İzzet Baysal University, Since 2015 – Bolu

¹Ph.D. Suat CUN, Harran University, Department of Field Crops, suatcun@harran.edu.tr, (Corresponding author)

²M.Sc. Student Hakan YILDIRIM, Harran University, Department of Field Crops, hakann.yildirim7@gmail.com

³Ph.D. Zemzem FIRAT, Harran University, Department of Soil Science and Plant Nutrition, zemzemfirat63@gmail.com

INTRODUCTION

Sunflower (*Helianthus annuus* L.) is a significant crop, primarily cultivated for its edible seeds and notable oil content (Hanafy and Sadak, 2023). Globally, sunflower is grown on approximately 28 million hectares of land (FAO, 2023). Major producing countries include Russia, Ukraine, Argentina, and Türkiye, with global sunflower oil production reaching nearly 20 million tons (USDA, 2016). Due to its inherent drought tolerance, sunflower is widely preferred in semi-arid regions (Day et al., 2011).

In arid and semi-arid regions where irrigation is limited and precipitation is insufficient, the yield of sunflower is significantly constrained not only by climatic conditions but also by certain soil quality parameters, particularly the deficiency of essential plant nutrients (Kiani et al., 2016). Therefore, in order to ensure the successful cultivation of sunflower under such climatic conditions, it is crucial to address the deficiencies of essential nutrients in soils and to enhance the adaptability of the plant (Ahmad et al., 2022).

Foliar fertilization, which involves the direct application of nutrients to the leaf surface, is an effective method to supply nutrients that are present in the soil but not adequately available to plants due to certain soil properties such as high pH and lime content. This method enhances nutrient uptake by minimizing the adverse effects of both soil-based and environmental limiting factors, thereby contributing to improved plant productivity (Murtaza et al., 2023). Especially in calcareous soils with high pH levels, the solubility of some essential nutrients in the soil solution is markedly reduced, hindering their uptake by plants. In such conditions, foliar applications offer a rapid and efficient means to correct nutrient deficiencies (Ishfaq et al., 2022).

In soils with elevated pH and lime content, the availability of potassium (K) to plants may be significantly restricted. The abundance of competing cations such as calcium (Ca^{+2}) and magnesium (Mg^{+2}) in these soils interferes with potassium uptake by roots (Marschner, 2011; Zörb et al., 2014). Additionally, the typically low organic matter content of calcareous soils further limits the concentration of potassium in the soil solution (White, 2013; Römheld and Kirkby, 2010). Consequently, potassium deficiency is frequently observed in plants grown under such conditions. Potassium plays a critical role in plant growth and development, regulating a wide array of enzymatic activities, maintaining cellular osmoregulation, and controlling stomatal movement during photosynthesis (Sanyal et al., 2020; Farouk and Al-Huqail, 2022). Moreover, potassium is recognized as a vital macronutrient that mitigates the adverse effects of abiotic stress factors on plants (Pandey et al., 2020; El-Beltagi et al., 2023; El-Shafei et al., 2023).

Similarly, the availability of zinc (Zn) in high pH and calcareous soils is substantially diminished. Under these conditions, Zn is often fixed in the soil as insoluble compounds such as $\text{Zn}(\text{OH})_2$ and ZnCO_3 , rendering it inaccessible to plant roots. Alloway (2008) emphasized that in alkaline and calcareous environments, the solubility of Zn declines markedly due to the transformation of Zn^{+2} ions into less available forms like $\text{Zn}(\text{OH})_2$ and ZnCO_3 . Correspondingly, Hafeez et al. (2013) reported that increasing pH levels reduce the presence of Zn in the soil solution, a condition that commonly results in widespread Zn deficiency in calcareous soils. Zinc deficiency can cause various physiological disorders, including stunted plant growth, chlorosis in young leaves, and reduced yield (Vendemiatti et al., 2025).

Although the agronomic roles of potassium and zinc have been well documented, studies integrating their combined foliar application with soil biochemical responses especially under semi-arid, calcareous soil conditions are still limited. Potassium regulates osmotic balance, enzyme activation, and photosynthetic efficiency (Sanyal et al., 2020; Johnson et al., 2022), while zinc plays a vital role in enzyme structure, protein synthesis, and antioxidant defense mechanisms (Alloway, 2008; Hafeez et al., 2013). Their combined foliar application may generate synergistic effects, simultaneously improving plant stress tolerance and metabolic efficiency, which can positively influence both plant growth and soil microbial activity (Amanullah et al., 2016; Silva et al., 2018). This gap is particularly relevant for second-crop sunflower systems in Türkiye, where nutrient deficiencies and soil degradation frequently occur (Cakmak, 2008; Ishfaq et al., 2022; Murtaza et al., 2023).

Soil enzyme activities, particularly catalase (CAT) and dehydrogenase (DHG), are widely recognized as sensitive bioindicators of soil quality and microbial activity. Catalase reflects the oxidative stress status and overall microbial functioning of soils (Beck, 1971), while dehydrogenase activity is closely associated with microbial respiration and nutrient cycling processes (Tabatabai, 1982). Including soil enzyme parameters in fertilization studies provides valuable insights into soil biological responses beyond plant nutrition.

This study investigates (i) the effects of foliar applications of K, Zn, and their combination (K + Zn) on the growth of sunflower cultivated in soils with high pH and lime content, and (ii) the impacts of these applications on certain soil enzyme activities.

MATERIAL AND METHOD

Material

The experiment was conducted in 2024 in Balkatan village of Haliliye district, Şanlıurfa province, according to the randomized complete block design with three replications. Selected soil properties of the experimental site are presented in Table 1.

Table 1. Selected soil properties of the experimental site.

Çizelge 1. Deneme yerinin toprak özellikleri.

Soil texture	O.M. (%)	pH	CaCO ₃ (%)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	N (%)	EC (dS m ⁻¹)	Mg (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Fe (mg kg ⁻¹)
Clayey	1.03	7.92	28.40	1.46	139.2	0.09	0.15	0.34	52	59

O.M: organic matter; EC: Electrical conductivity

The soil characteristics of the experimental area were as follows: the soil reaction was slightly alkaline (pH:7.92), the electrical conductivity (EC) was low (0.15 dS m⁻¹), the calcium carbonate (CaCO₃) content was high (28.4%), and the organic matter content was low (1.03%).

In the experiment, the plant material used was the Suomi sunflower (*Helianthus annuus* L.) cultivar, grown as a second crop. Potassium sulfate (K₂SO₄) was used as the potassium (K) source, while zinc sulfate (ZnSO₄·7H₂O) served as the source of zinc (Zn).

Before sowing, the plots were prepared and a basal fertilizer containing 15 kg da⁻¹ of diammonium phosphate (DAP, 18-46-0) was applied. This fertilizer was incorporated into the soil using a rake to make it ready for sowing. After sowing, in order to meet the nitrogen requirement of the plant, 18 kg da⁻¹ of nitrogen (N) in the form of urea (46% N) was applied at the 4–6 leaf stage. In total, 10.98 kg da⁻¹ of pure nitrogen (N) and 6.9 kg da⁻¹ phosphorus (P) were supplied to the soil.

Method

Establishment of the experiment

The experiment was established in a randomized complete block design with three replications, and each plot consisted of six rows. The plot length was 6 meters, with 75 cm row spacing and 19.2 cm intra-row spacing. A buffer zone of 3 meters was left between blocks as well as between plots.

A foliar application concentration of 0.25% for potassium (K₂SO₄) and zinc (ZnSO₄·7H₂O) was selected based on previous studies demonstrating its effectiveness in enhancing nutrient uptake under semi-arid conditions, while remaining within a safe range that minimizes the risk of leaf burn or phytotoxicity (Cakmak, 2008; Mehmood et al., 2021; Ishfaq et al., 2022). The foliar fertilization treatments were applied twice to coincide with two critical phenological stages of sunflower development: (i) the 6–8 leaf stage, corresponding to rapid vegetative growth and increased nutrient demand, and (ii) the pre-flowering stage, which is essential for head formation and seed set. Targeting these stages allows for more efficient nutrient absorption and has been reported to improve yield and physiological traits in sunflower and other field crops (Wada et al., 2019; Raza et al., 2018; Amanullah et al., 2016).

The experiment consisted of four foliar fertilization treatments. Applications were performed using a backpack sprayer at a rate of 20 L per decare, by spraying the prepared solution directly onto the leaf

surface during calm morning hours to ensure uniform coverage and minimize drift. The first application was carried out during the 6–8 leaf stage, while the second application was performed after flowering.

1. Control: No potassium (K) or zinc (Zn) was applied in this group; only pure water was sprayed.
2. Potassium (K): A 0.25% solution of potassium sulfate (K_2SO_4) was used.
3. Zinc (Zn): A 0.25% solution of zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$) was used.
4. Zn + K Combination: A mixed solution containing 0.25% Zn ($ZnSO_4 \cdot 7H_2O$) and 0.25% K (K_2SO_4), totaling a 0.5% concentration, was applied.

Investigated Characteristics

At harvest maturity, various morphological and yield-related parameters of the plants were assessed. Plant height (cm) was measured as the distance between the root collar and the point where the stem connects to the flower head on 10 randomly selected plants per plot (Bayraktar, 1991). The number of nodes per plant was determined by counting the nodes on the stems of the same plants, and the average value was recorded. Average internode length (cm) was calculated by dividing plant height by the number of nodes. Plant fresh and dry weight (g) were measured by recording the fresh weight of 10 randomly selected plants per plot, followed by oven-drying at 65–70 °C for 72 hours to determine dry matter accumulation (Peñuelas et al., 1994). Flower head diameter (cm) was measured at the widest point between the outer edges of the flower head, while the number of seeds per head was obtained by counting seeds from the same plants (Killı and Küçükler, 2005). Thousand-seed weight (g) was determined by weighing four sets of 100 seeds per plot on a 0.01 g precision scale and multiplying the average by 10 (Bayraktar, 1991). Seed length (mm) was measured as the distance from the back to the tip of 10 randomly selected seeds from each thousand-seed sample, and the mean was calculated. Kernel ratio (%) was assessed by randomly selecting 10 plants from the middle two rows of each plot, taking 10 g samples, dehulling, weighing, and calculating the internal seed percentage. Hectoliter weight ($kg L^{-1}$) was determined using a 1-liter capacity hectoliter apparatus after cleaning the seeds. Finally, seed yield ($kg da^{-1}$) was estimated by harvesting the two central rows per plot, excluding the border rows to avoid edge effects; the plants were manually harvested, threshed, weighed, and the values converted to yield per decare.

Measurement of Soil Enzyme Activities

For the determination of soil dehydrogenase activity, 5 g of air-dried soil was used for each sample. Triphenyl tetrazolium chloride (TTC) solution was added to the soil, and the samples were incubated at 25 °C for 24 hours. After incubation, the resulting triphenyl formazan (TPF) was extracted with an appropriate organic solvent, and its absorbance was measured spectrophotometrically at a wavelength of 485 nm (Tabatabai, 1982).

For the determination of soil catalase activity, 2 g of fresh soil was used for each sample. A pH 7.0 phosphate buffer and 3% hydrogen peroxide (H_2O_2) solution were added to the samples. After a 30-minute incubation period, the volume of oxygen released was measured using the gasometric method described by Beck (1971).

Data Analysis

The data for each parameter obtained from the experiment were analyzed using variance analysis based on the randomized complete block design with the JMP (13.2) statistical software. The means were grouped according to the Tukey-HSD test at a 0.05 significance level.

RESULTS AND DISCUSSION

Results

Plant Height (cm)

The foliar applications of K, Zn, and Zn+K on sunflower plants resulted in higher plant heights compared to the control group, although no statistically significant difference was observed between the treatments ($p \leq 0.05$). The lowest plant height was recorded in the control group (128 cm). When compared to the control group, the lowest plant height was found with the K treatment (132 cm), while the highest plant height was

recorded with the Zn+K combination (136 cm) (Figure 1). When the foliar applications of K, Zn, and Zn+K were compared to the control group, K showed a 2.65% increase, Zn showed a 4.21% increase, and Zn+K showed a 6.09% increase in plant height. The Zn+K combination resulted in a higher increase in plant height compared to the other two treatments.

Number of Nodes (per plant⁻¹)

The variance analysis results for the number of nodes showed no statistically significant differences among the treatments. Although no significant differences were found between the treatments, foliar applications of K, Zn, and Zn+K showed a tendency to increase growth compared to the control, and as a result, the number of nodes also increased compared to the control group. The lowest plant node number (19.0 per plant⁻¹) was observed in the control group. Compared to the control group, the lowest value was found in the Zn application (19.3 per plant⁻¹), while the highest value was found in the Zn+K application (20.1 per plant⁻¹) (Figure 1). According to Figure 1, foliar applications of K, Zn, and Zn+K resulted in an increase in the node number by 1.73% for Zn, 3.47% for K, and 5.95% for Zn+K, respectively.

Internode Length (cm)

The variance analysis results for internode length showed no statistically significant differences among the treatments. Upon examining the findings, the shortest internode length was observed in the K application (6.69 cm), while the highest was observed in the Zn application (6.90 cm). When the treatments were compared to the control group, the K application showed a slight decrease relative to the control group. Additionally, it can be inferred that the Zn application alone resulted in an increase compared to the Zn + K application, and in this case, the K application might have caused a reduction in the internode length (Figure 1). According to Figure 1, foliar applications of K, Zn, and Zn+K showed that the internode length (cm) decreased with the K application compared to the control, while Zn+K (0.15%) and Zn (2.22%) applications showed an increase compared to the control.

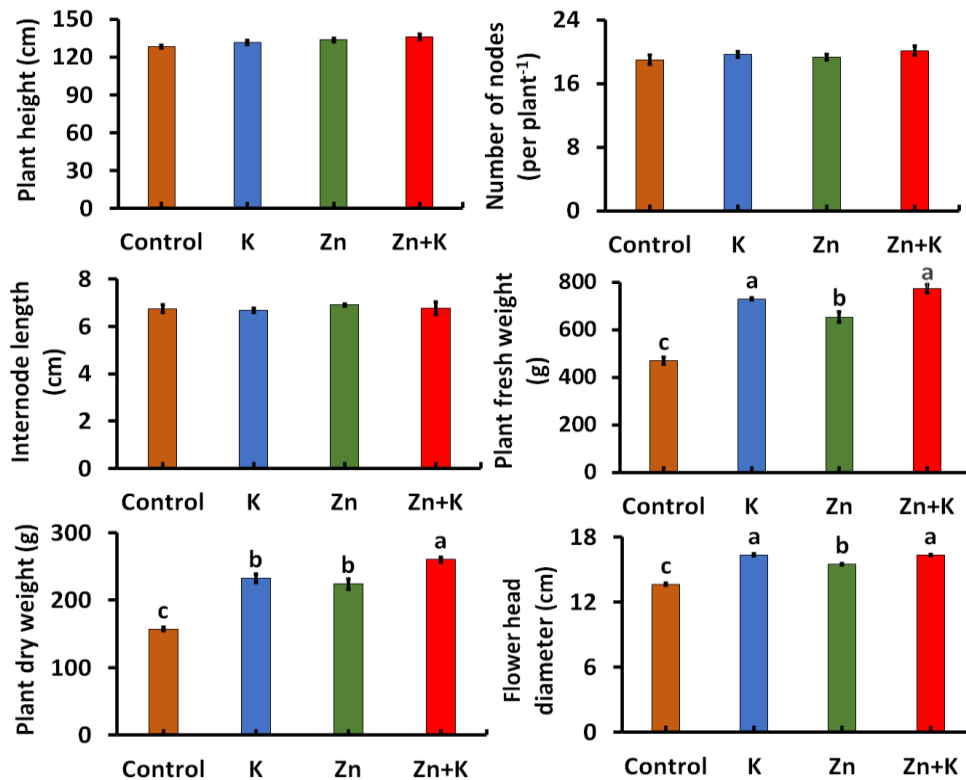


Figure 1. Effects of foliar applications of K, Zn, and Zn+K on plant height, number of nodes, internode length, plant fresh weight, plant dry weight, flower head diameter.

Şekil 1. K, Zn ve Zn+K'nun yapraktan uygulanmasının; bitki boyu, boğum sayısı, boğum arası uzunluğu, bitki yaş ağırlığı, bitki kuru ağırlığı ve tabla çapı üzerindeki etkileri.

Plant Fresh Weight (g)

The study's variance analysis results for plant fresh weight data revealed significant statistical differences between the treatments ($p \leq 0.01$). Upon examining the results, the control group exhibited the lowest plant fresh weight (471 g). In comparison to the control, the Zn treatment showed a lower value (654 g), while the highest value was recorded in the Zn+K treatment (774 g) (Figure 1). According to Figure 1, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in plant fresh weight by 39.0% for Zn, 55.1% for K, and 64.3% for Zn+K. The results indicate that K was effective in significantly increasing the plant fresh weight, showing that K has a positive effect on plant growth. Additionally, Zn was also observed to increase plant fresh weight, although not as much as K. In the Zn+K treatment, the combined application of both nutrients had the greatest effect on plant fresh weight.

Plant Dry Weight (g)

The variance analysis results for plant dry weight data indicated statistically significant differences between the treatments ($p \leq 0.01$). When the foliar applications of K, Zn, and Zn+K were compared with the control group, all treatments showed an increase. The lowest plant dry weight was observed in the control group (157 g), while the lowest value compared to the control group was found in the Zn treatment (224 g), and the highest was found in the Zn+K treatment (260 g) (Figure 1). According to Figure 1, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in plant dry weight by 42.3% for Zn, 47.8% for K, and 65.4% for Zn+K. Similarly, based on plant fresh weight, plant dry weight also showed comparable effects among the treatments.

Flower Head Diameter (cm)

In the study, the variance analysis results for the flower head diameter data indicated statistically significant differences between the treatments ($p \leq 0.01$). When the treatments were compared, it was determined that the control group, which did not receive any nutrient supplementation, had the lowest value (13.7 cm). Compared to the control group, the lowest value was observed in the Zn treatment (15.5 cm), while the highest value was observed in the Zn+K treatment (16.4 cm) (Figure 1). According to Figure 1, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in flower head diameter by 13.5% for Zn, 19.7% for K, and 19.8% for Zn+K. Based on the obtained findings, although Zn+K had the highest value, there was no significant difference between the K and Zn+K treatments, and it was observed that K application alone significantly increased the table diameter.

Number of Seeds Per Head (count)

The variance analysis results for the number of seeds per head data showed statistically significant differences between the treatments ($p \leq 0.01$). It was observed that all foliar applications of K, Zn, and Zn+K resulted in an increase compared to the control group. The lowest value among the treatments was observed in the control group (774 count), while the K application and Zn application recorded 963 and 946 count, respectively. The highest value was observed in the Zn+K application, with 1003.

In terms of the number of seeds per head, it was observed that the K application was more effective than the Zn application. However, when both nutrients were used together in the Zn+K treatment, a more significant effect on seed number was observed (Figure 2).

1000-Seeds Weight (g)

The variance analysis results for the 1000-seeds weight data indicated statistically significant differences between the treatments ($p \leq 0.01$). In the study, the lowest value was observed in the control group (64.0 g). When the treatments were compared to the control group, the lowest value was found in the Zn treatment (71.0 g), while the highest value was recorded in the Zn+K treatment (74.6 g). It was observed that the K application was more effective than the Zn application; however, the combination of both nutrients in the Zn+K treatment resulted in the best outcome for 1000-seeds weight (Figure 2). According to Figure 2, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in 1000-seeds weight by 11.0% for Zn, 15.7% for K, and 16.5% for Zn+K.

Hectoliter Weight (kg L⁻¹)

In the study, the values obtained for hectoliter weight in the control group and the foliar applications of K, Zn, and Zn+K were quite similar, and no statistically significant differences were observed. According to the findings, the lowest hectoliter weight was observed in the control group (46.5 kg L⁻¹). When compared to the control group, the lowest value was found in the K treatment (46.8 kg L⁻¹), while the highest value was recorded in the Zn treatment (47.2 kg L⁻¹) (Figure 2). According to Figure 2, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in hectoliter weight by 0.80% for K, 1.51% for Zn+K, and 1.94% for Zn.

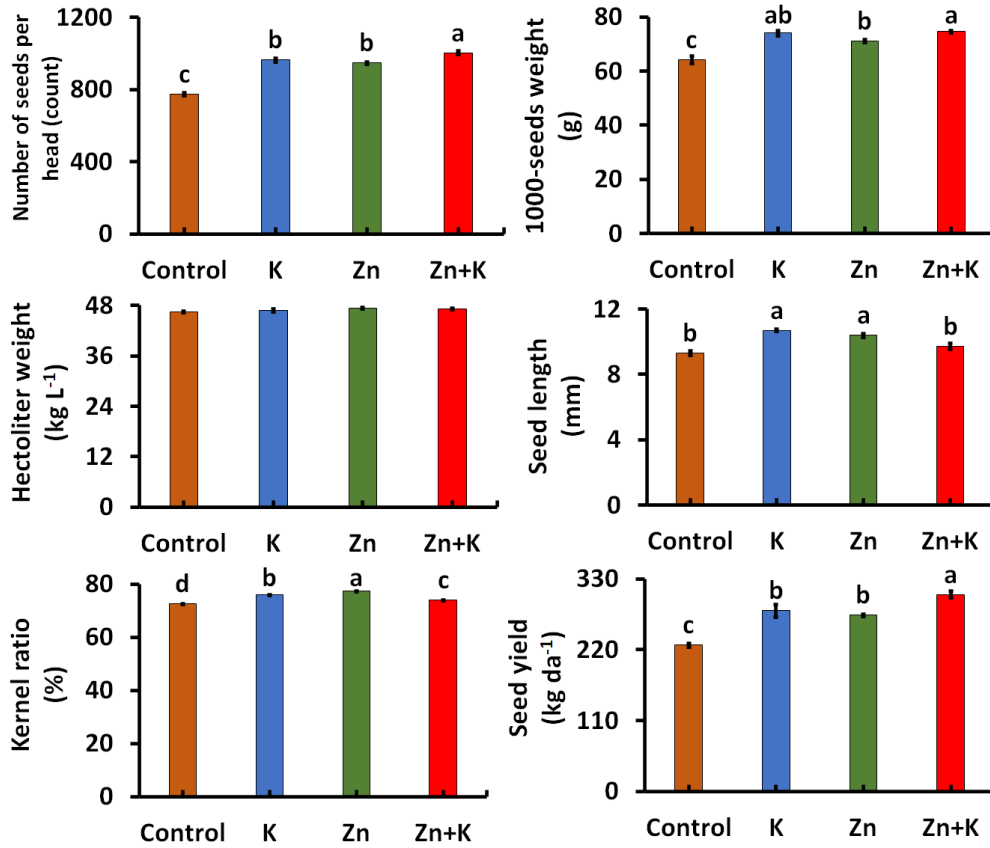


Figure 2. Effects of foliar applications of K, Zn, and Zn+K on number of seeds per head, 1000-seeds weight, hectoliter weight, seed length, kernel ratio, seed yield.

Şekil 2. K, Zn ve Zn+K'nın yapraktan uygulanmasının; tabla başına tohum sayısı, 1000 tohum ağırlığı, hektolitre ağırlığı, tohum uzunluğu, iç oranı ve tohum verimi üzerindeki etkileri.

Seed Length (mm)

The variance analysis results for seed length data showed statistically significant differences between the treatments ($p \leq 0.01$). The lowest value was observed in the control group (9.30 mm). Compared to the control, the lowest value was found in the K+Zn treatment (9.73 mm), while the highest value was recorded in the K treatment (10.70 mm). According to Figure 2, foliar applications of K, Zn, and Zn+K resulted in an increase in seed length by 4.62% for K+Zn, 11.83% for Zn, and 15.05% for K.

Kernel Ratio (%)

The variance analysis results for kernel ratio data revealed statistically significant differences between the treatments ($p \leq 0.01$). The lowest value was observed in the control group (72.5%). Compared to the control, the lowest value was found in the K+Zn treatment (74.0%), while the highest value was recorded in the Zn treatment (77.4%). It was determined that the K application was more effective than the K+Zn application; however, the application of the Zn nutrient resulted in the best outcome for the kernel ratio. According to Figure 2, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in seed internal ratio by 2.16% for K+Zn, 4.74% for K, and 6.77% for Zn.

Seed Yield ($kg\ da^{-1}$)

The variance analysis results for seed yield data showed statistically significant differences between the treatments ($p \leq 0.01$). The control group exhibited the lowest yield ($227\ kg\ da^{-1}$). It was observed that all foliar applications of K, Zn, and Zn+K resulted in an increase compared to the control group. When compared to the control, the lowest seed yield was found in the Zn treatment ($274\ kg\ da^{-1}$), while the highest seed yield was recorded in the Zn+K treatment ($306\ kg\ da^{-1}$). It was observed that the foliar application of Zn increased seed yield, but not to the extent of the K application. However, when both nutrients were applied together in the Zn+K treatment, a significant increase in seed yield was achieved (Figure 2). According to Figure 2, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in seed yield by 20.6% for Zn, 23.6% for K, and 34.7% for Zn+K.

Catalase Enzyme Activity ($ml\ O_2\ g^{-1}\ dm\ 5\ min^{-1}$)

In the study, the variance analysis results for the soil catalase (CAT) enzyme activity data showed statistically significant differences between the treatments ($p \leq 0.01$). When comparing the foliar applications of K, Zn, and Zn+K to the control group, all treatments resulted in an increase. Upon reviewing the data, the lowest value was observed in the control group ($80.67\ ml\ O_2\ g^{-1}\ dm\ 5\ min^{-1}$), while the lowest value among the treatments was found in the K application ($89.3\ ml\ O_2\ g^{-1}\ dm\ 5\ min^{-1}$), and the highest value was observed in the Zn+K application ($123\ ml\ O_2\ g^{-1}\ dm\ 5\ min^{-1}$). It was noted that the K application resulted in a significant increase compared to the control, but the Zn application was more effective than K. Moreover, the combination of both nutrients in the Zn+K treatment caused a considerable difference in soil enzyme activity (Figure 3). According to Figure 3, the application of K, Zn, and Zn+K via foliar spraying resulted in an increase in catalase (CAT) activity by 10.85% for K, 32.2% for Zn, and 52.9% for Zn+K.

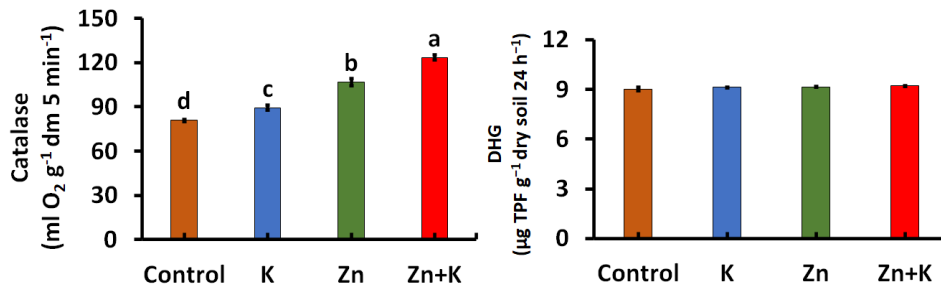


Figure 3. Effects of foliar applications of K, Zn, and Zn+K on catalase and dehydrogenase enzyme activity.
 Şekil 3. K, Zn ve Zn+K'nın yaprakтан uygulanmasının katalaz ve dehidrogenaz enzim aktivitesi üzerindeki etkileri.

Dehydrogenase Enzyme Activity ($\mu g\ TPF\ g^{-1}\ dry\ soil\ 24\ h^{-1}$)

In the study, the variance analysis results for dehydrogenase (DHG) enzyme activity showed no statistically significant differences between the treatments. It was observed that the foliar applications did not have a significant effect compared to the control. According to the findings of the study, the lowest value was found in the control group ($9.02\ \mu g\ TPF\ g^{-1}\ dry\ soil\ 24\ h^{-1}$). When comparing the treatments to the control, the lowest value was observed in the K application ($9.14\ \mu g\ TPF\ g^{-1}\ dry\ soil\ 24\ h^{-1}$), while the highest value was found in the Zn+K application ($9.20\ \mu g\ TPF\ g^{-1}\ dry\ soil\ 24\ h^{-1}$) (Figure 3). According to Figure 3, the foliar applications of K, Zn, and Zn+K resulted in an increase in DHG activity by 1.33% for K, 1.44% for Zn, and 2.0% for Zn+K.

Visualization of the Effects of Zn and K Applications on Multiple Plant Traits: A Matrix Diagram

In Figure 4, an analysis of the connections between treatments and parameters reveals that the control group exhibits weak correlations with plant growth and yield parameters. In the K application, a positive effect was observed on parameters such as plant height, seed yield, 1000-seeds weight, and hectoliter weight. K is a crucial nutrient, particularly during the grain-filling period, as it supports active metabolic activities in plants. The strong positive correlation between K application and seed yield, 1000-seeds weight, and plant height in the graph aligns with the findings of Johnson et al. (2022), Sanyal et al. (2020),

and Farouk and Al-Huqail (2022), who emphasized the essential role of potassium (K) in plant growth and development, as well as its involvement in regulating various critical physiological functions.

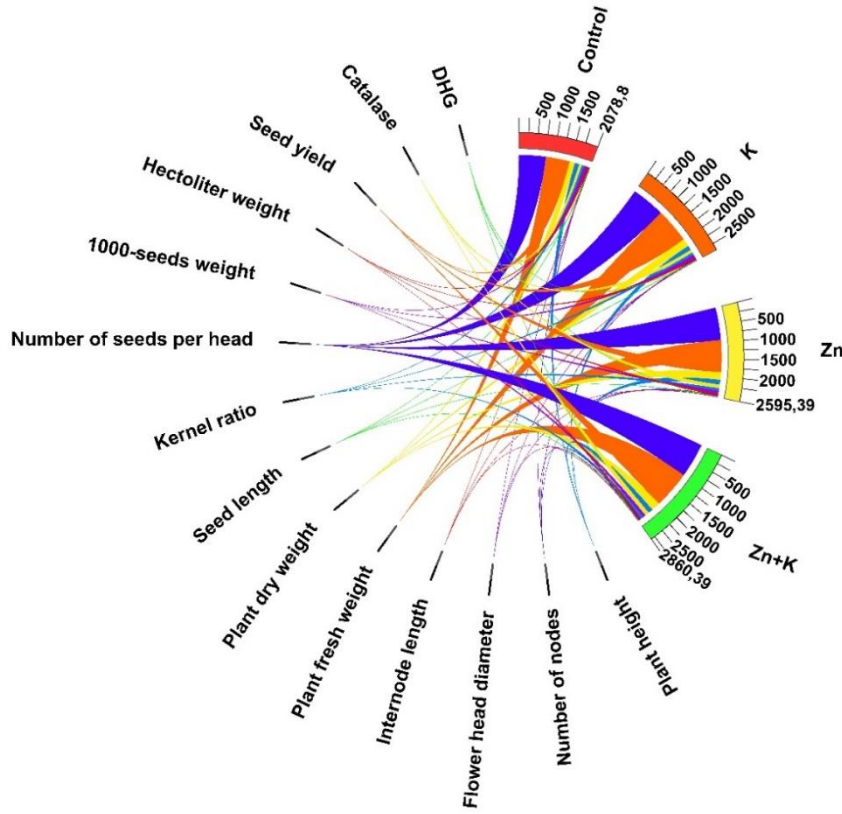


Figure 4. presents a matrix diagram illustrating the effects of potassium (K), zinc (Zn), and combined zinc and potassium (Zn+K) applications on plant growth, yield, and soil enzymes. (The connections between the graph lines represent the relationships among these factors, with thicker lines indicating stronger correlations).

Şekil 4. Potasyum (K), çinko (Zn) ve kombine çinko ve potasyum (Zn+K) uygulamalarının bitki büyümesi, verim ve toprak enzimleri üzerindeki etkilerini gösteren bir matris diyagramını sunmaktadır. (Grafik çizgileri arasındaki bağlantılar, bu faktörler arasındaki ilişkileri temsil etmekte olup, çizgi kalınlığının artması daha güçlü korelasyonları göstermektedir).

An examination of Zn application indicates a significant association with plant growth, development, and quality parameters. Key factors affecting seed quality, such as seed length, kernel ratio, and the number of seeds per head, exhibited positive responses to Zn applications. Furthermore, Zn applications were found to enhance soil catalase and dehydrogenase enzyme activities, which may contribute to improved plant resistance against oxidative stress.

When the Zn+K combination was analyzed, it demonstrated stronger and more significant effects compared to the individual applications of K and Zn. Specifically, it was found to be directly associated with plant height, flower head diameter, internode length, and fresh plant weight. These findings suggest that the Zn+K combination represents the most effective strategy for promoting plant growth and development.

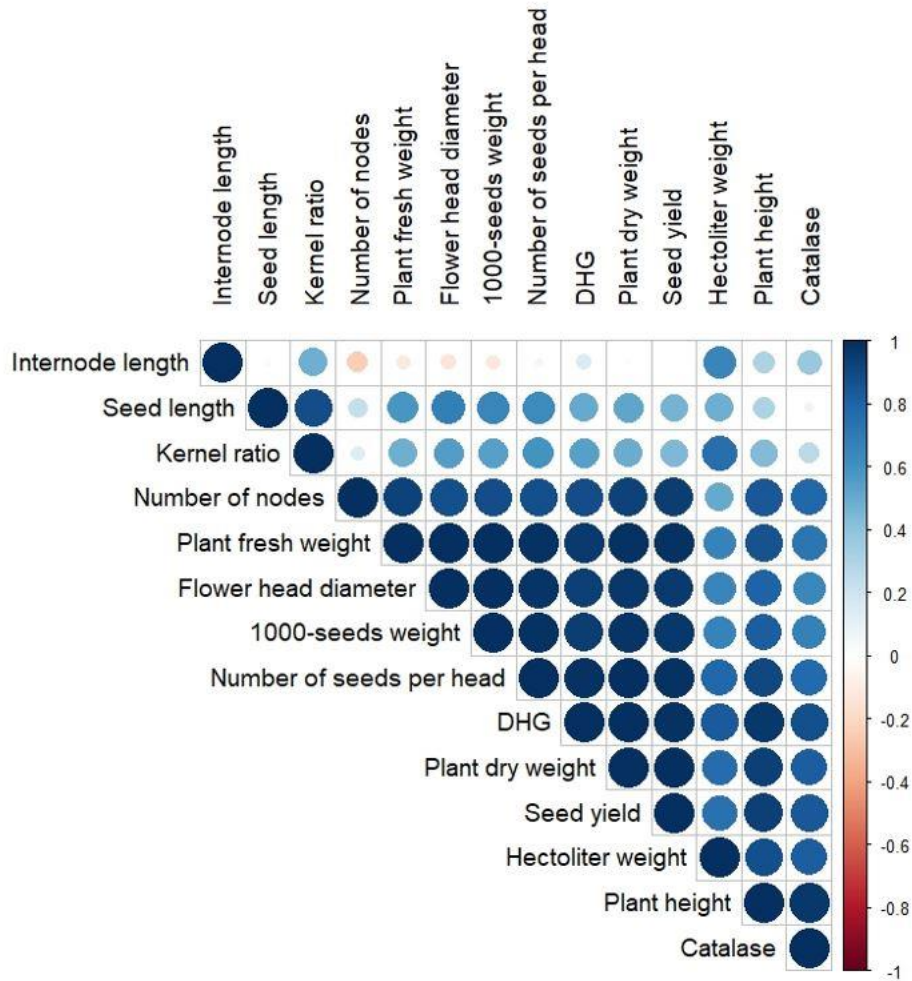
Data Clustering Technique: Representation on the Correlation Graph

Figure 5. Correlation graph representing the relationships among the examined parameters (Blue indicates a positive correlation, while red and orange represent negative correlations. The intensity of the colors signifies the strength of the correlation, and the size of the circles denotes statistical significance).

Şekil 5. İncelenen parametreler arasındaki ilişkileri temsil eden korelasyon grafiği (Mavi, pozitif korelasyonu; kırmızı ve turuncu ise negatif korelasyonları göstermektedir. Renklerin yoğunluğu, korelasyonun gücünü, dairelerin büyüklüğü ise istatistiksel anlamlılığı belirtmektedir)

Figure 5 shows strong relationships between plant growth, seed yield, and CAT activity in the soil. A particularly strong positive correlation ($r = 0.98$) was observed between seed yield and number of seeds per head. This indicates a direct relationship between the two parameters, where as the number of seeds per head increases, seed yield also increases. Additionally, a strong positive relationship ($r = 0.98$) was observed between 1000-seeds weight and number of seeds per head. This suggests a correlation with the production of heavier seeds or a higher number of seeds per head. Another parameter that showed a strong correlation ($r = 0.98$) with number of seeds per head was the flower head diameter. It is believed that as the flower head diameter increases, number of seeds per head will also increase, which will directly affect seed yield.

When the plant's fresh weight and dry weight were examined, a very strong correlation ($r = 0.99$) was identified between the two parameters. As the fresh weight of the plant increased, the dry matter content also increased. Furthermore, CAT activity in the soil was found to have a strong positive relationship ($r = 0.97$) with plant height.

Discussions

The foliar application of nutrients has become an essential technique for ensuring sustainable crop production globally. "Foliar feeding" refers to the direct delivery of dissolved mineral nutrients to the

foliage of plants. This method is recognized for its rapid action, precision targeting, and environmental compatibility, offering an effective way to achieve higher yields under both favorable and challenging growth conditions (Bahrami-Rad and Hajiboland, 2017; Ruiz-Navarro et al., 2019; White et al., 2015; Malhotra et al., 2020). Under field conditions, factors such as soil alkalinity and calcareousness can hinder the uptake of micronutrients, making foliar applications particularly valuable (Mehmood et al., 2021).

Ishfaq et al. (2022) and Murtaza et al. (2023) have underlined the significant impact of foliar feeding in boosting agricultural productivity and crop quality, especially amid growing challenges like demographic expansion and climate change. Additionally, Murtaza et al. (2023) pointed out that foliar fertilization can serve not only as a complementary approach but also as a potential alternative to root fertilization, with promising effects on yield improvement and production quality. Ishfaq et al. (2022) also presented a detailed evaluation of recent advancements in foliar fertilization strategies across diverse agricultural systems, emphasizing its capacity to enhance resilience against environmental stresses. Furthermore, foliar nutrient applications have been found to improve plants' antioxidant defenses, aiding protection against oxidative damage, particularly under saline stress conditions (Mehmood et al., 2021; Hajihashemi and Kazemi, 2022). Intensive cropping systems have reduced intrinsic soil fertility, leading to deficiencies in essential plant nutrients and consequently inadequate productivity. Therefore, increasing nutrient supply is critical to enhancing sunflower productivity.

In the study, according to the results of the analysis of variance for plant height, number of nodes, internode length, and hectoliter weight, no statistically significant differences were found between the treatments. Based on the findings, foliar applications of K, Zn, and Zn+K did not show a significant effect compared to the control treatments (no application of K, Zn, or Zn+K), although there was a general increase observed. In terms of plant height and number of nodes, the most effective treatment was the combination of foliar Zn+K, while for internode length and hectoliter weight, foliar Zn application was observed to be more effective.

Most research on micronutrients, particularly Zn, in foliar applications has focused on correcting deficiencies, for example, in apple (Basso et al., 1990) and wheat (Brennan, 1991). There is limited literature regarding the effect of foliar-applied zinc on sunflower plants. As reported by Pathak and Pandey (2010), foliar Zn application has been documented as a simple method for rapidly improving plant nutritional status. Most research on foliar Zn application has focused on correcting deficiencies in wheat and maize, particularly in semi-arid regions of the world (Cakmak, 2008; Potarzycki and Grzebisz, 2009).

Research on foliar potassium application in sunflower plants, similar to zinc, is limited. Wada et al. (2019) found that potassium positively influences sunflower yield. Additionally, Raza et al. (2018) reported that foliar potassium application significantly enhanced plant height as well as morphological and physiological parameters. In the study, according to the results of the analysis of variance for plant fresh weight, plant dry weight, flower head diameter, seed length, kernel ratio, 1000-seeds weight, number of seeds per head, and seed yield, significant statistical differences ($p < 0.01$) were determined between the treatments. Foliar applications of K, Zn, and Zn+K showed a significant effect compared to the control treatments (no application of K, Zn, or Zn+K), leading to a general increase in these parameters. The most effective treatment in terms of plant fresh weight, plant dry weight, flower head diameter, 1000-seeds weight, number of seeds per head, and seed yield was the foliar Zn+K application, while seed size was most affected by K application, and kernel ratio was most influenced by Zn application. It was also determined that the individual applications of K and Zn significantly increased these parameters compared to the control group with no application.

The observed improvements in growth and yield parameters following foliar K, Zn, and Zn+K applications can be explained by their essential roles in plant physiological processes. Potassium regulates stomatal conductance, osmotic adjustment, and the activation of numerous enzymes, thereby promoting efficient photosynthesis and assimilate transport to developing organs (Johnson et al., 2022; Raza et al., 2018). Adequate K supply also enhances water-use efficiency and maintains cell turgor, which is particularly

beneficial under semi-arid conditions. Zinc, on the other hand, is vital for auxin biosynthesis, protein synthesis, and membrane integrity, contributing to cell division, elongation, and reproductive development (Hafeez et al., 2013; Farooq et al., 2022). Additionally, Zn plays a crucial role in the plant's antioxidant defense system by stabilizing membranes and enhancing the activity of reactive oxygen species (ROS)-scavenging enzymes, thereby improving tolerance to environmental stresses.

The combined foliar application of Zn and K likely triggered complementary physiological responses, including improved stomatal behavior, nutrient translocation, and enzymatic activity. These synergistic effects can account for the consistent increases observed in plant height, flower head diameter, seed filling, and yield components under Zn+K treatments compared to individual applications

Abdelhameed and Abd El-Hady (2018) found that foliar potassium application increased zinc concentration in plants. Similarly, Amanullah et al. (2016) reported that foliar applications of potassium and zinc boosted photosynthesis intensity and chlorophyll content in leaves, leading to an increase in plant biomass. Foliar application of potassium and zinc in maize plants can help compensate for yield loss caused by stress by improving seed production capability and increasing 1000-seeds weight (Silva et al., 2018; Kouchak Dezfouli et al., 2024).

It has been reported that potassium fertilization in sesame during drought stress improves photosynthesis capacity and hormonal regulation, thereby enhancing the plants' tolerance to drought (Fang et al., 2023). In canola, foliar potassium application has also been reported to increase yield (Waraich et al., 2020).

The analysis of variance revealed significant differences ($p < 0.01$) among treatments for soil catalase (CAT) activity, whereas no significant variation was detected for dehydrogenase (DHG) activity. All foliar nutrient applications increased CAT activity relative to the control, with the highest value observed under the Zn+K treatment. Individual K and Zn applications also enhanced CAT activity significantly, though to a lesser extent. In contrast, DHG activity remained statistically unchanged across treatments, showing only slight numerical increases under Zn+K application.

The marked increase in CAT activity under Zn and Zn+K treatments indicates a stimulation of soil microbial oxidative processes. Catalase is closely associated with the decomposition of hydrogen peroxide and reflects the oxidative metabolic capacity of soil microbial communities (Beck, 1971). Zinc likely contributed to enhanced enzyme synthesis and stability, while potassium may have indirectly supported microbial activity through improved root growth and exudation, leading to better soil aeration and substrate availability (Zhang et al., 2021). The lack of significant differences in DHG activity may be attributed to the relatively short experimental period or the lower sensitivity of this enzyme to foliar-applied nutrients compared to catalase.

CONCLUSION

The results of this study demonstrate that foliar applications of zinc (Zn), potassium (K), and their combination (Zn+K) can significantly influence both plant performance and soil biochemical activity under semi-arid conditions. Foliar nutrient applications led to notable improvements in plant fresh and dry weights, seed yield, yield components (including 1000-seed weight, number of seeds per head, kernel ratio, and flower head diameter), and soil catalase (CAT) enzyme activity. Although differences in plant height, internode length, and dehydrogenase (DHG) activity were not statistically significant, positive trends were still observed compared to the control. Among the treatments, the combined Zn+K application consistently outperformed individual nutrient applications in nearly all parameters, highlighting a synergistic interaction between these elements in supporting physiological and biochemical processes.

From a practical perspective, these findings suggest that Zn and K foliar fertilization, particularly in combination, may be a promising strategy for improving sunflower productivity and soil biological health in calcareous soils with nutrient limitations. Such approaches could contribute to more sustainable and efficient crop production systems by enhancing nutrient use efficiency and supporting soil enzymatic activity, which is crucial for long-term soil fertility.

However, this study was conducted at a single location and during a single growing season. Further multi-year and multi-location experiments are needed to validate these findings across different agro-ecological conditions and to assess potential long-term effects on soil nutrient dynamics and enzyme activities. Future research should also investigate optimal application timings and concentrations to maximize the synergistic effects of foliar Zn and K fertilization.

CONFLICT OF INTEREST

There is no disagreement between the authors.

DECLARATION OF AUTHOR CONTRIBUTION

The authors contributed equally to each stage of the study.

REFERENCES

- Abdelhameed, A., & Abd El-Hady, M. (2018). Response of tomato plant to foliar application of calcium and potassium nitrate integrated with different phosphorus rates under sandy soil conditions. *Egyptian Journal of Soil Science*, 58(1), 45-55.
- Ahmad, H. M., Wang, X., Fiaz, S., Azeem, F., & Shaheen, T. (2022). Morphological and physiological response of *Helianthus annuus* L. to drought stress and correlation of wax contents for drought tolerance traits. *Arabian Journal for Science and Engineering*, 1-15. <https://doi.org/10.1007/s13369-021-06098-1>
- Alloway, B. J. (2008). *Zinc in soils and crop nutrition* (2nd ed.). Brussels, Belgium: International Zinc Association (IZA).
- Amanullah, S. A., Iqbal, A., & Fahad, S. (2016). Foliar phosphorus and zinc application improve growth and productivity of maize (*Zea mays* L.) under moisture stress conditions in semi-arid climates. *Journal of Microbial & Biochemical Technology*, 8(5), 433-439. <https://doi.org/10.4172/1948-5948.1000321>
- Bahrami-Rad, S., & Hajiboland, R. (2017). Effect of potassium application in drought-stressed tobacco (*Nicotiana rustica* L.) plants: Comparison of root with foliar application. *Annals of Agricultural Sciences*, 62(2), 121-130. <https://doi.org/10.1016/j.aos.2017.08.001>
- Basso, C., Suzuki, A., Wilms, F. W. W., & Stuker, H. (1990). Control of zinc deficiency in apple orchards in southern Brazil. In *Plant Nutrition—Physiology and Applications: Proceedings of the Eleventh International Plant Nutrition Colloquium, 30 July–4 August 1989, Wageningen, The Netherlands* (pp. 257-260). Dordrecht: Springer Netherlands.
- Bayraktar, N. (1991). Yield-affecting factors in winter and spring safflower (*Carthamus tinctorius* L.) progenies. *Publications of Ankara University, Faculty of Agriculture*, No. 1215.
- Beck, T. H. (1971). The determination of catalase activity in soils. *Journal Plant Nutrition Soil Science*, 130:68–81.
- Brennan, R. F. (1991). Effectiveness of zinc sulfate and zinc chelate as foliar sprays in alleviating zinc deficiency of wheat grown on zinc-deficient soils in Western Australia. *Australian Journal of Experimental Agriculture*, 31(6), 831-834. <https://doi.org/10.1071/EA9910831>
- Cakmak, I. (2008). Enrichment of cereal grains with zinc: agronomic or genetic biofortification?. *Plant and Soil*, 302, 1-17. <https://doi.org/10.1007/s11104-007-9466-3>
- Day, S., Kolsarıcı, Ö., Kaya, M. D., & Kaya, M. D. (2011). Effects of timing and doses of humic acid application on yield, yield components and oil content in sunflower (*Helianthus annuus* L.). *Akdeniz University Journal of the Faculty of Agriculture*, 24(1), 33–37.
- El Shafei, W. A., Mohamed, M.M., Ibrahim, A. A. E., & Nossier, M. I. (2023). Evaluation of the efficiency of foliar potassium applications as drought mitigation. *Egyptian Journal of Soil Science*, 63(2), 187-196. <https://doi.org/10.21608/ejss.2023.198085.1576>
- El-Beltagi, H. S., Al-Otaibi, H. H., Parmar, A., Ramadan, K. M., Lobato, A. K. D. S., & El-Mogy, M. M. (2023). Application of potassium humate and salicylic acid to mitigate salinity stress of common bean. *Life*, 13(2), 448. <https://doi.org/10.3390/life13020448>
- Fang, S., Yang, H., Duan, L., Shi, J., & Guo, L. (2023). Potassium fertilizer improves drought stress alleviation potential in sesame by enhancing photosynthesis and hormonal regulation. *Plant Physiology and Biochemistry*, 200, 107744. <https://doi.org/10.1016/j.plaphy.2023.107744>

- FAO. (2023). *Statistical databases*. The Food and Agriculture Organization of the United Nations. [Access date: December 13, 2023].
- Farouk, S., & Al-Huqail, A. A. (2022). Sustainable biochar and/or melatonin improve salinity tolerance in borage plants by modulating osmotic adjustment, antioxidants, and ion homeostasis. *Plants*, 11(6), 765. <https://doi.org/10.3390/plants11060765>
- Hafeez, B. M. K. Y., Khanif, Y. M., & Saleem, M. (2013). Role of zinc in plant nutrition-a review. *American Journal of Experimental Agriculture*, 3(2): 374-391.
- Hajihashemi, S., & Kazemi, S. (2022). The potential of foliar application of nano-chitosan-encapsulated nano-silicon donor in amelioration the adverse effect of salinity in the wheat plant. *BMC Plant Biology*, 22(1), 148. <https://doi.org/10.1186/s12870-022-03531-x>
- Hanafy, R. S., & Sadak, M. S. (2023). Foliar spray of stigmasterol regulates physiological processes and antioxidant mechanisms to improve yield and quality of sunflower under drought stress. *Journal of Soil Science and Plant Nutrition*, 23(2), 2433-2450. <https://doi.org/10.1007/s42729-023-01197-4>
- Ishfaq, M., Kiran, A., ur Rehman, H., Farooq, M., Ijaz, N. H., Nadeem, F., & Wakeel, A. (2022). Foliar nutrition: Potential and challenges under multifaceted agriculture. *Environmental and Experimental Botany*, 200, 104909. <https://doi.org/10.1016/j.envexpbot.2022.104909>
- Johnson, R., Vishwakarma, K., Hossen, M. S., Kumar, V., Shackira, A. M., Puthur, J. T., & Hasanuzzaman, M. (2022). Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiology and Biochemistry*, 172, 56-69. <https://doi.org/10.1016/j.plaphy.2022.01.001>
- Kılı, F., & Küçükler, İ. (2005). Effects of different sowing times and potassium applications on seed yield and plant characteristics of safflower (*Carthamus tinctorius* L.). In: *The Role and Importance of Potassium in Agriculture*, p. 101.
- Kiani, M., Gheysari, M., Mostafazadeh-Fard, B., Majidi, M. M., Karchani, K., & Hoogenboom, G. (2016). Effect of the interaction of water and nitrogen on sunflower under drip irrigation in an arid region. *Agricultural Water Management*, 171, 162-172. <https://doi.org/10.1016/j.agwat.2016.04.008>
- Kouchak Dezfouli, M., Shokuhfar, A., Lak, S., Alavi Fazel, M., & Mojaddam, M. (2024). Effect of foliar application of potassium and zinc elements on maize yield and grain nutrient content under water-deficit conditions. *Communications in Soil Science and Plant Analysis*, 55(1), 1-20. <https://doi.org/10.1080/00103624.2023.2256860>
- Malhotra, H., Pandey, R., Sharma, S., & Bindrabhan, P. S. (2020). Foliar fertilization: possible routes of iron transport from leaf surface to cell organelles. *Archives of Agronomy and Soil Science*, 66(3), 279-300. <https://doi.org/10.1080/03650340.2019.1616288>
- Marschner, H. (2011). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press.
- Mehmood, A., Ahmed, J., Rukh, S., Shahzad, K., Rafique, M., Imran, M., & Chung, G. (2021). Response to foliar micronutrients application: oil content, fatty acid profiling, growth and yield attributes in sunflower hybrids. <https://doi.org/10.21203/rs.3.rs-394987/v1>
- Murtaza, D. F., Roşculete, E., Roşculete, C. A., & Păunescu, G. (2023). Foliar fertilization-an integral part of complex and integrated fertilizations—A review. " *Annals of the University of Craiova-Agriculture Montanology Cadastre Series* ", 52(2), 100-107. <https://doi.org/10.52846/aamc.v52i2.1395>
- Pandey, G. K., Mahiwal, S., Pandey, G. K., & Mahiwal, S. (2020). Potassium in abiotic stress. *Role of Potassium in Plants*, 45-49.
- Pathak, G. C., & Pandey, N. (2010). Improving zinc density and seed yield of green gram by foliar application of zinc at early reproduction phase. *Indian Journal of Plant Physiology*, 15(4), 338.
- Peñuelas, J., Gamon, J. A., Freeden, A. L., Merino, J., & Field, C. B. (1994). "Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves", *Remote Sensing of Environment*, 48, 145-146. [https://doi.org/10.1016/0034-4257\(94\)90136-8](https://doi.org/10.1016/0034-4257(94)90136-8)
- Potarzycki, J., & Grzebisz, W. (2009). Effect of zinc foliar application on grain yield of maize and its yielding compone. *Plant, Soil and Environment*, 55(12), 519-527.

- Raza, M. A. S., Saleem, M. F., Khan, I. H., Hussain, M. B., & Shah, G. M. (2018). Amelioration in growth and physiological efficiency of sunflower (*Helianthus annuus* L.) under drought by potassium application. *Communications in Soil Science and Plant Analysis*, 49(18), 2291-2300. <https://doi.org/10.1080/00103624.2018.1499764>
- Römheld, V., & Kirkby, E. A. (2010). Research on potassium in agriculture: needs and prospects. *Plant and Soil*, 335, 155-180. <https://doi.org/10.1007/s11104-010-0520-1>
- Ruiz-Navarro, A., Fernandez, V., Abadia, J., Abadia, A., Querejeta, J. I., Albaladejo, J., & Barbera, G. G. (2019). Foliar fertilization of two dominant species in a semiarid ecosystem improves their ecophysiological status and the use efficiency of a water pulse. *Environmental and Experimental Botany*, 167, 103854. <https://doi.org/10.1016/j.envexpbot.2019.103854>
- Sanyal, S. K., Rajasheker, G., Kishor, P. K., Kumar, S. A., Kumari, P. H., Saritha, K. V., & Pandey, G. K. (2020). Role of protein phosphatases in signaling, potassium transport, and abiotic stress responses. *Protein phosphatases and stress management in plants: Functional Genomic Perspective*, 203-232.
- Silva, S., Guimarães, R. F. B., Nascimento, R. D., Oliveira, H. D., Teodoro, I., Cardoso, J. A. F., & Penha, J. L. D. (2018). Economic use of water in drip-irrigated maize in semi-arid region of Brazil. *Journal of Agricultural Science*, 10(3), 364-364.
- Tabatabai, M. A. (1982). Soil Enzymes. (Ed: A.L. Page, R.H. Miller, D.R. Keeney). *Methods of Soil Analysis*, ASA, SSSA, Publisher, Madison, WI, s. 903-947.
- USDA. (2016). *World agricultural supply and demand estimates*. United States Department of Agriculture. [Access date: May 10, 2016].
- Vendemiatti, E., Moreira, R. O., Dos Reis, G. L., Hernandez-De Lira, I. O., Peña-Yewtukhiw, E., Hippler, F. W.R., & Benedito, V.A. (2025). Global transcriptional modulation and nutritional status of soybean plants following foliar application of zinc borate as a suspension concentrate fertilizer. *Scientific Reports*, 15(1), 3309.
- Wada, S., Takagi, D., Miyake, C., Makino, A., & Suzuki, Y. (2019). Responses of the photosynthetic electron transport reactions stimulate the oxidation of the reaction center chlorophyll of photosystem I, P700, under drought and high temperatures in rice. *International Journal of Molecular Sciences*, 20(9), 2068. <https://doi.org/10.3390/ijms20092068>
- Waraich, E. A., Rashid, F., Ahmad, Z., Ahmad, R., & Ahmad, M. (2020). Foliar applied potassium stimulate drought tolerance in canola under water deficit conditions. *Journal of Plant Nutrition*, 43(13), 1923-1934. <https://doi.org/10.1080/01904167.2020.1758132>
- White, C. A., Roques, S. E., & Berry, P. M. (2015). Effects of foliar-applied nitrogen fertilizer on oilseed rape (*Brassica napus*). *The Journal of Agricultural Science*, 153(1), 42-55.
- White, P. J. (2013). Improving potassium acquisition and utilisation by crop plants. *Journal of Plant Nutrition and Soil Science*, 176(3), 305-316. <https://doi.org/10.1002/jpln.201200121>
- Zhang, Y., Guo, S., Wang, R., & Li, H. (2021). Soil enzyme activities and microbial community responses to nutrient management: Implications for sustainable agriculture. *Applied Soil Ecology*, 165, 104005.
- Zörb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture—status and perspectives. *Journal of Plant Physiology*, 171(9), 656-669.