SCIENTIA AGRICULTURAE BOHEMICA

Article

The effects of nanostructured and chelated zinc on the productivity of wheat varieties

Mohsen JANMOHAMMADI [1]*, Asghar EBADI-SEGHERLOO[2], Mehdi MOHEBODINI[3], Naser SABAGHNIA[1]

1 Department of Plant Production and Genetics, Faculty of Agriculture, University of Maragheh, Maragheh, Iran; mjanmohammadi@maragheh.ac.ir; sabaghnia@maragheh.ac.ir

2 Moghan College of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil, 1136756199, Iran; asghar_ebadi@uma.ac.ir

3 Department of Horticultural Science, Faculty of Agricultural Science and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran; mohebodini@uma.ac.ir

* Correspondence: mjanmohammadi@maragheh.ac.ir (Iran)

Abstract: Poor physicochemical properties of soils in the drought-prone areas of northwestern Iran have led to a significant zinc deficiency in wheat production systems. A field study was conducted to evaluate the impact of applying EDTA chelated zinc fertilizer through soil and the foliar application of zinc oxide nanoparticles on wheat cultivars (G_1: Gonbad, G_2: Shiroudi, G_3: Chamran, G_4: N-87-20, G_5: Morvarid, G_6: Darya) in the northwest area. The results showed that the heaviest spikes were produced with foliar spray of zinc oxide nanoparticles in G_5 (2.27 g), while the application of chelated zinc fertilizer in G_1 produced heavier spikes (2.02 g). The highest grain yield was obtained in G_5 and G_4 with chelated zinc (1279 and 1224 kg/ha, respectively) and in G_6 and G_2 with zinc nanoparticle spray (1185 and 1207 kg/ha, respectively). The findings showed that the genotypes Darya, Marvarid, Chamran, and Gonbad exhibited a strong response to the types of zinc fertilizers used. The findings indicated that the optimal methods of zinc application are also influenced by the genotype. The choice of application methods must be made deliberately and based on climate, soil conditions, and genotypes.

Keywords: greenness index, relative water content, silique number, soil improvement, synergistic relationships

Received for publication on October 13, 2025

Accepted for publication on April 04, 2026

1. Introduction

While semi-arid areas are significantly impacted by climate change, their populations continue to grow (Karimi et al., 2024). This increase heightens the demand for food and energy. In this scenario, prioritizing the provision of eco-friendly and renewable energy is essential. To accomplish this, it is crucial to minimize fossil fuel consumption and greenhouse gas emissions as much as possible (Abdoos et al., 2025). Over recent decades, the extraction of biodiesel from oilseed crops has gained attention. However, crop species must possess specific traits to thrive in semi-arid environments. Among oilseed crops, Camelina sativa from the Brassicaceae family is being considered for oil and biofuel production. When compared to other oilseed crops, Camelina has a higher oil content (35–40%) and protein content (24–47%). Its distinctive fatty acid composition and significant proportion of linolenic acid also make it an excellent candidate for animal feed (Sydor et al., 2022).

Semi-arid regions typically have low-quality soil due to insufficient rainfall, uneven distribution of rainfall, overgrazing, not returning crop residues to the soil, intensive agricultural practices, improper crop rotation, unprincipled tillage methods, misuse of chemical fertilizers, and low levels of organic soil matter. In such areas, soil pH tends to be elevated (Nehrani et al., 2020). Among various oilseed plants, Camelina is particularly well-suited for low-input and low-tillage farming systems. It is capable of yielding crops even in marginal areas with limited moisture availability (Mohsenpour et al., 2025). Due to the existence of both spring and winter varieties, incorporating Camelina into crop rotations is more straightforward, thereby enhancing the flexibility of rotation schemes (Royo-Esnal and Valencia-Gredilla, 2018). The soil in these regions frequently faces significant nutrient deficiencies, and supplementing nutrients for agricultural crops can substantially boost yields. Nitrogen is regarded as the most crucial nutrient for plant development. It plays a vital role in numerous biological functions as it is a component of amino acids and, by extension, proteins. Nonetheless, the effectiveness of nitrogen on plant growth is influenced by several variables, including climatic conditions, soil moisture, soil pH, temperature, and the specific plant species (Farhan et al., 2024). Enhancing soil moisture and improving both the physical and chemical properties of the rhizosphere through soil amendments can heighten plant responsiveness to nitrogen and further enhance economic returns (Ray et al., 2025). Under ideal moisture conditions, while keeping soil moisture close to field capacity, nitrogen applications can be raised to 150 kg ha^{-1} (Soils et al., 2013). Although sulfur is necessary for growth, its requirement is lower than that of nitrogen, and it is still categorized as a macronutrient. The use of sulfur is strongly recommended in oilseed crop production systems, as a direct correlation has been established between sulfur application and oil content in these crops (Kumari et al., 2025). Furthermore, sulfur affects plant growth and quality while also influencing soil chemistry; by adjusting soil pH, it can enhance the impact of nitrogen in the rhizosphere. Insufficient sulfur access can adversely affect both the quantity and quality of the harvested crops (Sharma et al., 2024). Research indicates that nitrogen and sulfur utilization in Camelina can influence protein levels, oil content, and the concentrations of monounsaturated and polyunsaturated fatty acids. However, the interaction between nitrogen and sulfur is largely dependent on environmental factors and soil conditions. The response of Camelina to nitrogen and sulfur levels does not appear to be linear. Planting time, soil organic matter content, and the amount of water available to the root system can influence the plant's response to nitrogen (Soils et al., 2013). Although interactions between nitrogen and sulfur have been studied in some plants (Rossini et al., 2018; Carciochi et al., 2020; Fattahi et al., 2024), there is still limited information about their interaction in the semi-arid regions of northwest Iran. Therefore, specific research is needed for each agro-climatic zone regarding nitrogen consumption patterns, the effect of sulfur, and the performance and quality of adaptable plants such as Camelina. This experiment aimed to investigate the simultaneous application of different levels of sulfur and nitrogen on agronomic traits and oil content in Camelina in northwest Iran.

2. Materials and Methods

2.1. Site description

A field experiment was conducted during the 2024–2025 crop year in the Maragheh region (37°23′N, 46°16′E, 1,448 m above sea level). This region is located 135 km southwest of East Azerbaijan Province, east of Lake Urmia, on the slopes of Mount Sahand, and adjacent to the Sufi-Chay River. According to the Köppen climate classification, the climate of the study area is semi-arid cold temperate. Before the experiment, soil samples were collected from a depth of 0–30 cm and analyzed. The soil texture was sandy loam, with an electrical conductivity of 1.24 dS m^{-1}, pH 8.04, soil moisture content at field capacity of 25.9%, moisture content at wilting point of 13.4%, total nitrogen of 0.64 g kg^{-1}, sulphur 5.67 mg kg^{-1}, phosphorus of 8.9 mg kg^{-1}, potassium of 367 mg kg^{-1}, and cation exchange capacity of 24.3 Cmolc kg^{-1}. The trends in air temperature and precipitation during the Camelina growth period are shown in Figure 1.

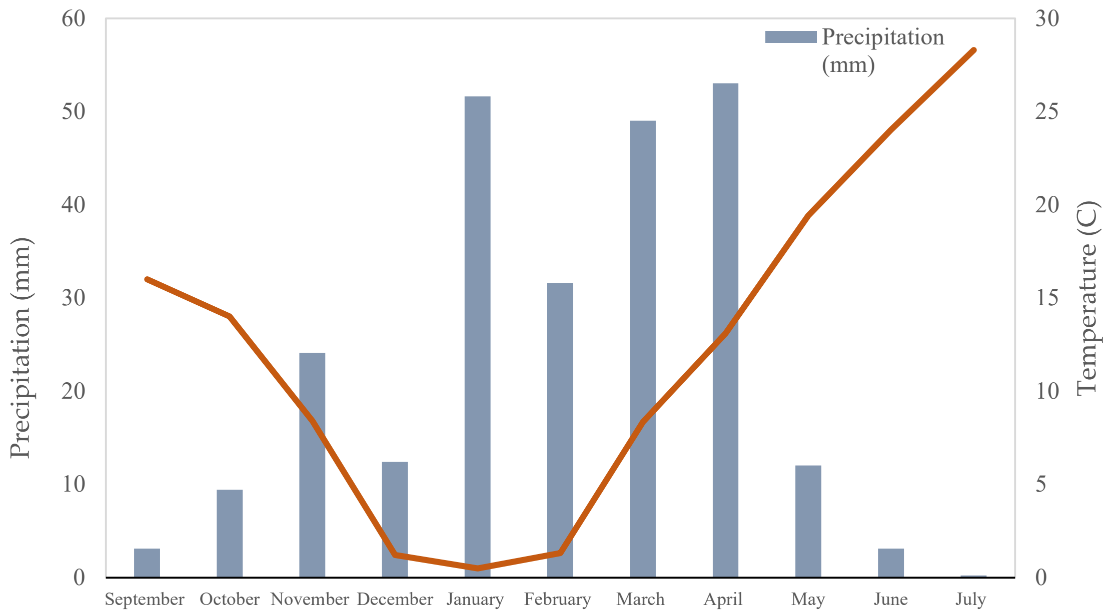

Figure 1. Average monthly temperatures and total monthly rainfall during the growing seasons of 2024 and 2025.

2.2. Execution of experimental treatments

In October, initial tillage was performed with a moldboard plow. After determining the experimental plot boundaries, different amounts of sulfur were applied to the plots. Sulfur was then mixed into the soil to a depth of 20 cm using a rotavator. For secondary tillage, a disk harrow was used to crush the lumpy soil and soften the topsoil as much as possible. The soil surface was shaped into a ridge and furrow format using a furrower.

The experiment followed a randomized complete block design with three replications in a factorial arrangement. The nitrogen factor was applied at five levels: zero (control), 40, 80, 120, and

160 kg ha^{-1}, supplied through urea fertilizer. The sulfur factor was applied at four levels: 0, 25, 50, and 75 kg ha^{-1}, using elemental sulfur fertilizer (99%) during the soil tillage stage. One-third of the nitrogen was applied at planting, one-third at the stem elongation stage, and one-third at the flowering stage as a top dressing. Each experimental plot covered 15 m^2 and consisted of 10 rows, each 3 m long. Inter-row and intra-row spacing were 50 cm and 5 cm, respectively. After final tillage and preparation of the ridge and furrow pattern, seeds were sown manually on top of the ridges. For better germination, seeds were primed in distilled water for 16 hours. The field was irrigated immediately after sowing. Irrigation was provided from a deep well using a pressurized system and polyethylene pipes and teaps. The rainfall during the growing season was 260 mm, and the irrigation rate was 323 mm. The field was irrigated once more at the rosette stage, and the remaining irrigations were applied during tillering, flowering, silique formation, and grain filling. At the seed sowing stage, 70 kg ha^{-1}, of phosphorus and 30 kg ha^{-1}, of potassium were applied as triple superphosphate and potassium chloride, banded 2 cm adjacent to the sowing line and 5 cm below the seed.

2.3. Assessment of agronomic characteristics

At the silique growth phase, the relative water content of the uppermost fully expanded leaves was assessed. For this purpose, leaf disc samples were gathered from the field early in the day and transported to the lab on ice, where the initial fresh weight (FW) was recorded. The turgid weight (TW) was subsequently determined by immersing the leaf discs in distilled water for 8 hours. The dry weight (DW) was obtained by drying the samples in an oven at 60°C for 48 hours. The relative water content was calculated using the following formula: $RWC = [(FW - DW) / (TW - DW)] \times 100$. To assess the greenness index, which is indicative of chlorophyll content, a Konica Minolta SPAD 502 was employed during the seed filling phase. At the time of plant maturation, after the siliques had dried and turned brown, ten plants were randomly chosen from each experimental plot, and characteristics such as the number of lateral branches, stem height, number of siliques per plant, number of seeds per silique, and the weight of 1000 seeds were recorded. To determine biological weight and yield, a random quadrat sampling method with a size of one square meter was utilized. After drying the plants at 65°C for 48 hours, the total plant weight was measured, and the seed weight was obtained after threshing and separating the straw. Oil was extracted from the seeds using a Soxhlet extractor.

2.4. Data Analysis

After data collection, normality was assessed using Minitab software. An F-test and one-way analysis of variance were performed using SAS software. Mean comparisons were conducted using the LSD test at the 5% significance level. Box plots were generated with SPSS software. Component analysis was performed with Minitab software to illustrate the distribution of treatment combinations and the relationships among the evaluated traits.

3. Results

3.1. Vegetative traits

The results of variance analysis indicated a significant effect of nitrogen and sulfur on stem height. With increasing nitrogen applications to 80, 120, and 160 kg ha^{-1}, stem height increased by 6% and 59% compared to the control. However, no difference was observed among the 0, 25, and 50 kg ha^{-1} sulfur levels in terms of stem height (Table 1).

Table 1. Evaluation of the impact of different levels of nitrogen and sulfur application on the growth characteristics and yield components of Camelina in the semi-arid region of Maragheh, situated in northwestern Iran.

Effects	HS	GI	BN	RWC	BIY	NSP	TGW	HI
Nitrogen (N)								
N_0	44.34e	34.26e	3.32e	63.99d	3910.78c	22.83d	0.88b	23.06e
N_{40}	46.60d	37.58d	4.09d	65.10d	4376.35b	26.80c	0.90a	23.56d
N_{80}	54.44c	42.70c	5.42c	69.82b	4812.65a	31.31a	0.89a	25.23b
N_{120}	64.88b	50.64b	5.58b	73.77a	4274.16b	29.37b	0.90a	25.76a
N_{160}	70.53a	53.75a	6.18a	67.46c	3933.17c	28.22b	0.88c	24.39c
Sulphur (S)								
S_0	54.59b	41.43c	4.85b	67.43b	4075.99c	26.55c	0.90a	24.31ab
S_{25}	55.56b	43.55b	4.87b	67.81ab	4265.48b	27.42bc	0.90a	24.16b
S_{50}	55.69b	44.83a	4.99a	68.11ab	4417.08a	28.79a	0.88b	24.60a
S_{75}	58.79a	45.33a	4.95ab	68.75a	4287.14ab	28.06ab	0.89b	24.53a
Interactions								
N_0S_0	42.40i	32.30i	3.13g	62.97j	3583.5l	21.87i	0.87ghi	23.67fg
N_0 S_{25}	43.43hi	33.43hi	3.13g	63.57ij	3907.5J	23.67hi	0.89defg	22.60h
N_0 S_{50}	43.30hi	35.57gh	3.20g	63.93ij	4199.0fghi	23.27i	0.86ij	22.60h
N_0 S_{75}	48.23f	35.73gh	3.80f	65.50ghij	3953.0I	22.50i	0.92bc	23.37g
$N_{40}S_0$	45.30gh	36.10gh	4.00ef	66.60fgh	4287.0efg	25.77gh	0.92abc	23.23gh
N_{40} S_{25}	46.30fg	37.50fg	4.17e	65.07ghij	4605.0cd	26.67fg	0.93a	23.17gh
N_{40} S_{50}	46.40fg	39.37ef	4.13e	64.27hij	4252.7efgh	26.97efg	0.85j	24.23ef
N_{40} S_{75}	48.40f	37.33fg	4.07e	64.47hij	4360.6def	27.80defg	0.89defg	23.60fg
$N_{80}S_0$	53.53e	39.13f	5.37C	66.90fg	4368.5def	28.80def	0.91c	25.20cd
N_{80} S_{25}	53.87e	41.87de	5.37cd	69.80de	4729.6bc	31.37abc	0.90d	25.27cd
N_{80} S_{50}	52.70e	42.40d	5.73b	71.07cd	5115.3a	33.03a	0.88fgh	25.67bc
$N_{80}S_{75}$	57.67d	47.40c	5.20d	71.50bcd	5037.3ab	32.03a	0.89def	24.80de
$N_{120}S_0$	63.17c	47.13c	5.57bc	74.13a	4169.8fghi	28.27def	0.89de	25.23cd
N_{120} S_{25}	63.90c	51.17b	5.60bc	73.20abc	4278.7efgh	27.90defg	0.89d	25.27cd
$N_{120}S_{50}$	64.40c	51.50b	5.60bc	73.87ab	4529.3cde	31.63ab	0.93ab	26.00ab
N_{120} S_{75}	68.07b	52.77ab	5.53bc	73.87ab	4118.8fghik	29.67bcd	0.87ghi	26.53a
$N_{160}S_0$	68.57b	52.50b	6.20a	66.57fgh	3971.0hijk	28.03defg	0.88fgh	24.20ef
N_{160} S_{25}	70.30ab	53.80ab	6.10a	67.40fg	3806.5kl	27.50defg	0.89def	24.50e
N_{160} S_{50}	71.67a	55.30a	6.30a	67.43efg	3989.1ghik	29.03cde	0.88efg	24.50e
N_{160} S_{75}	71.60a	53.40ab	6.13a	68.43ef	3966.0hijk	28.30def	0.87hij	23.67fg
Significance level								
N	<0.0001	<0.0001	<0.0001	0.002	<0.0001	<0.0001	<0.0001	<0.0001
S	<0.0001	<0.0001	0.0368	0.0970	<0.0001	0.0009	<0.0001	0.0166
N×S	0.3196	<0.0001	<0.0001	0.0421	0.0369	0.2811	<0.0001	0.0005
CV%	3.75	6.25	7.36	9.37	10.21	6.14	5.32	4.21

N0–N160 refer to nitrogen applications of 0, 40, 80, 120, and 160 kg ha^{-1}. S0–S75 refer to sulfur applications of 0, 25, 50, and 75 kg ha^{-1}. CV stands for the coefficient of variation (%), HS indicates stem height, GI refers to the greenness index, BN denotes branch number, OC represents oil content, HI stands for harvest index, RWC signifies relative water content, GNS means grain number per silique, NSP indicates silique number per plant, GY refers to grain yield, BIY denotes biological yield, and TGW is the thousand-grain weight. For each trait, means represented by different letters show that they have responded differently to the treatments with a significance level of $p < 0.05$ when analyzed through the LSD test. The significance tests (p values) are provided to assess the level of significance, where values below 0.05 and 0.01 indicate significance at the 5% and 1% statistical levels, respectively.

The tallest stems were obtained with an application of 75 kg ha^{-1} sulfur. The interaction effects of S × N on the greenness index were significant at the 1% level. With increasing nitrogen application, this index increased in a relatively linear manner. The effect of sulfur on this component was slightly less than that of nitrogen; however, the highest greenness index was observed with applications of 50 and 75 kg ha^{-1} sulfur. The highest greenness index was recorded in plants grown under N160+S50 (55.30), N160+S75 (53.40), and N120+S75 (52.75) conditions. Several indices showed significant S × N effects. The highest number of branches was obtained in plants grown with high nitrogen levels. High sulfur application (75 kg/ha) reduced the number of lateral branches compared to other levels. Relative leaf water content (RWC), an important indicator for evaluating plant water status, was affected by the treatments studied. Application of medium doses of nitrogen increased RWC by 9–15% compared to plants under control conditions. Sulfur applications also improved RWC compared to no sulfur application (Table 1). The highest RWC was recorded under N_{120}+S_0 conditions. High nitrogen application significantly reduced RWC. Under no nitrogen application, RWC showed a slight increase with increasing sulfur application (Table 1).

Biological yield (BIY), as a measure of total vegetative growth, was affected by the interaction effects of S × N at the 5% level. Although nitrogen application increased BIY compared to the control, the highest values were obtained with 80 kg/ha. Sulfur applications also significantly increased BIY compared to the control. The highest BIY values were observed with 50 and 75 kg ha^{-1} sulfur applications. The highest BIY values were recorded in plants under N_{80}+S_{50} (5115 kg ha^{-1}) and N_{80}+S_{75} (5037 kg ha^{-1}) conditions (Table 1).

3.2. Yield components

Nitrogen application significantly increased the silique number per plant (SNP) compared to the control. However, the highest SNP was obtained with 80 kg of nitrogen per hectare (31.32). Increasing nitrogen applications above 80 kg ha^{-1} caused a slight decrease in SNP. Sulfur applications also significantly increased SNP, but the trend was not completely linear. Application of 25, 50, and 75 kg ha^{-1} sulfur increased SNP by 3%, 8%, and 5%, respectively, compared to the control. The interaction effects of S × N on grain number per silique (GNS) were significant. With increasing nitrogen application, GNS showed a significant decrease. The highest GNS values were recorded under the N_0+S_{50} conditions. Under high nitrogen application rates, sulfur applications had no significant effect on GNS (Figure 2).

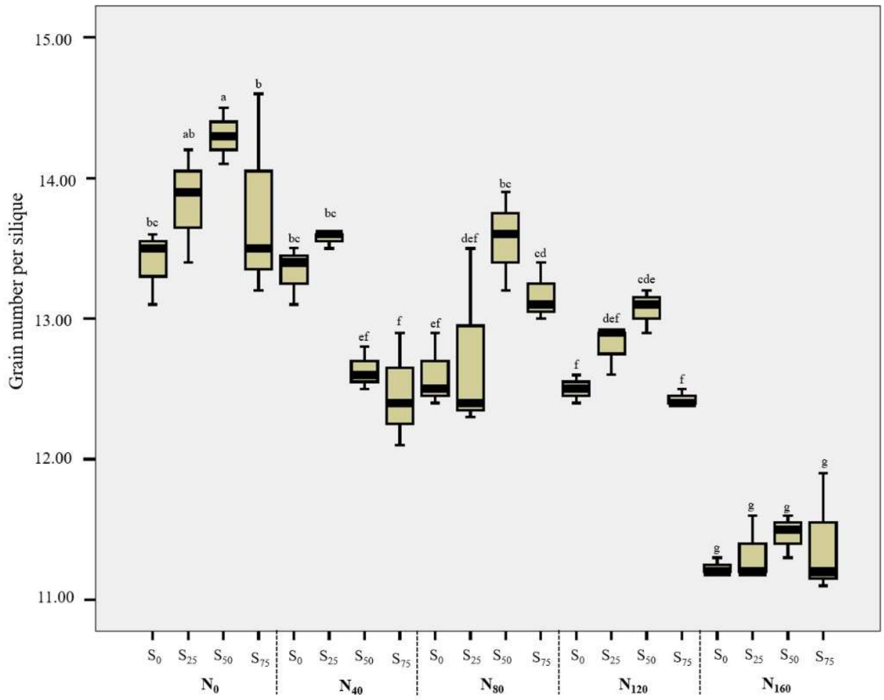

Figure 2. An investigation into the effects of nitrogen (0, 40, 80, 120, and 160 kg ha-1) and sulfur (0, 25, 50, and 75 kg ha-1) on the number of grains per silique in Camelina grown in the Maragheh region of northwestern Iran. Containers displaying identical letters do not show statistically significant differences at the 0.05 level.

The interaction effect of S × N was significant for 1000-grain weight. The heaviest grain was recorded under N_{40}+S_{25} (0.931 g) and N_{120}+S_{50} (0.925 g). High doses of sulfur and nitrogen reduced grain weight compared to the control. The lowest grain weight was observed under N_{160}+S_{75} (0.861 g). Grain yield evaluation showed that increasing nitrogen application up to 80 kg ha^{-1} significantly increased yield compared to the control. In most nitrogen applications, sulfur applications up to 50 kg ha^{-1} increased yield. The greatest effect of sulfur was observed under 80 and 120 kg ha^{-1} nitrogen application. The highest yield was recorded under N_{80}+S_{50} at 1312.53 kg ha^{-1}, with plants growing under N_{80}+S_{75} ranking second. High nitrogen application significantly reduced yield, and under these conditions, sulfur application had no significant effect on grain yield (Figure 3).

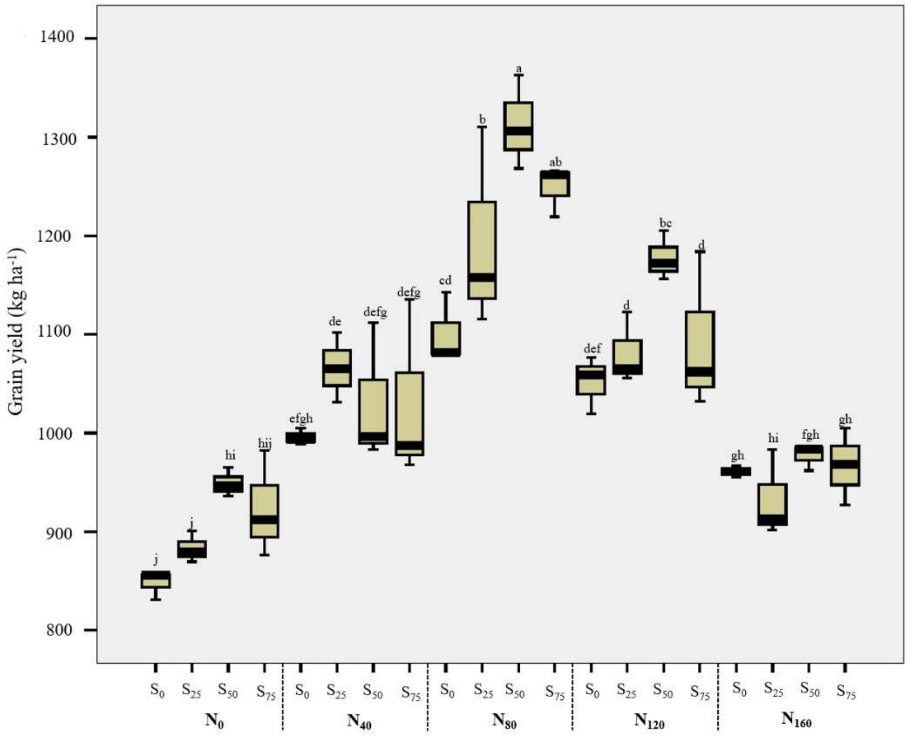

Figure 3. The grain yield of Camelina grown in the semi-arid region of northwestern Iran was influenced by varying levels of nitrogen (0, 40, 80, 120, and 160 kg ha^{-1}) and sulfur (0, 25, 50, and 75 kg ha^{-1}).

Harvest index was affected by the interaction effects of S × N. The highest harvest index was obtained with N_{120}+S_{75} application (26.53%). The highest harvest index was observed with 80 and 120 kg ha^{-1} nitrogen application along with medium and high sulfur application. N_{120} application was the most effective dose for increasing harvest index.

Oil content also showed an increasing trend with higher nitrogen application up to 120 kg ha^{-1}. N_{40}, N_{80}, N_{120}, and N_{160} applications increased the oil content extracted from the grain by 2.7%, 4.6%, 6.2%, and 6.0%, respectively, compared to the control. The highest oil content was recorded under N_{160}+S_{75} (33.4%) and N_{120}+S_{25} (32.76%). The effect of sulfur on protein content was more pronounced under N_{160} conditions. Under N_{120} conditions, high sulfur application significantly reduced this component (Figure 4).

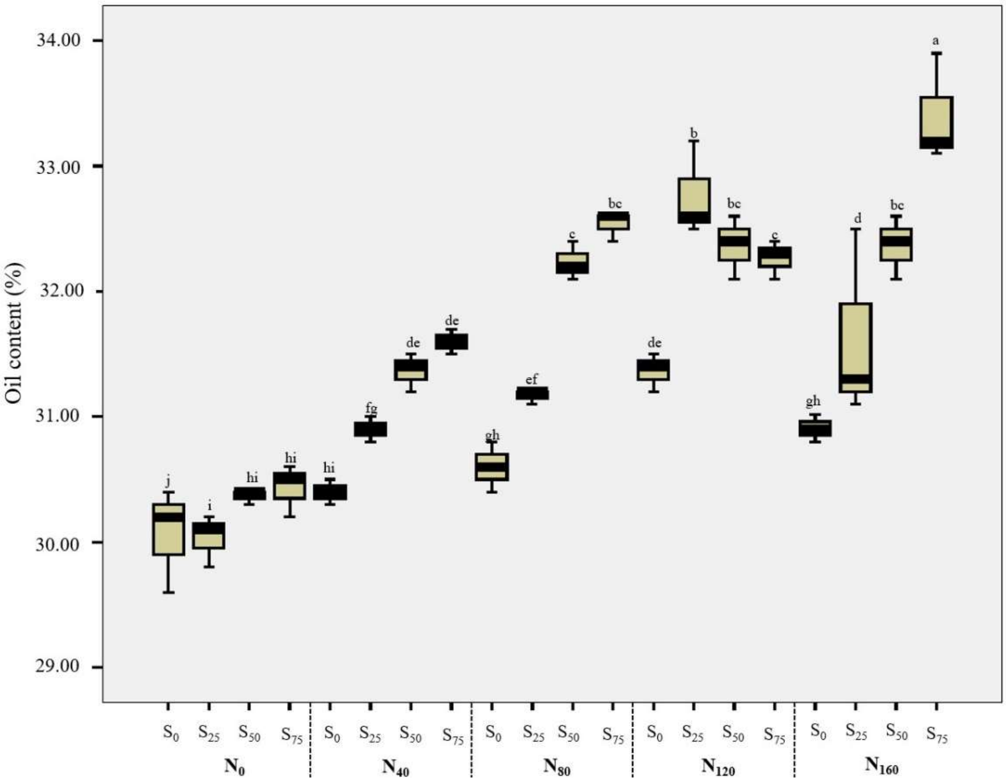

Figure 4. The impact of varying amounts of nitrogen (0, 40, 80, 120, and 160 kg ha^{-1}) and sulfur (0, 25, 50, and 75 kg ha^{-1}) on the oil content obtained from camelina seeds cultivated in the semi-arid area of northwestern Iran.

Principal component analysis (PCA) showed that the treatment combinations N_0+S_0, N_0+S_{25}, N_{160}+S_0, N_{160}+S_{25}, and N_{160}+S_{75} were the least effective, affecting the evaluated traits less than other treatments, and the plants showed the lowest expression under these conditions. Vegetative traits such as stem height and greenness index increased significantly with higher nitrogen doses. The highest values for vegetative traits were obtained with N_{160}. Oil content and number of lateral branches were more affected by N_{120}+S_{25} and N_{120}+S_{75} treatments. Biological and economic performance was highest under N_{80}+S_{75}, N_{80}+S_{50}, and N_{80}+S_{75} conditions (Figure 5). The number of seeds and 1000-seed weight showed the greatest changes under N_{40}+S_{25} conditions compared to the control. The most effective treatment group included the application of medium doses of nitrogen with 50 to 75 kg ha^{-1} sulfur per hectare.

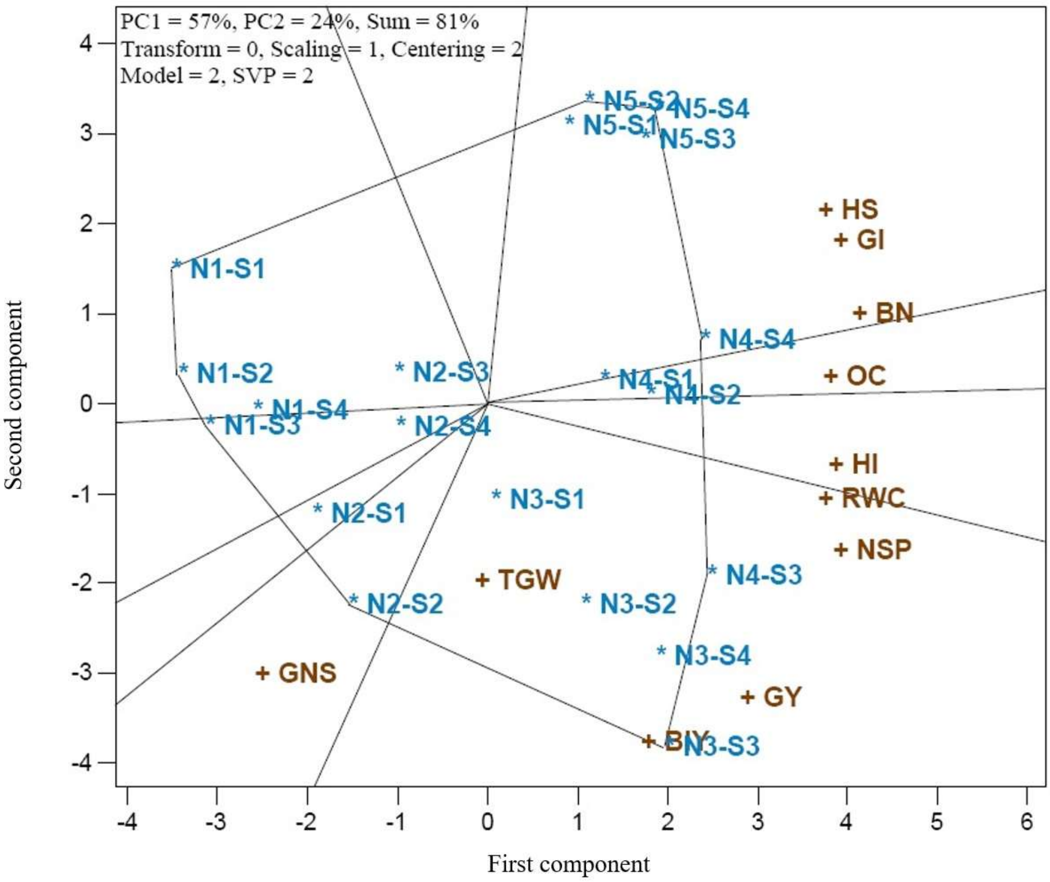

Figure 5. The biplot illustrates the results of the Principal Component Analysis (PCA) regarding Polygon type, which aids in understanding how treatment combinations are distributed and clarifies the similarities in the effects of agronomic traits across varying levels of nitrogen and sulfur in the Maragheh region. N1–N5 denote nitrogen applications of 0, 40, 80, 120, and 160 kg ha^{-1}. S1–S4 indicate sulfur applications of 0, 25, 50, and 75 kg ha^{-1}. HS: stem height, GI: greenness index, OC: oil content, HI: harvest index, RWC: relative water content, GNS: grain number per silique, NSP: silique number per plant, GY: grain yield, BIY: biological yield, TGW: thousand-grain weight.

4. Discussion

The soil in the study area was poor, and its chemical conditions were not very favorable. Rainfall in the area was 249 mm, and the total irrigation during the growing period was 333 mm. However, the evapotranspiration rate during the growing period was estimated at about 875 mm. These results show that, despite irrigating the field at different growth stages, high evapotranspiration and moisture loss – especially at the end of the growing period – were inevitable. Due to severe nitrogen deficiency in the soil, nitrogen application produced a highly significant response in Camelina plants. Vegetative growth components increased significantly with higher nitrogen application. This trend was evident in traits such as plant height, greenness index, and number of branches. A similar pattern was observed with medium and high sulfur doses. However, reproductive traits and yield components decreased at high nitrogen doses. This difference in the response of vegetative and reproductive traits to nitrogen doses may be partly due to varying moisture conditions during the formation of yield components (Clemente et al., 2023). In semi-arid Mediterranean regions, Camelina's reproductive period usually coincides with a sharp decrease in rainfall and a significant increase in temperature. These conditions can cause temporary drought stress for the plant by increasing soil moisture loss, and nitrogen application may have negative effects (Rahimi-Moghaddam et al., 2021). Additionally, applying high doses of nitrogen may increase the rate of transpiration and the loss of stored soil moisture by stimulating vegetative growth and increasing leaf area (Haghaninia et al., 2024). The results showed that using medium and high doses of sulfur produced better outcomes. In the study area, the semi-arid climate, irregular rainfall patterns, and high pH reduced the availability of elements. Using sulfur as a soil acidifying agent to adjust pH improved nutrient absorption. Sulfur is also effective in eliminating certain soil pathogens. In addition, absorption of this element can improve protein synthesis, enzyme function, and chlorophyll biosynthesis (Sharma et al., 2024). The present findings were similar to those of Obeng et al. (2020). These researchers found that in northwestern Kansas, under moisture-limited conditions, nitrogen applications above 40 kg ha^{-1} caused a slight reduction in yield. However, nitrogen and sulfur applications (20 kg ha^{-1}) did not affect oil content, protein percentage, or monounsaturated and polyunsaturated fatty acid content. With increasing nitrogen application, nitrogen use efficiency, nitrogen uptake efficiency, and nitrogen agronomic efficiency significantly decreased. It appears that low sulfur applications do not affect these components. Studies indicate that in camelina production systems in rainfed areas with limited soil moisture, camelina's response to nitrogen and sulfur depends on rainfall, other climatic conditions during the growing season, planting date, and soil conditions. In some years, low doses of nitrogen, and in other years, medium doses of nitrogen had a greater positive effect (Soils et al., 2013; Sintim et al., 2015). Nitrogen fertilizer application can also affect source-sink relationships in plants (Shen et al., 2025). Increased vegetative growth from nitrogen application can indicate a larger reservoir, and a higher greenness index can indicate greater reservoir activity. Oil content evaluation showed that high doses of nitrogen and sulfur resulted in the highest levels of these components. Sulfur plays a key role as a functional component in many enzymes involved in the biosynthesis of oil, vitamins, and secondary metabolites related to the quality of oilseed plants (Kumari et al., 2025). However, in the present experiment, this increase did not increase or stimulate the reproductive sink. In the studied area, under high nitrogen doses, reservoir limitation appears evident. Despite increased prosthetic area and a greater supply of photoassimilates, there was no change in yield components. The likely reason is a limitation in the use of photoassimilates, the inability to store photosynthetic products, or the inability to remobilize these substances to the reproductive sink under unfavorable conditions at the end of the season (Zhang and Flottmann, 2018). However, moderate sulfur applications resulted in significant increases in yield components. The findings indicated that applying 50-75 kg ha^{-1} of sulfur exerted positive effects, possibly by modifying soil chemical conditions. Sulfur applications increased nitrogen availability, especially at doses of 80-120 kg ha^{-1}.

5. Conclusions

Soil analysis results indicated a deficiency of nitrogen and sulfur in the area studied. The soil pH was also high, highlighting the need for sulfur application. Vegetative growth components and greenness index increased with higher nitrogen application. Applying nitrogen at rates above 40 kg ha^{-1} led to a significant increase in both vegetative and reproductive components. Nitrogen application in the studied area should exceed 40 kg ha^{-1}. The best growth and yield components were achieved with 80–120 kg ha^{-1} of nitrogen and 50 kg ha^{-1} of sulfur. Although the highest oil content was obtained at high levels of sulfur and nitrogen, economic considerations favored the N_{80} S_{50} treatment combination. The combined application of sulfur and nitrogen increased the effectiveness of nitrogen fertilizers and improved both the quantitative and qualitative aspects of camelina. Therefore, nutritional management should focus on adjusting soil chemical conditions by applying sulfur fertilizers.

Author Contributions: "Conceptualization, M.J. and A.E.; methodology, M.J. and N.S.; software, N.S and M.M.; validation, A.E., M.J. and N.S..; formal analysis, N.S.; investigation, M.J. and A.E.; resources, M.J. and N.S.; data curation, A.E.; writing—original draft preparation, M.J. and A.E.; writing—review and editing, M.J. and M.M.; visualization, N.S..; supervision, A.E. and N.S.; project administration, M.J.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.".

Funding: This research received no external funding.

Acknowledgments: We would like to thank and appreciate all those who participated in the implementation of the farm project, such as plowing, plot preparation, irrigation, and weed control.

Conflicts of Interest: The authors declare no conflict of interest.

Data availability statement: The data that supports the findings of this study are available on request from the corresponding author.

6. References

1. Abdoos M, Noorollahi Y, Shahee A, Yousefi H, Rezaeifard M, Moltames R. (2025): Energy PLAN-based evaluation of renewable energy scenarios in semi-arid contexts. Results in Engineering 26(1), 107007. https://doi.org/10.1016/j.rineng.2025.107007

2. Carciochi WD, Salvagiotti F, Pagani A, Calvo NIR, Eyherabide M, Rozas HRS, Ciampitti IA (2020): Nitrogen and sulfur interaction on nutrient use efficiencies and diagnostic tools in maize. European Journal of Agronomy 116(1), 126045. https://doi.org/10.1016/j.eja.2020.126045
3. Clemente C, Ercolini L, Rossi A, Foschi L, Grossi N, Angelini LG, et al (2023): Spectral response of camelina (Camelina sativa (L.) Crantz) to different nitrogen fertilization regimes under mediterranean conditions. Agronomy 13(6), 1539. https://doi.org/10.3390/agronomy13061539
4. Farhan M, Sathish M, Kiran R, Mushtaq A, Baazeem A, Hasnain A, et al (2024): Plant nitrogen metabolism: balancing resilience to nutritional stress and abiotic challenges. Phyton 93(3), 581-609. https://doi.org/10.32604/phyton.2024.046857
5. Fattahi M, Janmohammadi M, Sabaghnia N (2024): Effect of nitrogen and sulphur on the safflower fatty acids profile. Pesquisa Agropecuária Tropical 54(1), 79201. https://doi.org/10.1590/1983-40632024v5479201
6. Haghaninia M, Javanmard A, Kahrizi D, Bahadori MB, Machiani MA (2024): Optimizing oil quantity and quality of camelina (*Camelina sativa* L.) with integrative application of chemical, nano and bio-fertilizers under supplementary irrigation and rainfed condition. Plant Stress 11(1), 100374. https://doi.org/10.1016/j.stress.2024.100374
7. Karimi M, Tabiee M, Karami S, Karimi V, Karamidehkordi E (2024): Climate change and water scarcity impacts on sustainability in semi-arid areas: Lessons from the South of Iran. Groundwater for Sustainable Development 24(1), 101075. https://doi.org/10.1016/j.gsd.2023.101075
8. Kumari VV, Gopinath KA, Chandran MS, Sunitha B, Sriram K, Ansari MA, et al. (2025): The importance of Sulphur in Oilseed production–A South Asian Context. Oil Crop Science 10(2), 118-130. https://doi.org/10.1016/j.ocsci.2025.04.001
9. Mohsenpour A, Janmohammadi M, Shekari F, Sabaghnia N (2025): Assessment of Camelina sativa performance under deficit irrigation with application of animal manure and micronutrients nano-fertilizers. Agrotechniques in Industrial Crops 5(4), 240-250. https://doi.org/10.22126/ATIC.2025.11812.1198
10. Nehrani SH, Askari MS, Saadat S, Delavar MA, Taheri M, Holden NM (2020): Quantification of soil quality under semi-arid agriculture in the northwest of Iran. Ecological Indicators 108(1): 105770. https://doi.org/10.1016/j.ecolind.2019.105770
11. Obeng E, Obour AK, Nelson NO, Ciampitti IA, Wang D (2020): Nitrogen and sulfur application effects on camelina seed yield, fatty acid composition, and nutrient removal. Canadian Journal of Plant Science 101(3), 353-365. https://doi.org/10.1139/cjps-2020-0104
12. Rahimi-Moghaddam S, Eyni-Nargeseh H, Ahmadi SAK, Azizi K (2021): Towards withholding irrigation regimes and drought-resistant genotypes as strategies to increase canola production in drought-prone

environments: A modeling approach. Agricultural Water Management 243(1), 106487. https://doi.org/10.1016/j.agwat.2020.106487
13. Ray RL, Kularathna KM, Griffin RW, Abeysingha N, Woldesenbet S, Elhassan A, et al (2025): Enhancing plant and soil health through organic amendments in a humid environment. Rhizosphere 35(1), 101126. https://doi.org/10.1016/j.rhisph.2025.10112
14. Rossini F, Provenzano ME, Sestili F, Ruggeri R (2018): Synergistic effect of sulfur and nitrogen in the organic and mineral fertilization of durum wheat: Grain yield and quality traits in the Mediterranean environment. Agronomy 8(9), 189. https://doi.org/10.3390/agronomy8090189
15. Royo-Esnal A, Valencia-Gredilla F (2018): Camelina as a rotation crop for weed control in organic farming in a semiarid Mediterranean climate. Agriculture 8(10), 156. https://doi.org/10.3390/agriculture8100156
16. Sharma RK, Cox MS, Oglesby C, Dhillon JS (2024): Revisiting the role of sulfur in crop production: A narrative review. Journal of Agriculture and Food Research 15(1), 101013. https://doi.org/10.1016/j.jafr.2024.101013
17. Shen D, Wang K, Ming B, Fang L, Wang Z, Sun L, et al (2025): Impact of planting density and nitrogen application on maize source-sink relationships and yield under drip irrigation. Journal of Agriculture and Food Research 21(1), e 102000. https://doi.org/10.1016/j.jafr.2025.102000
18. Sintim HY, Zheljazkov VD, Obour AK, Garcia AG, Foulke TK (2015): Influence of nitrogen and sulfur application on camelina performance under dryland conditions. Industrial Crops and Products 70(1), 253-259. https://doi.org/10.1016/j.indcrop.2015.03.062
19. Solis A, Vidal I, Paulino L, Johnson BL, Berti MT (2013): Camelina seed yield response to nitrogen, sulfur, and phosphorus fertilizer in South Central Chile. Industrial Crops and Products 44(1), 132-138. https://doi.org/10.1016/j.indcrop.2012.11.005
20. Sydor M, Kurasiak-Popowska D, Stuper-Szablewska K, Rogoziński T (2022): Camelina sativa. Status quo and future perspectives. Industrial Crops and Products 187(1), 115531. https://doi.org/10.1016/j.indcrop.2022.115531
21. Zhang H, Flottmann S (2018): Source-sink manipulations indicate seed yield in canola is limited by source availability. European Journal of Agronomy 96(1), 70-76. https://doi.org/10.1016/j.eja.2018.03.005