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Original Paper

The Effects of Nitrogen and Sulfur on the Performance of Camelina (*Camelina sativa* L. Crantz) in a Drought-Prone Region

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Low soil fertility in semi-arid areas is a significant issue affecting agricultural output, and climate change has further worsened this problem. Nutritional management, such as applying elements with complementary interactions appear to enhance the growth and yield of oilseed crop systems. A field trial was conducted to assess the impact of various sulfur fertilizer rates (0, 25, 50, and 75 kg/ha designated as S_0, S_{25}, S_{50}, and S_{75}, respectively) and nitrogen fertilizer levels (0, 40, 80, 120, and 160 kg/ha designated as N_0, N_{40}, N_{80}, N_{120}, and N_{160}, respectively) on the growth and productivity of Camelina in the northwestern part of Iran. As nitrogen application rates increased, traits such as plant height (57%), relative water content (1%), number of lateral branches (86%), and greenness indices (55%) showed notable increases. However, application of high levels of nitrogen (N_{160}) reduced relative leaf water content and the number of siliques per plant. The impact of nitrogen application on these traits was greater than that of sulfur application. Nevertheless, the most beneficial effect of sulfur was achieved with the S_{50} application. Assessing grain yield while considering the economic implications of fertilizer use showed that applying $N_{80} + S_{50}$ (1,312 kg/ha) is more rational. Overall, the results showed that using $N_{80} + S_{50}$ saved nitrogen fertilizer and achieved acceptable economic performance. Increasing the productivity of Camelina production systems in the studied semi-arid region requires soil amendment with sulfur.

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

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1 Introduction

Although semi-arid regions are heavily affected by climate change, the population there continues to increase (Karimi et al., 2024). This growth increases the demand for food and energy. In this context, prioritizing eco-friendly and renewable energy sources is essential. To achieve this, minimizing fossil fuel consumption and greenhouse gas emissions is crucial (Abdoos et al., 2025). In recent decades, biodiesel extraction from oilseed crops has attracted attention. However, crop species must have specific traits to thrive in semi-arid environments. Among oilseed crops, *Camelina sativa* of the Brassicaceae family is being considered for oil and biofuel production. Compared to other oilseed crops, Camelina has higher oil content (35–40%) and protein content (24–47%). Its unique fatty acid composition and high proportion of linolenic acid also make it an excellent candidate for animal feed (Sydor et al., 2022).

Semi-arid regions typically have low-quality soils due to insufficient and unevenly distributed rainfall, overgrazing, failure to return crop residues to the soil, intensive agricultural practices, improper crop rotation, unprincipled tillage methods, misuse of chemical fertilizers, and low levels of soil organic matter (Rasoulzadeh et al., 2019). In these areas, soil pH tends to be elevated (Nehrani et al., 2020). Among oilseed plants, Camelina is particularly well-suited for low-input and low-tillage farming systems (Avola et al., 2021). It can produce yields even in marginal areas with limited moisture availability (Mohsenpour et al., 2025). Because both spring and winter varieties exist, incorporating Camelina into crop rotations is more straightforward,

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thereby enhancing the flexibility of rotation schemes (Royo-Esnal & Valencia-Gredilla, 2018). Soils in these regions frequently face significant nutrient deficiencies, and supplementing nutrients for agricultural crops can substantially boost yields. Nitrogen is considered the most crucial nutrient for plant development. It plays a vital role in many biological functions as a component of amino acids and, by extension, proteins. However, the effectiveness of nitrogen on plant growth is influenced by several factorcs, including climatic conditions, soil moisture, soil pH, temperature, and the specific plant species (Farhan et al., 2024). Improving soil moisture and the physical and chemical characteristics of the rhizosphere via soil amendments can increase plant responsiveness to nitrogen, thereby boosting economic returns (Ray et al., 2025). Under optimal moisture conditions, maintaining soil moisture near field capacity allows for nitrogen applications to increase to 150 kg/ha (Soils et al., 2013). While sulfur is essential for growth, its necessity is less than that of nitrogen, and it remains classified 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 and also influences soil chemistry; by adjusting soil pH, it can enhance the effect of nitrogen in the rhizosphere. Insufficient sulfur can adversely affect both the quantity and quality of harvested crops (Sharma et al., 2024). The majority of the sulfur present in soil is found in organic forms and must be converted to sulfate by various oxidizers. Therefore, the availability of sulfur in soil, along with sulfur-oxidizing bacteria, effectively improves soil nutritional properties and reduces soil pH (Patel et al., 2024). Research shows that nitrogen and sulfur utilization in Camelina can affect protein levels, oil content, and the concentrations of monounsaturated and polyunsaturated fatty acids. However, the interaction between nitrogen and sulfur depends largely 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. Given the specific soil and climatic conditions of semi-arid Mediterranean regions, the severe nitrogen deficiency, and the need for chemical soil amendment with sulfur, further research is required. Therefore, research specific to each agro-climatic zone is needed 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 Material 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-Geiger climate classification, the climate of the study area is semi-arid cold temperate (BSk). 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, 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, sulfur 5.67 mg/kg, phosphorus 8.9 mg/kg, potassium 367 mg/kg, and cation exchange capacity 24.3 Cmolc/kg. Trends in air temperature and precipitation during the Camelina growth period are shown in Figure 1.

2.2 Execution of Experimental Treatments

In October, initial tillage was performed with a moldboard plow. After establishing the experimental plot boundaries, varying amounts of sulfur were applied to the plots. Sulfur was then incorporated into the soil to a depth of 20 cm using a rotavator. For secondary tillage, a disk harrow was used to break up clods and soften the topsoil as much as possible. The soil surface was shaped into a ridge and furrow pattern using a furrower.

The experiment used 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, supplied as urea fertilizer. The sulfur factor was applied at four levels: 0, 25, 50, and 75 kg/ha, 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

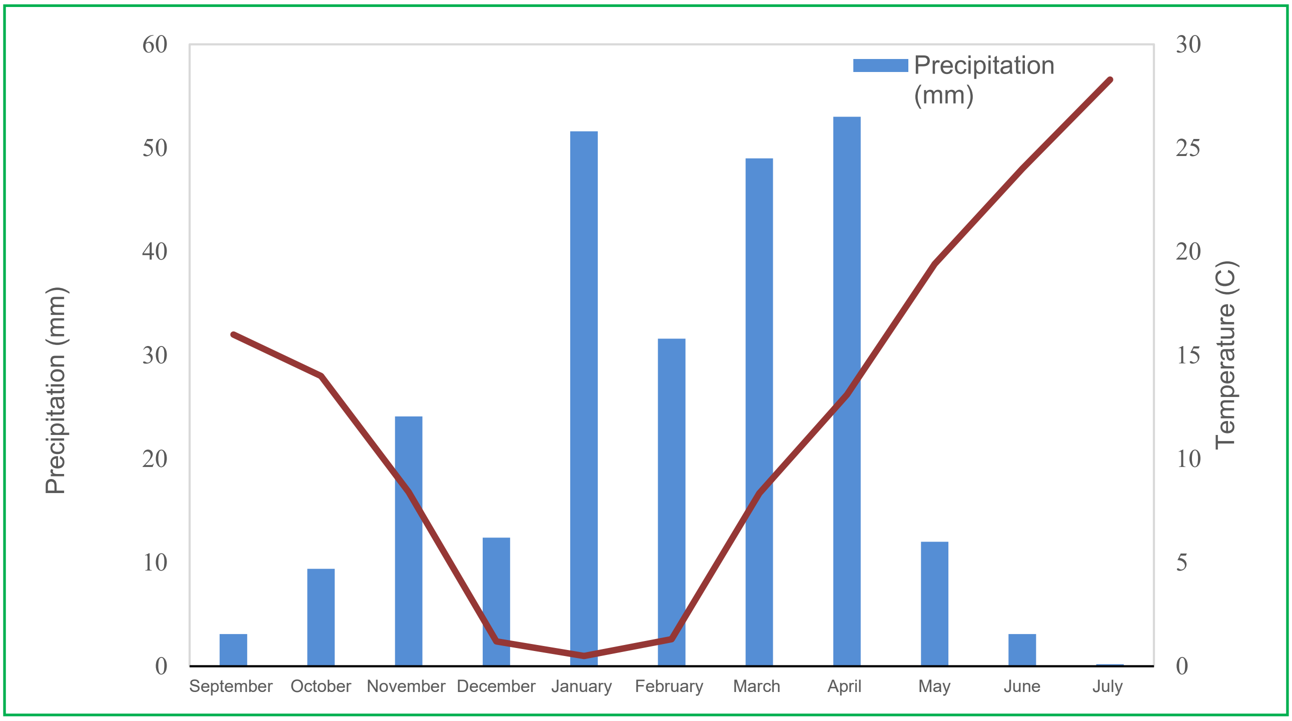

Figure 1 Average monthly temperatures and total monthly rainfall during the growing seasons of 2024 and 2025

a pressurized system with polyethylene pipes and taps. 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, with the remaining irrigations applied during tillering, flowering, silique formation, and grain filling. At the seed sowing stage, 70 kg/ha, of phosphorus and 30 kg/ha, of potassium were applied as triple superphosphate and potassium chloride, positioned in a band typically 2 cm above and 5 cm below the seed in the planting row during sowing.

2.3 Assessment of Agronomic Characteristics

During the silique growth phase, the relative water content of the uppermost fully expanded leaves was measured. Leaf disc samples were collected from the field early in the day and transported to the laboratory on ice, where the initial fresh weight (FW) was recorded. The turgid weight (TW) was then 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. Relative water content was calculated using the formula:

$$RWC = \left[(FW - DW)/(TW - DW)\right] \times 100$$

To assess the greenness index, which indicates chlorophyll content, a Konica Minolta SPAD 502 was used during the seed filling phase. At plant maturity, after the siliques had dried and turned brown, ten plants were randomly selected 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 1,000 seeds were recorded. To determine biological weight and yield, a random quadrat sampling method with a size of one square meter was used. After drying the plants at 65 °C for 48 hours, total plant weight was measured, and 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 with 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 and Discussion

3.1 Vegetative Traits

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

The tallest stems were obtained with an application of 75 kg/ha 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 sulfur. The highest greenness index was recorded in plants grown under $N_{160} + S_{50}$ (55.30 SPAD unit), $N_{160} + S_{75}$ (53.40 SPAD unit), and $N_{120} + S_{75}$ (52.75 SPAD unit) 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 application 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. Without 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 application also significantly increased BIY compared to the control. The highest BIY values were observed with 50 and 75 kg/ha sulfur application. The highest BIY values were recorded in plants under $N_{80} + S_{50}$ (5,115 kg/ha) and $N_{80} + S_{75}$ (5,037 kg/ha) conditions (Table 1).

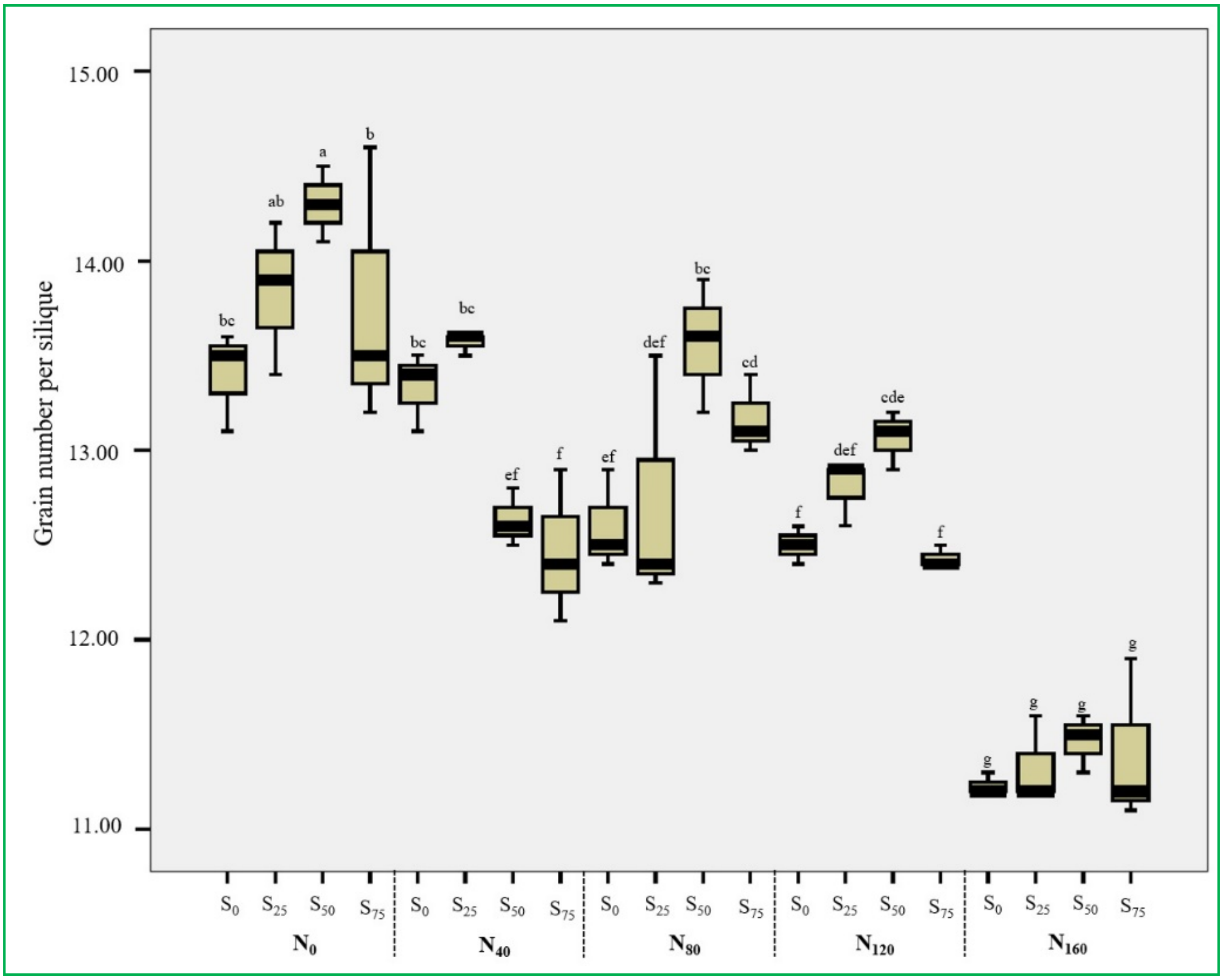

Figure 2 An investigation into the effects of nitrogen (0, 40, 80, 120, and 160 kg/ha) and sulfur (0, 25, 50, and 75 kg/ha) on the number of grains per silique in Camelina grown in the Maragheh region of northwestern Iran. Containers displaying identical letters do not show statistically significant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

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	3,910.78c	22.83d	0.88b	23.06e
N_{40}	46.60d	37.58d	4.09d	65.10d	4,376.35b	26.80c	0.90a	23.56d
N_{80}	54.44c	42.70c	5.42c	69.82b	4,812.65a	31.31a	0.89a	25.23b
N_{120}	64.88b	50.64b	5.58b	73.77a	4,274.16b	29.37b	0.90a	25.76a
N_{160}	70.53a	53.75a	6.18a	67.46c	3,933.17c	28.22b	0.88c	24.39c
Sulphur (S)								
S_0	54.59b	41.43c	4.85b	67.43b	4,075.99c	26.55c	0.90a	24.31ab
S_{25}	55.56b	43.55b	4.87b	67.81ab	4,265.48b	27.42bc	0.90a	24.16b
S_{50}	55.69b	44.83a	4.99a	68.11ab	4,417.08a	28.79a	0.88b	24.60a
S_{75}	58.79a	45.33a	4.95ab	68.75a	4,287.14ab	28.06ab	0.89b	24.53a
Interactions								
N_0S_0	42.40i	32.30i	3.13g	62.97j	3,583.5l	21.87i	0.87ghi	23.67fg
$N_0 S_{25}$	43.43hi	33.43hi	3.13g	63.57ij	3,907.5J	23.67hi	0.89defg	22.60h
$N_0 S_{50}$	43.30hi	35.57gh	3.20g	63.93ij	4,199.0fghi	23.27i	0.86ij	22.60h
$N_0 S_{75}$	48.23f	35.73gh	3.80f	65.50ghij	3,953.0l	22.50i	0.92bc	23.37g
$N_{40}S_0$	45.30gh	36.10gh	4.00ef	66.60fgh	4,287.0efg	25.77gh	0.92abc	23.23gh
$N_{40} S_{25}$	46.30fg	37.50fg	4.17e	65.07ghij	4,605.0cd	26.67fg	0.93a	23.17gh
$N_{40} S_{50}$	46.40fg	39.37ef	4.13e	64.27hij	4,252.7efgh	26.97efg	0.85j	24.23ef
$N_{40} S_{75}$	48.40f	37.33fg	4.07e	64.47hij	4,360.6def	27.80defg	0.89defg	23.60fg
$N_{80}S_0$	53.53e	39.13f	5.37C	66.90fg	4,368.5def	28.80def	0.91c	25.20cd
$N_{80} S_{25}$	53.87e	41.87de	5.37cd	69.80de	4,729.6bc	31.37abc	0.90d	25.27cd
$N_{80} S_{50}$	52.70e	42.40d	5.73b	71.07cd	5,115.3a	33.03a	0.88fgh	25.67bc
$N_{80}S_{75}$	57.67d	47.40c	5.20d	71.50bcd	5,037.3ab	32.03a	0.89def	24.80de
$N_{120}S_0$	63.17c	47.13c	5.57bc	74.13a	4,169.8fghi	28.27def	0.89de	25.23cd
$N_{120} S_{25}$	63.90c	51.17b	5.60bc	73.20abc	4,278.7efgh	27.90defg	0.89d	25.27cd
$N_{120}S_{50}$	64.40c	51.50b	5.60bc	73.87ab	4,529.3cde	31.63ab	0.93ab	26.00ab
$N_{120} S_{75}$	68.07b	52.77ab	5.53bc	73.87ab	4,118.8fghik	29.67bcd	0.87ghi	26.53a
$N_{160}S_0$	68.57b	52.50b	6.20a	66.57fgh	3,971.0hijk	28.03defg	0.88fgh	24.20ef
$N_{160} S_{25}$	70.30ab	53.80ab	6.10a	67.40fg	3,806.5kl	27.50defg	0.89def	24.50e
$N_{160} S_{50}$	71.67a	55.30a	6.30a	67.43efg	3,989.1ghik	29.03cde	0.88efg	24.50e
$N_{160} S_{75}$	71.60a	53.40ab	6.13a	68.43ef	3,966.0hijk	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

N_0–N_{160} refer to nitrogen applications of 0, 40, 80, 120, and 160 kg/ha. S_0–S_{75} refer to sulfur applications of 0, 25, 50, and $_{75}$ kg/ha. 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

3.2 *Yield Components*

Nitrogen application significantly increased the silique number per plant (SNP) compared to the control. However, the highest SNP was observed with 80 kg nitrogen per hectare (31.32). Increasing nitrogen application above 80 kg/ha caused a slight decrease in SNP. Sulfur application also significantly increased SNP, but the trend was not completely linear. Application of 25, 50, and 75 kg/ha 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. As nitrogen application rates rose, there was a notable decline in GNS. The peak GNS values were observed in the $N_0 + S_{50}$ conditions. Under conditions of elevated nitrogen application, the impact of sulfur application on GNS was not statistically significant (Figure 2).

The interaction effect of S × N was significant for 1,000-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). Assessments of grain yield indicated that raising nitrogen application to 80 kg/ha markedly enhanced yield in comparison to the control. In the majority of nitrogen applications, applying sulfur up to 50 kg/ha resulted in increased yield. The greatest effect of sulfur was observed under 80 and 120 kg/ha nitrogen application. The highest yield was recorded under $N_{80} + S_{50}$ at 1,312.53 kg/ha, with plants grown 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).

Harvest index was affected by the interaction between sulfur and nitrogen (S × N). The highest harvest index was achieved with the $N_{120} + S_{75}$ application (26.53%). The highest harvest index was observed with 80 and 120 kg/ha nitrogen application combined with medium and high sulfur levels. N_{120} application was the most effective

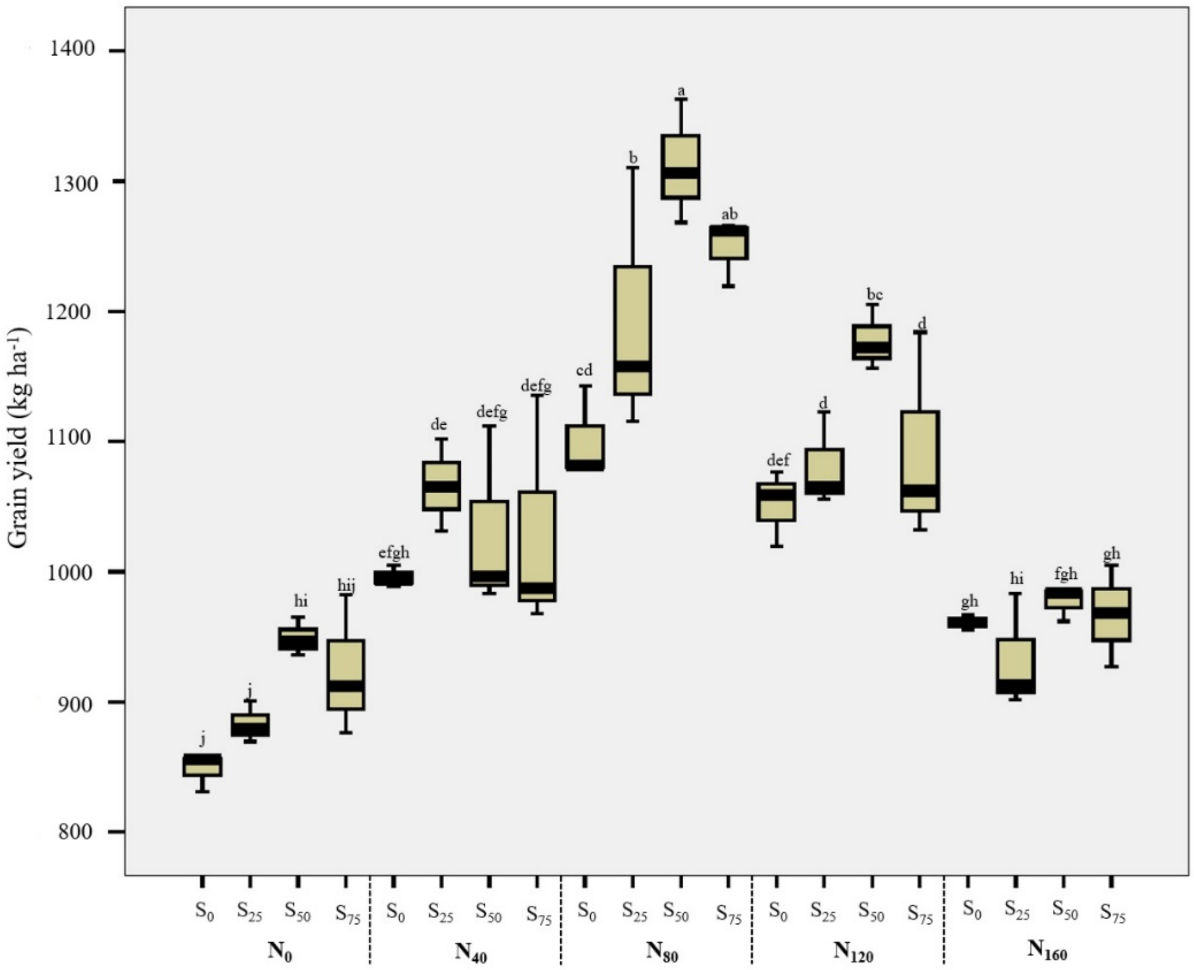

Figure 3 The grain yield of Camelina grown in the semi-arid region of northwestern Iran was influenced by varying levels of nitrogen (0, 40, 80, 120, and 160 kg/ha) and sulfur (0, 25, 50, and 75 kg/ha)

dose for increasing harvest index.Oil content also showed an increasing trend with higher nitrogen application up to 120 kg/ha. 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 protein content (Figure 4).

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 exhibited the lowest performance 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 the $N_{120} + S_{25}$ 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 1,000-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 sulfur. The proximity of the traits in the figure indicates their high correlation and similar trends in response to nitrogen and sulfur treatments. Grain yield showed the highest correlation with siliques per plant, relative water content, and biological yield. The results showed that high biological yield, reflecting vigorous vegetative growth, can ensure high yield.

The soil in the study area was poor, and its chemical conditions were unfavorable. Rainfall totaled 249 mm, and 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 indicate that, despite irrigating the field

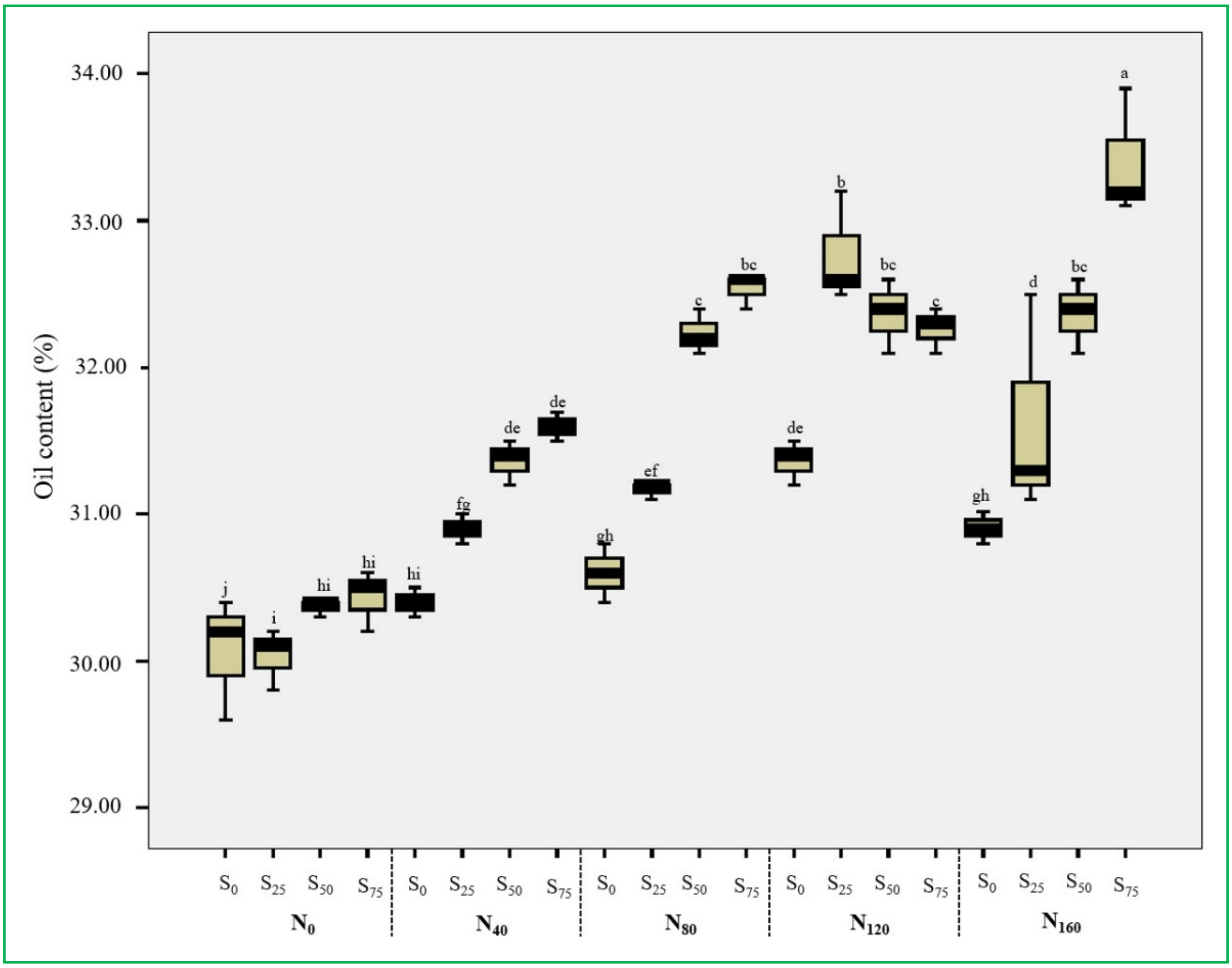

Figure 4 The effect of different levels of nitrogen (0, 40, 80, 120, and 160 kg/ha) and sulfur (0, 25, 50, and 75 kg/ha) on the oil yield from camelina seeds grown in the semi-arid region of northwestern Iran

at different growth stages, high evapotranspiration and moisture loss – especially at the end of the growing period – were unavoidable. 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, as seen in traits such as plant height, greenness index, and number of branches. A comparable trend was noted with medium and high levels of sulfur. Nonetheless, reproductive characteristics and yield components declined when high amounts of nitrogen were applied. The varying responses of vegetative and reproductive traits to nitrogen levels might be partially attributed to different moisture conditions present during the development of yield components (Clemente et al., 2023).

In semi-arid Mediterranean regions, Camelina's reproductive period typically 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 transpiration and the loss of stored soil moisture by stimulating vegetative growth and increasing leaf area (Haghaninia et al., 2024). The results showed that medium and high doses of sulfur produced better outcomes. In the studied 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

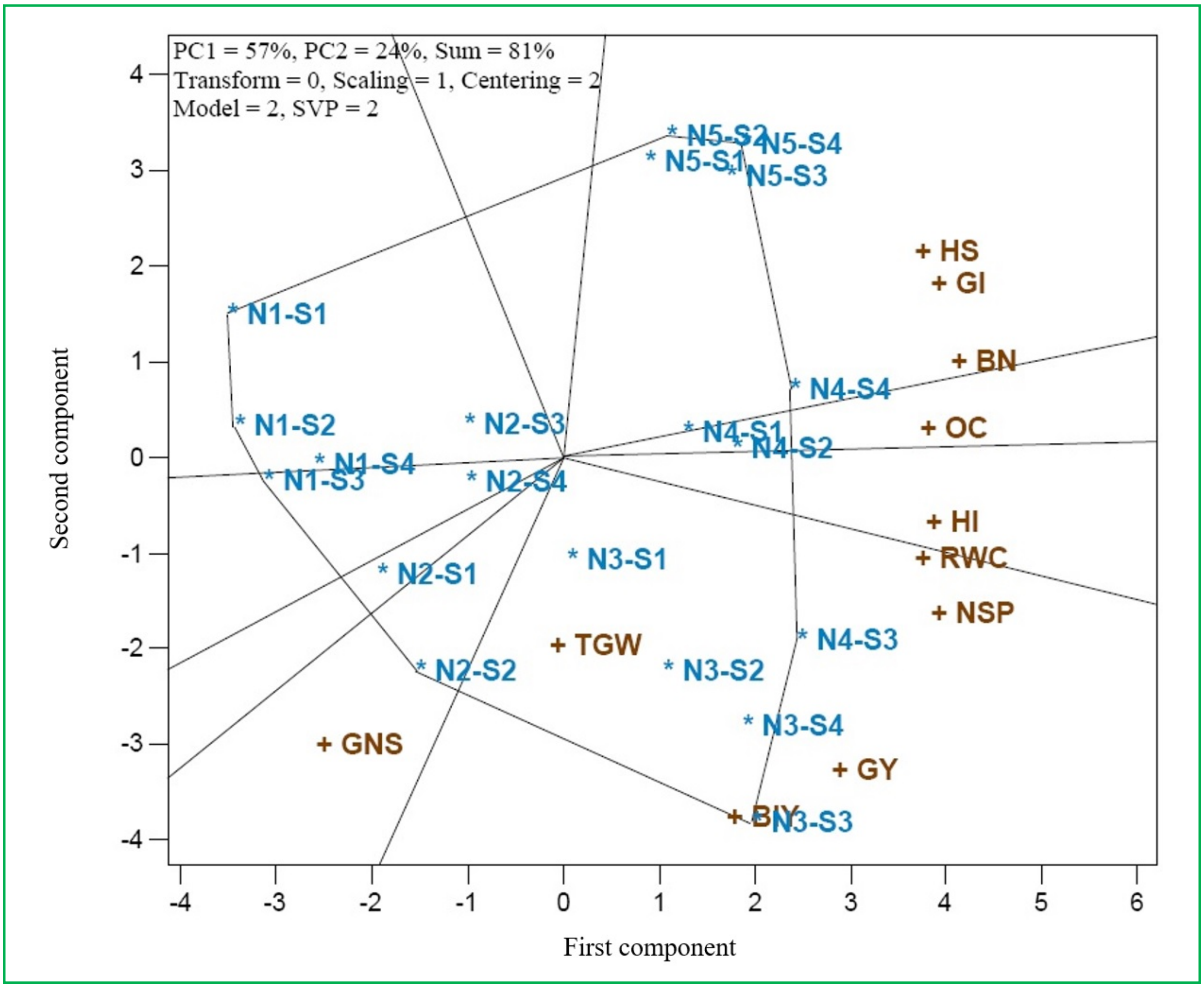

Figure 5 The biplot illustrates the results of the Principal Component Analysis (PCA) regarding Polygon type, which aids in understanding how treatment combinations are distributed and clarifies the similarities in the effects of agronomic traits across varying levels of nitrogen and sulfur in the Maragheh region

N1–N5 denote nitrogen applications of 0, 40, 80, 120, and 160 kg/ha; S1–S4 indicate sulfur applications of 0, 25, 50, and 75 kg/ha; 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 soil pathogens. Furthermore, 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 caused a slight reduction in yield. However, nitrogen and sulfur applications (20 kg/ha) did not affect oil content, protein percentage, or monounsaturated and polyunsaturated fatty acid content. As nitrogen application increased, 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 can also affect source-sink relationships in plants (Shen et al., 2025). Increased vegetative growth after nitrogen application can result in 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 oilseed plant quality (Kumari et al., 2025). However, in the present experiment, this increase did not enhance 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 & Flottmann, 2018). However, moderate sulfur application resulted in significant increases in yield components. The findings indicated that applying 50–75 kg/ha of sulfur had positive effects, possibly by modifying soil chemical conditions. Sulfur application increased nitrogen availability, especially at doses of 80–120 kg/ha.

4 Conclusions

Soil analysis results showed a deficiency of nitrogen and sulfur in the studied area. The soil pH was also high, indicating the need for sulfur application. Vegetative growth components and greenness index increased with higher nitrogen application. Applying nitrogen at rates above 40 kg/ha resulted in a significant increase in both vegetative and reproductive components. Nitrogen application in the studied area should exceed 40 kg/ha. The best growth and yield components were achieved with 80–120 kg/ha of nitrogen and 50 kg/ha 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 use of nitrogen and sulfur increases nitrogen efficiency and improves soil chemical conditions. In this context, supportive policies, such as providing subsidized sulfur fertilizers, can increase the efficiency of high-consumption chemical fertilizers like nitrogen and lead to significant economic benefits.

Conflict of Interest

The authors have no affiliation with any organization that has a direct or indirect financial interest in the subject matter discussed in the manuscript.

Author Contributions

M.J. and A.E. created the original concept proposal. N.S. developed the theory and performed the computations. A.E. verified the analytical methods. M.J. Design and implementation of an experimental plan on the field. A.E. and M.J. collected agronomic data. N.S. and A.E. conducted the statistical analysis and graph preparation. All authors discussed the results and contributed to the final manuscript.

AI and AI-Assisted Technologies Use Declaration

AI-assisted technologies were utilized for controlling English grammar.

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