Eurasian Journal of Soil Science 2025, 14(2), 133 - 139

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Effect of foliar fertilization applied at different phenological stages on wheat (*Triticum aestivum* L.) yield and grain nutrient content under greenhouse conditions

Tariverdi Islamzade [a], Sahil Guliyev [b], Zumrud Guliyeva [c], Samira Qaribova [d], Rahila Islamzade [e,*]

[a] Institute of Soil Science and Agrochemistry, Baku, Azerbaijan
[b] ADA University, Baku, Azerbaijan
[c] Azerbaijan State Agricultural University, Ganja, Azerbaijan
[d] Azerbaijan Research Institute of Crop Husbandry, Baku, Azerbaijan
[e] Sumgayit State University, Sumgayit, Azerbaijan

Article Info
Received : 30.07.2024
Accepted : 27.01.2025
Available online: 30.01.2025

Author(s)
T.Islamzade
S.Guliyev
Z.Guliyeva
S.Qaribova
R.Islamzade *

* Corresponding author

Abstract

This study aimed to evaluate the effects of foliar fertilization applied at different phenological stages on wheat (*Triticum aestivum* L.) yield, yield components, and grain nutrient content under controlled greenhouse conditions. The experiment was conducted using a randomized block design with four replications. Foliar fertilization treatments were applied at three key phenological stages: tillering (T), stem elongation (SE), and heading (H), along with their combinations (T+SE, T+H, SE+H, and T+SE+H). A control treatment without foliar fertilization was also included. Foliar fertilizers containing essential macro- and micronutrients were applied at a 0.5% concentration using a hand sprayer. The results demonstrated that foliar fertilization significantly improved wheat grain yield and nutrient composition compared to the control. The highest grain yield increase was observed in the T+SE and T+SE+H treatments, which enhanced yield by 71.01% and 73.45%, respectively, compared to the control. However, statistical analysis revealed no significant differences between these two treatments, suggesting that foliar fertilization at the tillering and stem elongation stages alone is sufficient to achieve maximum yield and nutrient uptake efficiency. Significant increases in nitrogen (N), phosphorus (P), potassium (K), and micronutrients such as iron (Fe), zinc (Zn), and manganese (Mn) were observed in response to foliar applications, while copper (Cu) content remained unchanged. These findings highlight the effectiveness of foliar fertilization in enhancing wheat productivity and nutrient content. Considering practical and economic aspects, the T+SE application is recommended as the most efficient approach. Nevertheless, further field trials are necessary to validate these results under real-world conditions and optimize foliar fertilization strategies for sustainable wheat production.

Keywords: Foliar fertilization, wheat yield, phenological stages, macro and micronutrients, greenhouse experiment.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important staple crops worldwide, providing a major source of calories and nutrients for human populations (Garg et al., 2021; Khalid et al., 2023). The demand for wheat continues to rise due to global population growth and changing dietary preferences, necessitating the adoption of advanced agricultural practices to optimize yield and grain quality (Pingali and Rosegrant, 1988; Awaad and Deshesh, 2019; Pandey and Mishra, 2024). One such practice is foliar fertilization, which has gained significant attention in recent years for its potential to enhance nutrient uptake efficiency, improve yield

: https://doi.org/10.18393/ejss.1629626
: https://ejss.fesss.org/10.18393/ejss.1629626
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

components, and increase the nutritional value of wheat grain (Gülser et al., 2019; Rossmann et al., 2019; McBeath et al., 2020; Andrade et al., 2024).

Foliar fertilization is a complementary strategy to traditional soil fertilization, offering several advantages, including rapid nutrient absorption, bypassing soil nutrient limitations, and targeted application at critical growth stages (Gülser et al., 2019; Bărdaş et al., 2024). Studies have shown that foliar nutrient applications can effectively enhance the uptake of macroelements such as nitrogen (N), phosphorus (P), and potassium (K), as well as essential micronutrients like iron (Fe), zinc (Zn), and manganese (Mn), thereby improving grain yield and quality parameters (McBeath et al., 2020; Abrol et al., 2021; Çolak Esetlili et al., 2024, Ferrari et al., 2025). Furthermore, foliar fertilization can play a crucial role in mitigating nutrient deficiencies and abiotic stress conditions, which are prevalent in wheat-growing regions (El-Hendawy et al., 2024; Shoormij et al., 2024).

The timing of foliar fertilizer application is critical to achieving optimal results (Peirce et al., 2019). Different phenological stages of wheat, such as tillering, stem elongation, and heading, exhibit varying nutrient demands, and applying fertilizers at these key growth stages can significantly influence plant development and final yield. Previous research has demonstrated that stage-specific foliar fertilization can enhance biomass accumulation, grain filling, and nutrient translocation within the plant (Abrol et al., 2021; Andrade et al., 2024; Bărdaş et al., 2024). However, there is limited consensus on the most effective phenological stage for foliar application to maximize wheat yield and quality under controlled conditions.

This study aims to evaluate the effects of foliar fertilization applied at different phenological stages on wheat yield, yield components, and grain nutrient content. The specific objectives are to (i) determine the impact of foliar fertilization timing on wheat yield and grain nutrient composition, (ii) identify the most effective stage for foliar application to achieve optimal agronomic benefits, and (iii) provide practical recommendations for improving wheat fertilization strategies.

Material and Methods

Experimental Materials

The wheat (Triticum aestivum L.) variety used in the experiment is a high-yielding local cultivar known for its suitability for the experiment. The seeds were obtained from a certified supplier.

The soil used in the experiment was collected from an agricultural field where wheat is commonly cultivated. The soil samples were air-dried in the shade, crushed with a wooden mallet, and passed through a 2 mm sieve to ensure homogeneity before being prepared for the experiment and subsequent analyses. To determine the physical and chemical properties of the soil, various standard methods were employed. Soil texture was analyzed using the hydrometer method (Bouyoucous, 1951). For chemical analyses, soil pH was measured in a 1:1 soil-to-water suspension using a pH meter (Peech, 1965), and electrical conductivity (EC) was measured in a 1:1 soil-to-water extract (Rowell, 1996). Organic matter content was determined by the Walkley-Black method (Walkley and Black, 1934), while total carbonate content was analyzed using the Scheibler calcimeter (Loeppert and Suarez, 1996). Total nitrogen (N) was measured using the Kjeldahl method (Bremner, 1965). Available phosphorus (P) was assessed using the Olsen method with a 0.5 M $NaHCO_3$ extraction (Olsen and Dean, 1965). Exchangeable cations (K, Ca, Mg, and Na) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965). Available micronutrients, including Fe, Cu, Zn, and Mn, were determined by DTPA extraction followed by Atomic Absorption Spectrophotometry (Lindsay and Norvell, 1978).

In the experiment, wheat seeds were sown with the application of diammonium phosphate (DAP) fertilizer containing 18% nitrogen (N) and 46% phosphorus pentoxide (P_2O_5). During the tillering and stem elongation stages, ammonium sulfate fertilizer (21% N) was applied. For foliar fertilization, Agrobigen D (17-17-17+micronutrients) was used during the tillering stage, and Agrobigen K (9-9-25+2MgO+ micronutrients) was applied during the stem elongation and heading stages. All fertilizers were procured from the market.

Experimental Design

This study was conducted under controlled greenhouse conditions to evaluate the effects of foliar fertilization applied at different phenological stages of wheat (Triticum aestivum L.) on yield and nutrient uptake. The experiment was designed using a randomized block design with four replications. For this purpose, 5 kg of soil (on a dry weight basis) was placed in each pot, and 30 wheat seeds were sown per pot. After the emergence of the first leaf, thinning was performed to leave 15 plants per pot. Basal fertilization

was carried out by applying 0.5 g of diammonium phosphate (DAP) fertilizer per pot at the time of sowing, equivalent to 25 kg DAP per decare. Additionally, a total of 0.5 g of ammonium sulfate fertilizer (equivalent to 25 kg ammonium sulfate per decare) was applied to each pot, with half of the dose applied during the tillering stage and the other half during the stem elongation stage. To maintain the soil moisture content at 50% of field capacity, the pots were weighed daily, and the missing water amount was replenished accordingly.

For the foliar fertilization treatments, three main phenological stages (tillering, stem elongation, and heading) and all their combinations were considered. Eight different treatments were applied in the experiment:

- Control (C): No foliar fertilizer was applied.
- Tillering (T): Foliar fertilizer was applied only during the tillering stage.
- Stem elongation (SE): Foliar fertilizer was applied only during the stem elongation stage.
- Heading (H): Foliar fertilizer was applied only during the heading stage.
- Tillering + Stem elongation (T + SE): Foliar fertilizer was applied during both the tillering and stem elongation stages.
- Tillering + Heading (T + H): Foliar fertilizer was applied during the tillering and heading stages.
- Stem elongation + Heading (SE + H): Foliar fertilizer was applied during the stem elongation and heading stages.
- Tillering + Stem elongation + Heading (T + SE + H): Foliar fertilizer was applied at all phenological stages.

Foliar fertilizers were prepared as a 0.5% solution. The solution was applied uniformly to the plant surface using a hand sprayer in the early morning hours. In each application, 20 mL of fertilizer solution was sprayed onto each pot.

Harvest and Analysis

On the 85th day of the experiment, the wheat plants reached maturity and were harvested. The harvested plant materials were separated into grain and straw fractions, which were then dried in an oven at 65°C until a constant weight was achieved. The dried samples were subsequently weighed using a precision balance to determine the grain yields per pot. For nutrient analysis, the dried grain samples were ground to a fine powder and analyzed for their N, P, K, Mg, and micronutrient (Fe, Zn, Cu, and Mn) contents. The nitrogen content was determined using the Kjeldahl method, while phosphorus was analyzed using the molybdo-vanadate spectrophotometric method. Potassium content was measured with a flame photometer. The concentrations of Mg, Fe, Cu, Zn and Mn were determined by Atomic Absorption Spectrophotometry (AAS) following the methodology described by Jones (2001).

Statistical Analysis

The obtained data were analyzed using analysis of variance (ANOVA) to determine the effects of different phenological stages and their combinations. Treatment means were compared using the Least Significant Difference (LSD) test at a 5% significance level. Statistical analyses were performed using SPSS 25.0 software.

Results and Discussion

The soil used in the experiment consisted of 58% clay, 24% silt, and 18% sand, with a pH of 7.45 and an electrical conductivity (EC) of 0.85 dS/m. The organic matter content was 1.08%, lime content was 18.03%, total nitrogen (N) was 0.089%, available phosphorus (P) was 6.26 mg/kg, exchangeable potassium (K) was 0.983 meq/100 g, exchangeable calcium (Ca) was 21.311 meq/100 g, exchangeable magnesium (Mg) was 3.692 meq/100 g, and exchangeable sodium (Na) was 0.578 meq/100 g. Additionally, the available micronutrient contents of the experimental soil were determined as follows: iron (Fe) 4.56 mg/kg, copper (Cu) 0.95 mg/kg, zinc (Zn) 1.23 mg/kg, and manganese (Mn) 15.08 mg/kg. Based on these results, the experimental soil was classified as clay-loam in texture, slightly alkaline in reaction, calcareous, non-saline, with a low organic matter content, free from sodicity issues, and characterized by low total nitrogen and available phosphorus content. The levels of potassium, calcium, and magnesium were found to be moderate, while the micronutrient (Fe, Cu, Zn, and Mn) contents were at adequate levels.

Effects on Wheat Yield and Yield Components

The application of foliar fertilizers at different phenological stages significantly influenced wheat yield and yield components, including grain weight per pot, thousand grain weight, and the number of grains per spike (Figure 1). Treatments involving tillering and stem elongation stages (T+SE) and all stages combined

(T+SE+H) demonstrated the most pronounced yield improvements of 71.01% and 73.45%, respectively. These findings align with previous studies, which reported that foliar fertilization at key phenological stages enhances nutrient availability and translocation, resulting in improved biomass accumulation and grain filling (Bărdaş et al., 2024).

Several studies confirm the positive impact of foliar applications on wheat productivity. For instance, Gülser et al. (2019), McBeath et al. (2020) and Ferrari et al. (2025) highlighted that foliar-applied nitrogen and phosphorus fertilizers during the stem elongation stage significantly enhance grain yield and protein content. Similarly, Bărdaş et al. (2024) reported that a balanced foliar fertilization approach during tillering and stem elongation stages maximizes nutrient use efficiency and promotes grain development. The increased number of grains per spike and thousand grain weight in the current study suggests improved source-sink relationships, corroborating findings by Wu et al. (2022) and Wei et al. (2023), who emphasized that foliar fertilization during critical growth stages optimizes assimilate partitioning and photosynthetic efficiency.

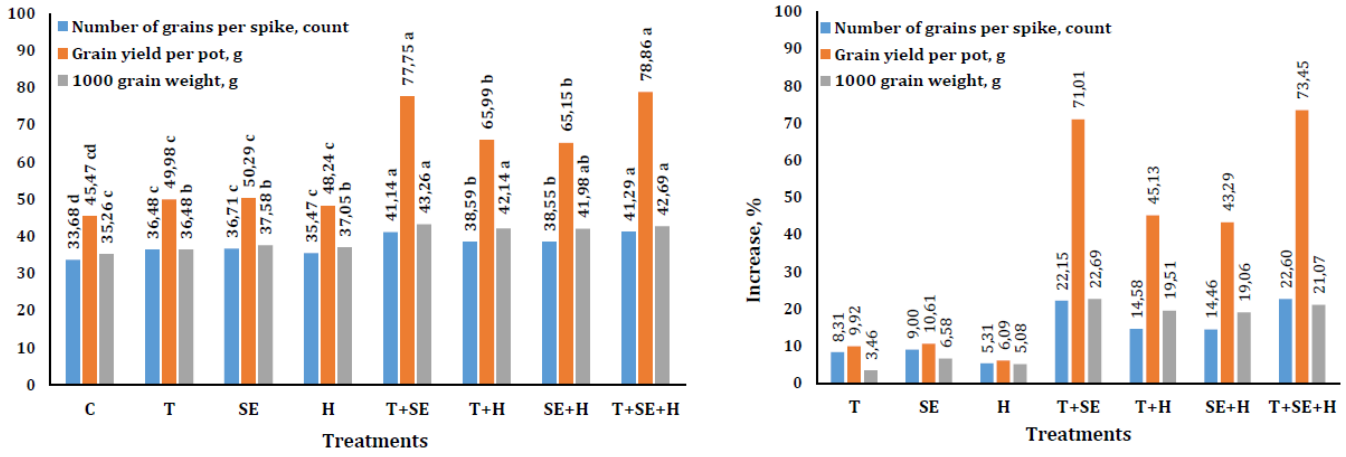

Figure 1. The effect of foliar fertilization applied at different phenological stages of wheat on grain yield, number of grains per spike, and thousand grain weight.

Effects on Macro Element Contents of Wheat Grain

The macroelement composition of wheat grains, including nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), exhibited significant variations depending on the foliar fertilization regimen (Figure 2). Treatments T+SE and T+SE+H resulted in the highest increases in N, P, and K contents. Phosphorus showed the most notable increase (34.62%), emphasizing the importance of foliar P application during critical growth phases in enhancing its uptake and utilization (Bărdaş et al., 2024).

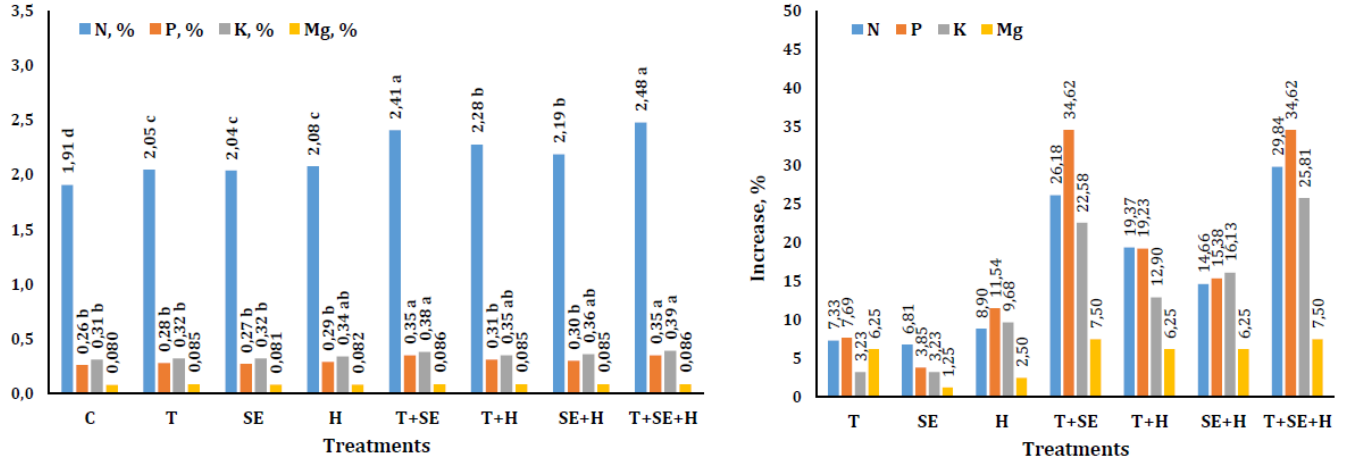

Figure 2. The effect of foliar fertilization applied at different phenological stages of wheat on the N, P, K, and Mg contents of the grain.

Shabnam et al. (2018) and Bourak et al (2023) reported similar trends, demonstrating that phosphorus fertilization at stem elongation enhances root development and energy transfer in wheat. The significant nitrogen content improvements align with findings by Rossmann et al. (2019), who found that foliar N application increases grain protein content and yield quality. Interestingly, the lack of significant changes in magnesium content in this study aligns with findings by Dölger et al. (2024), who suggested that Mg foliar applications are more effective under deficiency conditions rather than as a preventive measure.

Effects on Microelement Contents of Wheat Grain

Foliar fertilization significantly influenced the microelement composition of wheat grains, particularly iron (Fe), zinc (Zn), and manganese (Mn), whereas copper (Cu) did not show significant changes (Figure 3). The highest increases in Fe, Zn, and Mn contents were observed in the T+SE and T+SE+H treatments, highlighting the role of foliar applications in enhancing micronutrient bioavailability and uptake efficiency.

These results are in line with the findings of Wang et al. (2020), who reported that foliar Zn and Fe applications significantly improved wheat grain quality in rainfed conditions. Furthermore, recent studies indicate that foliar micronutrient supplementation can address hidden hunger in staple crops and improve human nutrition by increasing micronutrient density in grains (Saquee et al., 2023). The insignificant changes in Cu content suggest sufficient soil availability or potential antagonistic interactions with other nutrients, as discussed by Wairich et al. (2022), who recommended alternative application methods for better Cu uptake.

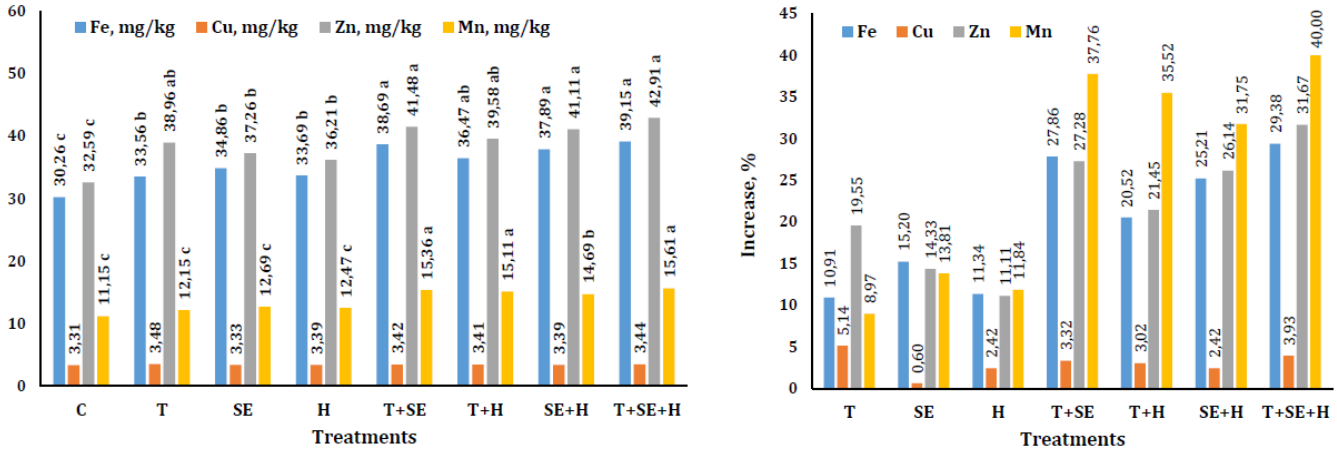

Figure 3. The effect of foliar fertilization applied at different phenological stages of wheat on the Fe, Cu, Zn, and Mn contents of the grain.

Conclusion

This greenhouse study demonstrates that foliar fertilization applied at different phenological stages significantly enhances wheat yield, yield components, and grain nutrient content. The findings indicate that foliar application at the tillering and stem elongation stages (T+SE) resulted in substantial improvements, comparable to the more comprehensive treatment including the heading stage (T+SE+H). However, considering economic feasibility and practical applicability, the T+SE treatment is recommended as an optimal strategy for improving wheat productivity.

Foliar fertilization has proven to be an effective agronomic practice for increasing nutrient availability, enhancing nutrient uptake efficiency, and ultimately improving grain yield and quality. By supplying essential nutrients directly to the plant during critical growth stages, foliar fertilization not only enhances yield components such as grain weight and number of grains per spike but also contributes to improved macro- and micronutrient concentrations in the grain. This highlights its importance in addressing nutrient deficiencies and optimizing plant growth.

Despite the promising results obtained under controlled greenhouse conditions, it is important to recognize that field environments present different challenges such as soil heterogeneity and climatic variability. Therefore, further field trials are essential to validate these findings and to determine the effectiveness of foliar fertilization under real-world conditions.

In conclusion, foliar fertilization is a valuable strategy for enhancing wheat productivity by improving both yield and nutritional quality. Future research should focus on field-scale implementation to confirm its practical benefits and to establish tailored fertilization strategies for sustainable wheat production.

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