Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-025-02751-y

ORIGINAL PAPER

Foliar Application of some Micronutrients Improves Productivity and Seed Quality of Camelina (*Camelina sativa* (L.) Crantz) Genotypes

Akram Rostamipour[1] · Reza Tavakkol Afshari[1] · Hamid Reza Khazaei[1] · Danial Kahrizi[2] · Hamid Reza Eisvand[3]

Received: 4 March 2025 / Accepted: 30 September 2025

Abstract

Camelina (*Camelina sativa* (L.) Crantz), an oilseed from the Brassicaceae family, is used in food and pharmaceutical industries. This study aimed to explore the impact of micronutrient foliar application on camelina seed yield and quality. The research was conducted during the 2021 and 2022 growing season at the farm of Faculty of Agriculture, Ferdowsi University of Mashhad, Iran. The study was conducted in a split factorial experiment based on a randomized complete block design (RCBD) with three replications. Two camelina genotypes (Soheil cultivar and Line 69) were used as materials in the study. The treatments used include foliar application of $FeSO_4$ (4 kg ha^{-1}), $ZnSO_4$ (3.6 kg ha^{-1}), $MnSO_4$ (2.5 kg ha^{-1}), a combined treatment of $FeSO_4$, $ZnSO_4$, and $MnSO_4$ (3.3 kg ha^{-1}), distilled water and control applied at two stages of 50% flowering and 50% podding. The measured traits included plant height, pod number, 1000-seed weight, seed yield, harvest index, seed protein content, seed oil content and fatty acid percentage. The result revealed a significant difference between genotypes in plant height, pod number, 1000-seed weight, seed yield, and harvest index. In both Soheil and Line 69, the control and distilled water treatments had the lowest 1000-seed weight, seed yield, and oil content. Moreover, oil content decreased as 1000-seed weight increased, and oleic acid content decreased with increasing seed weight. Plant height in Soheil is approximately 3.22% lower than in Line 69. However, the number of pods per plant in Soheil is about 7.18% higher. 1000-seed weight in Soheil is around 6.63% greater, and seed yield is approximately 7.45% higher compared to Line 69. Additionally, the harvest index in Soheil is 3.74% higher. Overall, Soheil demonstrates better performance than Line 69 in most key traits, particularly in pod number, seed weight, and seed yield. Foliar application at 50% flowering stage is recommended for increasing camelina seed yield. Moreover, $FeSO_4$ foliar application improves camelina oil production.

Keywords Micronutrient nutrition · Seed oil percentage · Seed protein percentage · Yield and yield components

1 Introduction

In recent years, oilseeds have garnered significant attention due to their vital role in human nutrition (Watts 2016). With increasing global population, rising nutritional standards, and the shift from animal fats to vegetable oils, there is a growing need for both quantitative and qualitative improvements in oilseed crops (Yantai et al. 2015). Nutritionally, oilseeds are considered the second most important food resource globally, after cereals (USDA 2015). Given their critical role in food security, developing new and improved oilseed genotypes has become essential.

Camelina (*Camelina sativa* (L.) Crantz) is an oilseed plant of the Brassicaceae family, also known as false flax (Bansal et al., 2016). This plant is highly adaptable to different climatic conditions. Camelina requires very little water and nutrients, has a relatively high resistance to pests and microbial diseases, and its oil composition has a high percentage of unsaturated fatty acids (Masella et al. 2014; Bansal et al., 2016).

Camelina is native to south-eastern Europe and south-western Asia (Belaynehet al. 2015). The 1000-seed weight

✉ Reza Tavakkol Afshari
tavakolafshari@um.ac.ir

[1] Department of Agrotechnology, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran

[2] Department of Biotechnology, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran

[3] Department of Plant Genetics and Production, Faculty of Agriculture, Lorestan University, Khorramabad, Iran

Published online: 23 October 2025

of this plant varies between 0.7 and 1.8 g (Jankowski et al. 2019; Righini et al. 2019; Zaluski et al. 2020) and its seed contains about 38–43% of oil (Walia et al. 2021). The seed oil consists of approximately 90% unsaturated fatty acids, including 25–42% alpha-linolenic acid (18:3), 13–21% linoleic acid (18:2), 14–20% oleic acid (18:1), 12–18% eicosenoic acid (20:1), and 2–4% erucic acid (22:1) (Vollmann et al. 2007). However, in camelina, the nutrition through foliar application of micronutrients such as $FeSO_4$ and $ZnSO_4$ during the flowering stage and beginning of leaf development showed positive effects on yield, quality and quantity of oil, protein content, and antioxidant enzyme levels by influencing chemical and physiological processes (Azhand et al., 2023). In agriculture, the most important input influencing the increase of crop yield is fertilizer. Among the fertilization methods, foliar application is one of the most effective methods due to its rapid penetration into the leaves, and fast and efficient absorption (Latha and Nadanas 2023).

In Iran, farmers rely on the use of macronutrients to improve crop yield. However, the importance and necessity of using micronutrients to increase yield is considered important. The application of micronutrient supplies the required nutrients to plants very quickly and to compensates for nutrient deficiencies for plant growth (Rengasamy et al. 2016). Micronutrients have an important effect on plant physiological processes, including germination, growth and tolerance to biotic and abiotic stresses (Dimkpa and Bindraban 2016). Zinc and manganese foliar application during flowering and grain filling stages under stress conditions increased the concentration of these elements in the safflower seed and has a positive effect on increasing germination parameters, including germination percentage and germination rate (Movahedi-Dehnavi et al., 2009).

They also have an effective function in increasing the plant ability to absorb nutrients, improving various parameters including the number of tillers, biological yield, protein yield, and the 1000-seed weight (Fakharzadeh et al. 2020). Elements such as iron (Fe), zinc (Zn) and manganese (Mn) are three important micronutrients in the processes of optimal growth and development in plants. Zinc and manganese appear to enhance lipid metabolism, which directly affects oil biosynthesis, thereby contributing to increased seed oil content and yield of safflower by alleviating environmental stress and meeting the plant's micronutrient requirements (Kamaraki and Galloway, 2012). When the concentration of macro and micronutrients in the plant fluctuates, it will have negative effects on the growth and development of the plant as well as the yield (Lynch 2019). Fe plays an important role in the absorption of other nutrients by the plant, which increases the efficiency of photosynthesis and accelerates the transfer of assimilates from the source to the destination, and finally increases the yield efficiency (Bera et al., 2015). Zn affects plant fertility both directly and indirectly. Indirectly, it causes changes in the amount and composition of plant nectar, leading to increased attraction of insects for pollination. In its direct effect, which is related to pollen grain production, Zn plays a role in the synthesis of pollen tube protein and results in greater seed formation (Borg and Berger 2015). In addition, Mn could affect plant growth and also acts as an enzyme cofactor in the processes of photosynthesis, respiration, inhibition of active oxygen species and hormonal signaling (Alejandro et al. 2020). Also, this element has an effective transfer from the flag leaf to the reservoir (seeds) and provides a suitable balance of photosynthetic materials between the source and reservoir organs (Zulfiqar et al. 2021). Fe and Zn, are essential micronutrients for optimal plant growth and biochemical activities such as enzymes in plants. The importance of these two elements in the food chain is such that the health of more than three billion people is facing problems due to the use of low-quality foods with low Fe and Zn content (Krishna et al., 2023).

Foliar application of $ZnSO_4$ and $MnSO_4$ solution in safflower and other oil crops had a positive effect on increasing yield and seed quality (Ghorbani et al. 2019), in other oil plants such as winter rapeseed, the beneficial effect of foliar application of micronutrients along with sulfur has been reported to improve plant growth and increase yield and yield components (Jarecki et al. 2019; Kaur et al. 2019). Micronutrients are essential in the biosynthesis of chlorophyll and the formation of carbohydrates (Candan et al. 2018). With the use of sulfur along with micronutrients in the oxidation process, sulfuric acid production and soil pH are reduced and the availability of phosphorus and low-consumption elements is increased (Khavazi et al. 2001).

Since foliar application is an effective option to enhance plant nutrient-use efficiency, the purpose of this study was to investigate the effects of foliar application to these micronutrients on the growth, yield, yield components and seed quality of camelina. Moreover, the hypotheses that fatty acids may impose a significant effect on the vigor of camelina seeds and fatty acid quality could change in response to the diversity of nutrient sources were examined.

2 Materials and Methods

2.1 Experiment Site

A field experiment was carried out over two consecutive years (2020–2021 and 2021–2022) at research farm of the Faculty of Agriculture of Ferdowsi University of Mashhad (36◦15′ N; 59◦28′E; 985 m asl). The weather data during the research period are presented in Table 1.

Table 1 Some meteorological data in the farm located at the experimental station, Faculty of Agriculture, Ferdowsi university of Mashhad, Iran

Year	Month	Average temperature (ºC)		Humidity (%)		Rainfall (mm)
2019–2023		Min	Max	Min	Max	
	January	−1.20	10.63	47.79	84.25	19.19
	Ferbruary	1.28	12.78	45.56	84.82	25.25
	March	5.91	17.15	46.11	82.29	42.68
	April	10.83	23.20	40.31	74.24	38.88
	May	15.03	27.99	35.34	69.75	38.07
	June	20.20	34.92	21.91	45.69	11.51
	July	22.36	36.08	23.25	45.78	3.64
	August	19.68	33.79	22.66	45.22	1.45
	September	14.93	29.85	24.42	49.44	0.05
	October	9.16	23.08	32.84	66.09	6.78
	November	4.23	16.10	46.52	82.33	9.18
	December	0.35	11.15	52.28	87.52	11.35

2.2 Experimental Design

The study was carried out as a split factorial experiment based on a randomized complete block design with three replications. In this study, the genotypes (Soheil cultivar and Line 69) were considered as the main plots, the foliar application stage (two levels, 50% flowering stage and 50% podding stage) as the sub plots, and the types of micronutrients $FeSO_4$ (4 kg/ha), $ZnSO_4$ (3.6 kg/ha), $MnSO_4$ (2.5 kg/ha) and combination of three micronutrients (3.38 kg/ha) as the sub-sub plots (Azhand et al. 2021). Additionally, distilled water and control were also used.

The appropriate amounts of foliar application were determined based on plant requirements and soil analysis. Based on the results of soil analyses, the alkaline soil pH (7.68) reduces the availability of micronutrients such as iron, zinc, and manganese. Moreover, based on international standards the manganese concentration is relatively low; zinc levels are at the threshold of deficiency, and Iron, although present in sufficient quantity, becomes less available under high pH conditions. The Soheil genotype (with 28% oil content and a yield of 2100 kg/ha) and Line-69 (with 28–37% oil content and a yield of 1900 kg/ha) are classified as intermediate genotypes between spring and autumn types. Both genotypes were developed by the Medicinal Plants Company, Biston Shafa, and officially registered under number 17,992 in Kermanshah Province, Iran, in 2020.

2.2.1 Agronomic Practices

Before preparing the field for cultivation, the physical and chemical characteristics of the experimental soil were analyzed after mixing 12 random samples taken from a depth of 0 to 30 cm (Table 2). The dimensions of each plot were determined to be 1.7 × 2 m. The distance between rows, plots, and replications was set as 0.3, 0.5, and 1.5 m, respectively. Micronutrient foliar application was conducted at two critical growth stages: 50% flowering and 50% podding. The spraying rate per m^2 was considered to be equivalent to 100 ml of treatments, and double distilled water was used to prepare the solutions and uniformly applied using a 5-liter pressure sprayer.

The seeds were sown (9 April 2021 and 11 March 2022) at a depth of 1 cm and density of the established plants was considered to be 400 per m^2 (Urbaniak et al. 2008). The first irrigation was immediately after planting and other irrigations were every 4 days until the establishment of the plants. In the subsequent growing season, irrigation rounds were weekly continued. In addition, weeds were controlled manually during the growing season. To control pests in the field, a 35% imidacloprid suspension was used as a foliar application at a rate of one liter per hectare before flowering. The foliar application of micronutrients was performed at sunset (6 PM).

Table 2 Physical and biochemical characteristics of soil test (0–30 cm) located at the experimental station, Faculty of Agriculture, Ferdowsi university of Mashhad, Iran

Year	Texture	EC (dS m^{-1})	pH	%		mg kg^{-1}				
				OC	*N*	*P*	K	Fe	Zn	Mn
2021	Silt- Loam	2.61	7.81	0.68	0.056	27.82	168.2	3.73	1.23	2.56
2022	Silt- Loam	2.93	7.68	0.57	0.087	22.00	156.7	2.87	1.18	2.32

EC = Electrical Conductivity

OC = Organic Carbon

3 Measurements

3.1 Yield and Yield Component Traits

The final maturity stage (21 July 2021 and 21 June 2022) was recorded when 85–95% of the seeds in the pods of the main stem and branches had turned brown and the seed moisture content was below 14%. At this time, 10 plants plot^{-1} were randomly selected from the two middle Lines and evaluated for some yield component. Final seed yields were measured by harvesting 1 m^2 of the central portion of each plot. Plant height, pod number, 1000-seed weight, and seed yield, harvest index, oil content, fatty acid, and protein levels were also measured. Plants that were damaged by wind or other factors were not selected.

3.1.1 Oil and Protein Content

In order to measure oil content, soxhlet extraction method was considered as explained by (Ramluckan et al. 2014). To measure the protein content of the camelina seed, a non-destructive analysis using Near-Infrared Spectroscopy (NIR) was employed (Wang et al. 2017). NIR DA 4250, manufactured by Pertern, Sweden.

3.1.2 Determination of Fatty Acid Composition

To determine the initial fatty acid composition, the seed samples were first ground, and oil was extracted with n-hexane (1:4 wt/vol, in a dark place at 25 °C for 48 h). Then samples evaporated *in vacuo* at 40 °C under dryness conditions (Farhoosh et al. 2009). After extracting the oil and methylating it, the fatty acid composition was analyzed using a VARIAN CP-3800 gas chromatograph, manufactured in Japan, and equipped with a Flame Ionization Detector (FID) at the Food and Drug Laboratory, Lorestan University of Medical Sciences. The chromatograph was fitted with a capillary column with a minimum length of 25 m and an internal diameter of 0.25 mm, and the analysis was conducted according to the method described by Cocks and Van Rede (1966). In this device, the temperature is increased gradually and according to a programmed schedule, allowing precise control over the temperature increments and their rate. Typically, the oven temperature starts from an initial value (for example, around 60 °C) and gradually rises at a specified rate (such as between 5 and 10 °C per minute) until it reaches the desired final temperature (for instance, up to 270 °C or higher).

3.2 Statistical Analysis

The data were initially tested for normal distribution. Bartlett test was employed to investigate the homogeneity of variance of experimental errors over the two cropping years. Considering the confirmed homogeneity of the variance of experimental errors, the data underwent a combined analysis of variance. The obtained data were analyzed using SAS 9.4 software. The mean comparison was conducted using the LSD test at a 5% probability level.

4 Results

4.1 Seed Yield-Related Traits

Due to the complexity and numerous variation sources, the effects of year and its related interactions, as well as all higher-order interactions, were excluded from the results. The results showed significant differences among genotypes in plant height, pod number, 1000-seed weight, and seed yield (Table 3). While Line 69 had a greater plant height than Soheil, Soheil outperformed Line 69 in pod number, 1000-seed weight, seed yield, and harvest index, with increases of up to 7.2%, 6.6%, 7.5%, and 3.6%, respectively. On average, foliar application at the 50% flowering stage had a greater positive impact on seed yield and oil content compared to the 50% podding stage. However, 1000-seed weight responded more favorably to foliar application during the podding stage. The highest seed yield was achieved in the Soheil cultivar when foliar application was performed at the 50% flowering stage (Table 4).

Significant variation was observed between the two genotypes and across different micronutrient treatments in terms of 1000-seed weight, seed yield, and seed oil content. In the Soheil genotype, the highest 1000-seed weight (1.083 g) and oil content (20.98 g 100 g^{-1}) were obtained with the combined application of $FeSO_4 + ZnSO_4 + MnSO_4$. However, the maximum seed yield (2079.42 kg ha^{-1}) was recorded with $FeSO_4$ alone. In contrast, the control treatment showed the lowest performance across all traits, with a 1000-seed weight of 1.026 g, seed yield of 1687.92 kg ha^{-1}, and oil content of 14.28 g 100 g^{-1}. In Line 69, $FeSO_4$ resulted in the highest seed yield (2018.83 kg ha^{-1}) and oil content (18.98 g 100 g^{-1}), while the highest 1000-seed weight (1.014 g) was observed with $ZnSO_4$. Again, the control treatment had the lowest values for all measured traits. According to LSD (0.05), the differences among treatments were statistically significant for all three traits: 1000-seed weight (LSD = 0.0098), seed yield (LSD = 131.259 kg ha^{-1}), and oil content (LSD = 0.421 g 100 g^{-1}) (Table 5).

Based on the results, foliar application at the 50% flowering stage generally had a more pronounced effect on the seed-related traits than the podding stage. For instance, when the plant was in the 50% flowering stage, foliar application of $FeSO_4$ solution had a 30% more effect than the same foliar application at the podding stage (Table 6).

Table 3 Effects of year, genotype, foliar application stage and micronutrient solution type on some seed yield traits in camelina genotypes

Experimental treatments	Plant height (cm)	Number of pods per plant	1000-seed weight (g)	Seed yield (kg ha^{-1})	Harvest index (%)	Seed protein content (g 100 g^{-1})	Seed oil content (g 100 g^{-1})
Year (Y)							
First (2021–2022)	63.14	114.65	1.075	1802.38	35.03	33.81	15.97
Second (2022–2023)	72.97	147.14	0.951	1922.94	42.36	29.95	20.34
LSD (0.05)	*0.930*	*2.140*	*0.0044*	*66.092*	*1.664*	*0.600*	*0.383*
Genotype (G)							
Soheil	66.94	135.43	1.046	1929.56	39.41	31.70	18.28
Line 69	69.17	126.36	0.981	1795.76	37.99	32.06	18.03
LSD (0.05)	*0.930*	*2.140*	*0.0044*	*66.092*	*1.664*	*0.600*	*0.383*
Foliar application stage (F)							
50% flowering	66.75	133.62	1.010	1883.07	38.75	31.8	18.32
50% podding	69.36	128.16	1.010	1842.25	38.65	31.95	17.98
LSD (0.05)	*0.930*	*2.140*	*0.0044*	*66.092*	*1.664*	*0.600*	*0.383*
Micronutrient solution type (M)							
$FeSO_4$	68.35	138.67	1.021	2049.13	40.65	31.81	19.48
$ZnSO_4$	69.28	122.33	1.028	1951.17	39.40	31.63	18.84
$MnSO_4$	68.28	123.54	1.000	1914.83	39.14	32.13	17.45
Mix ($FeSO_4$ + $ZnSO_4$ + $MnSO_4$)	67.08	130.00	1.043	1872.17	38.13	32.00	19.88
Distilled water	71.08	139.63	1.007	1753.67	38.28	31.84	18.05
Control	64.26	131.21	0.982	1635.00	36.60	31.87	15.23
LSD (0.05)	*1.610*	*3.707*	*0.0077*	*114.470*	*2.883*	*1.039*	*0.663*
Source of variance							
Y	**	**	**	*	**	**	**
G	**	**	**	*	*NS*	*NS*	*NS*
F	*	**	*NS*	*NS*	*NS*	*NS*	*NS*
M	**	**	**	**	*	*NS*	**
Y × G	*	*	**	**	*NS*	*	*NS*
Y × F	*	**	**	*NS*	*NS*	*NS*	*NS*
Y × M	*NS*	**	**	*	*NS*	*	**
G × F	*NS*	*NS*	*	*	*NS*	*NS*	*
G× M	*NS*	*NS*	**	**	*NS*	*NS*	**
F × M	*NS*	*NS*	**	**	*NS*	*NS*	**
Y × G × F	*	*NS*	**	*NS*	*	*NS*	**
Y × G × M	*NS*	**	**	*NS*	*NS*	*NS*	**
Y × F × M	*NS*	*NS*	**	*NS*	*NS*	*NS*	**
G× F × M	*NS*	**	**	*NS*	*NS*	*NS*	**
Y × G × F × M	*NS*	**	**	*NS*	*NS*	*NS*	**

**: significant at $P \leq 0.01$; *: significant at $0.01 < P \leq 0.05$; NS: non-significant ($P < 0.05$)

Table 4 Interaction effects of genotype and foliar application stage on some seed yield traits in camelina

Genotype	Foliar application stage	1000-seed weight (g)	Seed yield (kg ha^{-1})	Seed oil content (g 100 g^{-1})
Soheil	50% flowering	1.048	1938.72	18.64
	50% podding	1.044	1920.39	17.92
Line 69	50% flowering	0.978	1827.42	18.05
	50% podding	0.984	1764.11	18.00
LSD (0.05)		*0.0092*	*119.832*	*0.392*

4.1.1 Seed Oil-Related Traits

According to the results in Table 7, linoleic acid was the only fatty acid that was not significantly affected by any of the experimental treatments. On the other hand, it was observed that other fatty acids and glucosinolates had significant and different responses to the treatments (Table 7).

The studied genotypes had different values in terms of oleic, palmitic and stearic acids. For example, the concentrations of oleic and palmitic acids in the Soheil cultivar were recorded to be 2 and 5%, respectively, higher than in

Table 5 Interaction effects of genotype and micronutrient solution type on some seed yield traits in camelina

Genotype	Micronutrient solution	1000-seed weight (g)	Seed yield (kg ha^{-1})	Seed oil content (g 100 g^{-1})
Soheil	$FeSO_4$	1.044	2079.42	19.97
	$ZnSO_4$	1.042	2044.17	17.89
	$MnSO_4$	1.050	1997.67	18.91
	Mix ($FeSO_4$+$ZnSO_4$+$MnSO_4$)	1.083	1953.08	20.98
	Distilled water	1.032	1815.08	17.67
	Control	1.026	1687.92	14.28
Line 69	$FeSO_4$	0.998	2018.83	18.98
	$ZnSO_4$	1.014	1858.17	19.79
	$MnSO_4$	0.950	1832.00	15.99
	Mix ($FeSO_4$+$ZnSO_4$+$MnSO_4$)	1.003	1791.25	18.78
	Distilled water	0.981	1692.25	18.43
	Control	0.939	1582.08	16.18
LSD (0.05)		*0.0098*	*131.259*	*0.421*

Table 6 Interaction effects of foliar application stage and micronutrient solution type on some seed yield traits in camelina

Foliar application stage	Micronutrient solution	1000-seed weight (g)	Seed yield (kg ha^{-1})	Seed oil content (g 100 g^{-1})
50% flowering	$FeSO_4$	1.015	2143.67	20.83
	$ZnSO_4$	1.014	2007.50	17.95
	$MnSO_4$	1.010	1933.50	15.65
	Mix ($FeSO_4$+$ZnSO_4$+$MnSO_4$)	1.021	1865.58	20.33
	Distilled water	0.999	1717.08	18.82
	Control	1.017	1631.08	16.36
50% podding	$FeSO_4$	1.027	1954.58	18.13
	$ZnSO_4$	1.041	1894.83	19.73
	$MnSO_4$	0.990	1896.17	19.25
	Mix ($FeSO_4$+$ZnSO_4$+$MnSO_4$)	1.065	1878.75	19.43
	Distilled water	1.015	1790.25	17.28
	Control	0.947	1638.92	14.10
LSD (0.05)		*0.0098*	*131.259*	*0.421*

Line 69 (Table 7). This significant superiority was recorded in both 50% flowering and 50% podding stages (Fig. 1).

The oleic acid content responded positively to microelement treatments, showing an overall increasing trend (Fig. 2). The lowest value was recorded in the control treatment, whereas foliar application of $FeSO_4$ to the Soheil cultivar resulted in an increase of up to 6% (Table 8). In Line 69, the same treatment led to a 3% increase. Additionally, foliar application of microelements had a beneficial effect at both growth stages, with the most notable improvements observed following the application of $FeSO_4$ and $ZnSO_4$ at the 50% flowering stage (Fig. 2). Importantly, the foliar application of $FeSO_4$ and $ZnSO_4$ had a significantly greater impact on oleic acid content in the Soheil cultivar compared to Line 69 (Table 8).

Interestingly, the results showed that the oil content in the seed decreased when the 1000-seed weight had an increasing trend (Figure. 3a). Moreover, it is the result of cross-correlation, in fact there is a negative relationship between oil content and oleic acid (Figure. 3b).

4.1.2 Seed Protein Content

Comparing the genotypes, it was found that Line 69 had a higher protein content, with a 1.13% difference compared to the Soheil cultivar (Table 3). However, no significant differences were observed between the stages of foliar application. Although no significant differences were found between the various foliar application treatments, the $MnSO_4$ solution (32.13%) and the combined treatment (32%) showed higher effects in increasing seed protein content (Table 3).

Table 7 Effects of year, genotype, foliar application stage and micronutrient solution type on some oil traits in camelina genotypes

Experimental treatments	Fatty acid (g 100 g^{-1})						Glucosinolate (µmol g^{-1})
	Oleic	Linoleic	Linolenic	Palmitic	Stearic	Eicosenoic	
Year							
First (2021–2022)	41.67	29.80	11.50	3.46	0.58	12.99	23.15
Second (2022–2023)	45.51	29.98	12.35	4.07	0.65	7.45	39.55
LSD (0.05)	*0.936*	*0.621*	*0.403*	*0.145*	*0.032*	*0.931*	*1.459*
Genotype							
Soheil	44.43	30.16	11.79	3.84	0.69	10.08	28.03
Line 69	42.75	29.62	12.05	3.68	0.54	10.35	34.67
LSD (0.05)	*0.936*	*0.621*	*0.403*	*0.145*	*0.032*	*0.931*	*1.459*
Foliar application stage							
50% flowering	43.57	29.97	11.96	3.79	0.63	10.08	58.76
50% podding	43.61	29.81	11.89	3.73	0.60	10.35	57.39
LSD (0.05)	*0.936*	*0.621*	*0.403*	*0.145*	*0.032*	*0.931*	*1.459*
Micronutrient solution							
$FeSO_4$	43.57	29.95	11.86	3.85	0.69	10.09	58.74
$ZnSO_4$	43.99	29.84	12.00	3.85	0.62	9.71	58.23
$MnSO_4$	43.74	29.94	12.05	3.81	0.59	9.88	58.33
Mix ($FeSO_4$ + $ZnSO_4$ + $MnSO_4$)	43.30	29.92	11.91	3.67	0.58	10.63	58.02
Distilled water	43.88	29.76	11.96	3.72	0.58	10.11	58.06
Control	43.07	29.95	11.77	3.68	0.65	10.89	57.07
LSD (0.05)	*0.985*	*0.693*	*0.487*	*0.159*	*0.041*	*0.979*	*1.638*
Source of variance							
Y	**	*NS*	*	*	**	**	**
G	*	*NS*	*NS*	*	**	*NS*	*
F	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
M	*NS*	*NS*	*NS*	*	**	**	**
Y × G	*NS*	*NS*	*	*	*NS*	*NS*	*NS*
Y × F	*	*NS*	*	*NS*	*NS*	*	*NS*
Y × M	*	*NS*	*	*	*NS*	*NS*	**
G × F	*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
G × M	**	*NS*	*NS*	*	*	*	*NS*
F × M	*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Y ×G × F	*NS*	*NS*	*	*NS*	*NS*	*	**
Y × G × M	*NS*	*NS*	**	*NS*	*NS*	*NS*	**
Y × F × M	*NS*	*NS*	**	*NS*	*NS*	*NS*	**
G × F × M	*NS*	*NS*	*	*NS*	*	*NS*	**
Y × G × F × M	*NS*	*NS*	*	*NS*	*NS*	*NS*	**

**: significant at $P \leq 0.01$; *: significant at $0.01 < P \leq 0.05$; NS: non-significant ($P < 0.05$)

5 Discussion

The number of pods is an important determinant of plant yield and, in some ways, reflects the overall efficiency of the plant's metabolic activities (Sasane et al., 2023). As the pods are the site of grain placement and through photosynthesis, they contribute to the initial stages of grain filling in the process of grain growth and development (Rad et al. 2010). Therefore, the onset of pod formation is one of the sensitive stages of plant development because of higher nutrient demand in the plant at this stage and it is necessary to potentially plant yield improvement through micronutrient foliar application (Dass et al. 2016). This is because the increase in foliar micronutrient uptake occurs at a faster rate and therefore has the greatest effect on increasing final yield compared to plant growth characteristics (Dass et al. 2022). A study reported that the combination of micronutrients (Fe, Zn, Mn) increased the number of pods in the wheat. This is because foliar application of micronutrients increases cell division and longitudinal cell expansion, which may lead to more branching and more lateral branches in the plant (Seadh and Metwally, 2015).

Based on climatic data (Table 1), in the second year, with an increase in plant height and number of pods per plant under favorable temperature and moisture conditions, plant density, shading, and competition between plants increased.

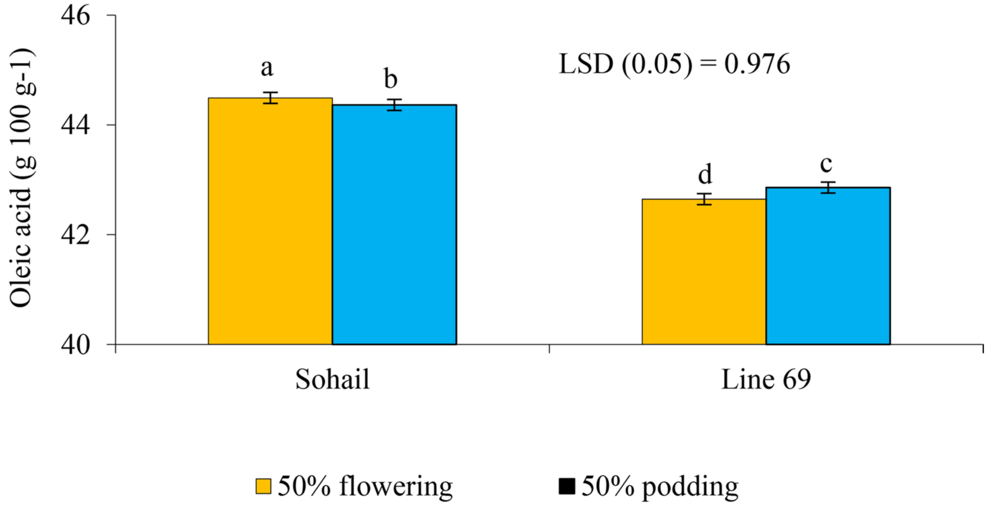

Fig. 1 Interaction effects of genotype and foliar application stage on oleic acid content in camelina genotypes

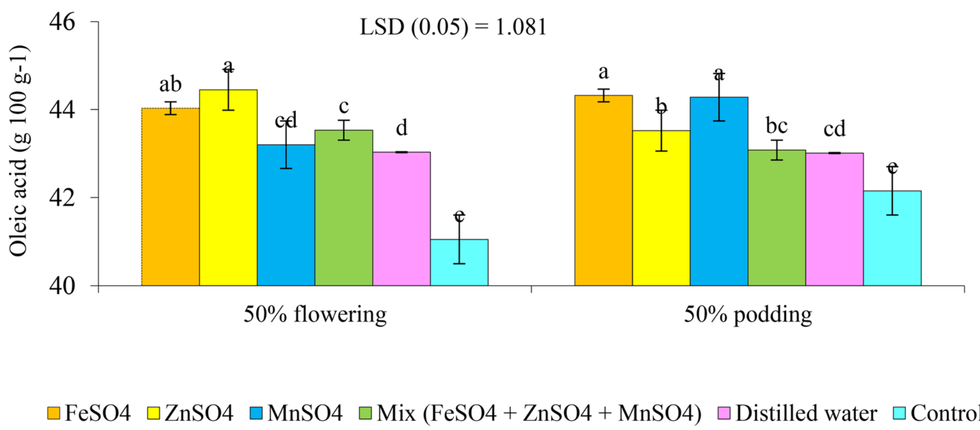

Fig. 2 Interaction effects of micronutrient solution type and micronutrient foliar application stage on oleic acid content in camelina

Table 8 Interaction effects of micronutrient solution type on some oil traits in camelina genotypes

Genotype	Micronutrient solution type	Fatty acid (g 100 g^{-1})			
		Oleic	Palmitic	Stearic	Eicosenoic
Soheil	$FeSO_4$	44.61	3.94	0.75	9.82
	$ZnSO_4$	44.53	3.81	0.64	9.94
	$MnSO_4$	44.22	3.85	0.68	10.26
	Mix ($FeSO_4+ZnSO_4+MnSO_4$)	44.28	3.90	0.70	9.86
	Distilled water	42.27	3.88	0.65	9.60
	Control	41.67	3.68	0.71	11.04
Line 69	$FeSO_4$	42.86	3.75	0.63	10.37
	$ZnSO_4$	43.45	3.89	0.59	9.48
	$MnSO_4$	43.26	3.76	0.49	9.50
	Mix ($FeSO_4+ZnSO_4+MnSO_4$)	42.00	3.44	0.46	11.41
	Distilled water	42.48	3.57	0.50	10.63
	Control	41.48	3.68	0.58	10.74
LSD (0.05)		*1.081*	*0.220*	*0.047*	*0.990*

As a result, the transfer of assimilates to the sink decreased, and parameters such as 1000-seed weight, harvest index, and protein yield also decreased. Usually, increased shading of plants with reduction in photosynthesis weakens their growth and development, as adequate light intensity is required to increase the amount of chlorophyll, natural growth and development, and increase yield (Shao et al. 2014). Therefore, in addition to the significant effect of nutrient status on plant growth, environmental conditions also play a role. Therefore, a decrease in moisture in the early vegetative stage leads to a decrease in yield by inhibiting the growth and development of nodes and branches, increasing the senescence trend of leaves, and shortening the grain-filling period (Brevedan and Egli 2003).

In the first year, the effect of environmental conditions including temperature increase (Table 1) during flowering and seed formation is more significant on the number of pods and seeds. The impact of environmental conditions, including temperature increase during pollination affects

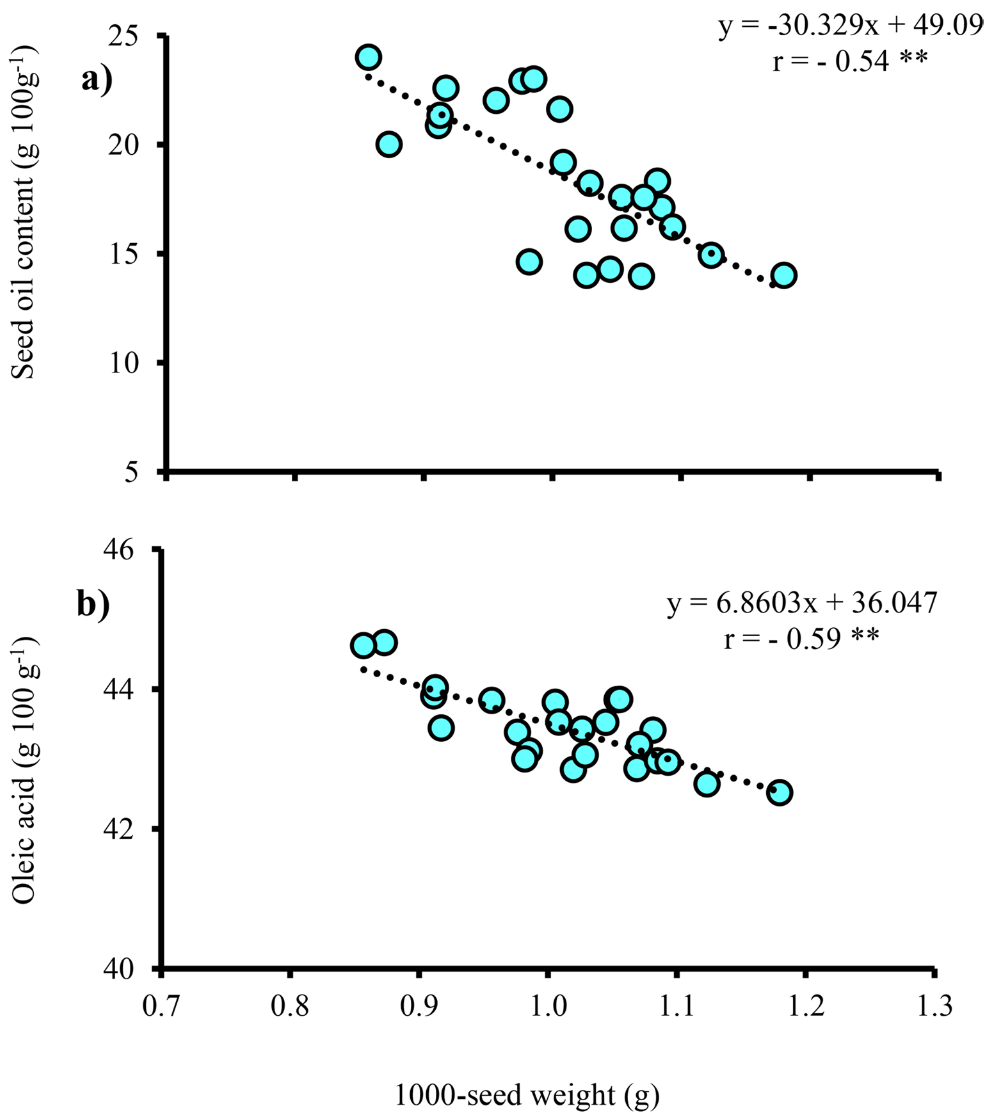

Fig. 3 Correlation between 1000-seed weight with oil content (**a**) and oleic acid content (**b**) **: Statistical significance at $P \leq 0.01$

the physiological processes of anther release, pollen grain reception by the stigma, pollen grain germination, pollen tube growth in the pistil, fertilization and embryo formation, resulting in seed non-formation and reduction of seed number (Farooq et al. 2011; Prasad and Djanaguiraman 2014). According to the results of this experiment (Table 4), the maximum number of pods per plant was observed in Soheil cultivar and Line 69 by micronutrient foliar application during two crop years at both stages of 50% flowering and 50% podding as compared to the control and distilled water, which indicates the positive effect of micronutrients on yield components and is in contract with the findings of (Nandan et al. 2018; Mahmoud et al. 2022).

Moreover, the results showed that the Soheil had a higher oleic acid content than Line 69. In addition, the Soheil cultivar usually showed a better response to foliar application. Such results can be a justification for choosing the Soheil for its usefulness in the food industry. In this regard, it was reported that with the application of Fe, Mn and Zn, a significant increase in oil yield and yield components was observed in sesame due to the improved effects on photosynthesis efficiency and net assimilation rate (Pal et al. 2021).

It was found that the Soheil and Line 69 benefited from micronutrient applications on seed yield, with $FeSO_4$ being the most effective at increasing this parameter. The use of Fe and its effect on different physiological and biochemical processes such as photosynthesis activity and translocation of assimilates to sink ultimately leads to maximum seed yield and oil content (Yadav et al. 2013; Vaghar et al. 2020). In addition, Fe by increasing the synthesis of the auxin hormone and proteins involved in vegetative growth, increases the dry matter in the plant, and under the condition of balance with other elements needed in the plant, it has a positive effect on the physiological processes, and ultimately, fatty acid synthesizes. As well it affects the growth and improve quality of oil seed crop (Kamble et al. 2021).

In canola plants, the use of micronutrients foliar application such as Mn and Zn improved fatty acid metabolism, seed yield, and oil yield by enhancing plant growth and increasing the level of fatty acids (Sanoei et al. 2024). Increasing seed weight as part of biological yield can lead to maximum biological yield (Tavakkol Afshari et al. 2024). However, in evaluating the effect cultivar, the Soheil cultivar compared to Line 69, usually has high adaptability and resistance to different environmental conditions, and this is expected to have higher seed yield per hectare. In this regard, cultivar selection is one of the important factors affecting the growth and yield of oil crops. Along with other environmental conditions, cultivar plays an important role in yield (Banotra et al. 2021).

By considering the results of this experiment, although micronutrient foliar application had a positive effect on increasing the protein content of seeds in both genotypes, there was no significant difference compared to the control. Additionally, micronutrient foliar application showing a significant difference from the control treatment, resulted in an increase in oil content in the Soheil cultivar and Line 69. However, considering the effect of separate micronutrient application, it can be said that Fe nutrition increases the activity of the enzyme nitrate reductase, which is necessary for the fatty acid cycle (Baishya et al. 2016; Briat et al. 2010).

Mn and Zn are also two important elements in protein biosynthesis by regulating the activity of peptidases and controlling protein metabolism (Hansch and Mendel, 2009). In the case of the effect of micronutrient foliar application on seed oil yield, it was concluded that $ZnSO_4$ increased the metabolism of fatty acids to some extent and increased oil accumulation in seed (Hanif et al. 2017). Also, many important enzymes are related to oil accumulation and fatty acid synthesis. Acetyl-CoA carboxylase is one of the enzymes involved in this process and Zn element is necessary for its function (Li et al. 2017). In the reproductive stages of camelina plant, micronutrients foliar application, including Zn, has a very important role on plant growth, improving yield, yield components, and oil yield (Ul Haq, 2022). On the other hand, foliar application Zn solution in the plant by increasing the content of chlorophyll, increasing auxin biosynthesis, absorption of nitrogen, phosphorus and decreasing the concentration of sodium ions in plant tissues causes an increase in yield and oil amount (Moinuddin and Imas 2008). Such explanations could have a supporting and justifying role in relation to the findings of this study in terms of fatty acid composition. According to the results, these can be considered as a practical application especially in high-stress conditions since camelina is mainly produced in arid and semi-arid climates.

As previously mentioned, an interestingly negative connection was observed between 1000-seed weight and oil content, with the same trend between 1000-seed weight and oleic acid. This behavior can be represented as a self-regulatory mechanism in the plant, especially after imposing stressful outcomes. When unfavorable situations are imposed against 1000-seed weight, camelina plants may respond to have higher inherent resistance by enhancing oil synthesis and fatty acid profiles. The effect of self-regulatory mechanisms through higher oil content has been previously reported (Seyyedi et al. 2018). Furthermore, the negative relationship between 1000-seed weight and oleic may indicate the crucial function of this acid in the improved adaptability of Camelina against pressured conditions. Therefore, it seems that smaller seeds, despite enduring more severe stress, retain a higher quality in terms of oil and oleic acid content. It should be noted that oleic acid, the most important fatty acid in the oil of Camelina seeds, accounts for an average of 43% of the total profile (Table 8).

6 Conclusion

Foliar application of micronutrients ($FeSO_4$, $ZnSO_4$, $MnSO_4$), particularly at the 50% flowering stage, positively influenced yield components and increased unsaturated fatty acid content in Camelina seeds. Significant differences were observed among genotypes, with the Soheil cultivar showing superior seed yield and oil quality. This agronomic practice is especially recommended under stress conditions to enhance final yield. Under adverse conditions, increased oil content particularly higher oleic acid concentration may reflect an adaptive physiological response worth further investigation.

Acknowledgements The research leading to these results received funding from the Ferdowsi University of Mashhad under Grant Agreement No. 3.55974 and highly appreciated.

Author Contributions Rostamipour and Tavakkol Afshari conceptualized the study and worked on the methodology. Rostamipour performed the investigation and prepared samples. Kahrizi provied the camelina seed. Rostamipour and Tavakkol Afshari wrote the manuscript. Kahrizi and Eisvand reviewed and revised the manuscript. All authors read and approved the final version of the manuscript.

Data Availability The dataset generated and analyzed during the current study is available from the corresponding author upon reasonable request, subject to applicable data protection regulations.

Declarations

Ethical approval This study adheres to all ethical guidelines and complies with the legal requirements of my country.

Consent to participate The authors provided informed consent to participate in this study on a voluntary basis.

Consent for publication The authors declare that they have no conflicts of interest and hereby consent to the submission of this manuscript to your journal for publication.

Clinical trial number Not applicable.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alejandro S, Holler S, Meier B, Peiter E (2020) Manganese in plants: from acquisition to subcellular allocation. Front Plant Sci 11:1–23

Azhand M, Saeidi M, Agha ABA, Kahrizi D (2023) Interactionof iron and zinc fortification and late-season water deficit on yield and fattyacid composition of Dragon's Head (*Lallemantia iberica* L.). Plant Physiol Biochem 201:107882. https://doi.org/10.1016/j.plaphy.2023.107882

Azhand M, Saeidi M, Beheshti Al Agha A, Kahrizi D (2021) Effect of foliar application of iron and zinc sulphate on yield and some physiological characteristics of camelina (*Camelina sativa* L. crantz) in rainfed conditions. Sci J Plant Physiol 12:155–172

Baishya LK, Sarkar D, Ansari MA, Singh KR, Meitei CB, Prakash N (2016) Effect of micronutrients, organic manures and lime on bio-fortified rice production in acid soils of Eastern Himalayan region. Eco Env Cons 22:199–206

Banotra M, Sharma BC, Kumar R, Mahajan A, Nandan B (2021) Cultivars and planting times effect on growth, yield, quality and economics of sweet corn (*Zea Mays* L. Var. Saccharata) under different conditions: review. Agric Mech Asia Afro Latin Asia 52:2807–2817

Bansal S, Durrett TP (2016) *Camelina sativa*: An ideal platform for the metabolic engineering and field production of industrial lipids. J Biochim 120:9–16. https://doi.org/10.1016/j.biochi.2015.06.009

Belayneh HD, Wehling RL, Cahoon E, Ciftci ON (2015) Extraction of omega-3-rich oil from *Camelina sativa* seed using supercritical carbon dioxide. J Supercrit Fluids 104:153–159. https://doi.org/10.1016/j.supflu.2015.06.002

Bera M, Ghosh JK (2015) Efficacy of sulphur sources on green gram (*Vigna radiata* L.) in red and lateritic soil of West Bengal. Int J Pl Anim Environm Sci 5:109–116

Borg M, Berger F (2015) Chromatin remodeling during male gametophyte development. Plant J 83:177–188. https://doi.org/10.1111/tpj.12856

Brevedan R, Egli DB (2003) Short periods of water stress during seed filling, leaf senescence, and yield of soybean. Crop Sci 43:2083–2088. https://doi.org/10.2135/cropsci2003.2083

Briat JF, Duc C, Ravet K, Gaymard F (2010) Ferrting and iron storage in plant. Biochim Biophys Acta 1800:806–814. https://doi.org/10.1016/j.bbagen.2009.12.003

Candan N, Cakmak I, Ozturk L (2018) Zinc-biofortified seeds improved seedling growth under zinc deficiency and drought stress in durum wheat. J Plant Nutr Soil Sci 181:388–395. https://doi.org/10.1002/jpln.201800014

Cocks LV, Van Rede C (1966) Laboratory handbook for oil and fats analysts. Academic, London, p 88

Dass A, Babu S, Yadav GS, Ansari MA, Singh R, Baishya LK, Ngachan SV (2016) Status and strategies for pulses production for food and nutritional security in north-eastern region of India. Indian J Agron 61:43–57

Dass A, Rajanna GA, Babu S, Lal SK, Choudhary AK, Singh R, Kumar B (2022) Foliar application of macro-and micronutrients improves the productivity, economic returns, and resource-use efficiency of soybean in a semiarid climate. Sustainability 14:5825. https://doi.org/10.3390/su14105825

Dimkpa CO, Bindraban PS (2016) Fortification of micronutrients for efficient agronomic production: a review. Agron Sustain Dev 36(7). https://doi.org/10.1007/s13593-015-0346-6

Fakharzadeh S, Hafizi M, Baghaei MA, Etesami M, Khayamzadeh M, Kalanaky S, Akbari ME, Nazaran MH (2020) Using nanochelating technology for biofortification and yield increase in rice. Sci Rep 10:4351. https://doi.org/10.1038/s41598-020-31660189-x

Farhoosh R, Haddad Khodaparast MH, Sharif A (2009) Bene hull oil as a highly stable and antioxidative vegetable oil. Eur J Lipid Sci Technol 111:1259–1265. https://doi.org/10.1002/ejlt.200900081

Farooq M, Bramley H, Palta JA, Siddique KHM (2011) Heat stress in wheat during reproductive and grain-filling phases. Crit Rev Plant Sci 30:491–507. https://doi.org/10.1080/07352689.2011615687

Ghorbani P, Eshghi S, Ershadi A, Shekafandeh A, Razzaghi F (2019) The possible role of foliar application of MnSO4 on mitigating adverse effects of water stress in grapevine. Commun Soil Sci Plant Anal 50:1550–1562. https://doi.org/10.1080/00103624.2019.1626873

Hanif MA, Nawaz H, Ayub MA, Tabassum N, Kanwal N, Rashid N, Ahmad M (2017) Evaluation of the effects of zinc on the chemical composition and biological activity of basil essential oil by using Raman spectroscopy. Ind Crop Prod 96:91–101. https://doi.org/10.1016/j.indcrop.2016.10.058

Hansch R, Mendel RR Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, Cl B (2009) Curr Opin Plant Biol 12:259–266. https://doi.org/10.1016/j.pbi.2009.05.006

Jankowski KJ, Sokolski M, Kordan B (2019) Camelina: yield and quality response to nitrogen and sulfur fertilization in Poland. Ind Crop Prod 141:111776. https://doi.org/10.1016/j.indcrop.2019.111776

Jarecki W, Buczek J, Bobrecka-Jamro D (2019) The response of winter oilseed rape to diverse foliar fertilization. Plant Soil Environ 65:125–130. https://doi.org/10.17221/5/2019-PSE

Kamaraki H, Galavi M (2012) Evaluation of foliar Fe, Zn and B micronutrients application on quantitative and qualitative traits of safflower (*Carthamus tinctorius* L). J Agroecol 4:201–206. https://doi.org/10.22067/jag.v4i3.15308

Kamble BM, Meena R, Gajbhiye PN (2021) Effect of iron nutrition on growth, quality and yield of soybean (*Glycine Max* L.) grown on problematic inceptisol. J Exp Agric Int 43:20–28. https://doi.org/10.9734/JEAI/2021/v43i1230779

Kaur M, Kumar S, Kaur A (2019) Effect of foliar application of nitrogen, phosphorus and sulphur on growth and yield of Gobhi Sarson (*Brassica Napus* L.) in central Punjab. J Oilseed Brassica 10:47–50

Khavazi K, Nourgholipour F, Malakouti MJ (2001) Effect of Thiobacillus and phosphate solubilizing bacteria on increasing P availability from rock phosphate for corn. In: International Meeting on Direcct Application of Rock Phosphate and Related Tecnology, Kuala Lumpur, Malaysia

Krishna TA, Maharajan T, Ceasar SA (2023) The role of membrane transporters in the biofortification of zinc and iron in plants. Biol Trace Elem Res 201:464–478. https://doi.org/10.1007/s12011-022-03159-w

Latha MR, Nadanas T (2023) Foliar nutrition in crops-A review. Agric Rev 24:229–234

Li QT, Lu X, Song QX, Chen HW, Wei W, Tao JJ, Bian XH, Shen M, Ma B, Zhang WK (2017) Selection for a zinc-finger protein contributs to seed oil increase during soybean domestication. Plant Physiol 173:2208–2224. https://doi.org/10.1104/pp.16.01610

Lynch JP (2019) Root phenotypes for improved nutrient capture: an underexploited opportunity for global agriculture. New Phytol 223:548–564. https://doi.org/10.1111/nph.15738

Mahmoud AVM, Ayad AA, Abdel-Aziz HSM, Williams LL, El-Shazoly RM, Abdel-Wahab A, Abdeldaym EA (2022) Foliar application of different iron sources improves morpho-physiological traits and nutritional quality of broad bean grown in sandy soil. Plants 11:2599. https://doi.org/10.3390/plants11192599

Masella P, Martinelli T, Galasso I (2014) Agronomic evaluation and phenotypic plasticity of camelina sativa growing in Lombardia, Italy. Crop Pasture Sci 65:453–460. https://doi.org/10.1071/CP14025

Moinuddin P, Imas P (2008) Effect of zinc nutrition on growth, yield, and quality of forage sorghum in respect with increasing potassium application rates. J Plant Nutr 33:2062–2081. https://doi.org/10.1080/01904167.2010.519081

Movahhedy-Dehnavy M, Modarres-Sanavy SAM, Mokhtassi-Bidgoli A (2009) Foliar application of zinc and manganese improves seed yield and quality of safflower (*Carthamus tinctorius* L.) grown under water deficit stress. Ind Crops Prod 30:82–92. https://doi.org/10.1016/j.indcrop.2009.02.004

Nandan B, Sharma BC, Chand G, Bazgalia K, Kumar R, Banotra M (2018) Agronomic fortification of Zn and Fe in Chickpea an emerging tool for nutritional security: A global perspective. Act Sci Nutr Health 2:12–19

Pal V, Singh G, Dhaliwal SS (2021) A new approach in agronomic biofortification for improving zinc and iron content in Chickpea (*Cicer arietinum* L.) grain with simultaneous foliar application of zinc sulphate, ferrous sulphate and Urea. J Soil Sci Plant Nut 21:883–896. https://doi.org/10.1007/s42729-021-00408-0

Prasad PVV, Djanaguiraman M (2014) Response of floret fertility and individual grain weight of wheat to high temperature stress: sensitive stages and thresholds for temperature and duration. Funct Plant Biol 41:1261–1269. https://doi.org/10.1071/FP14061

Ramluckan K, Moodley KG, Bux F (2014) An evaluation of the efficacy of using selected solvents for the extraction of lipids from algal biomass by the Soxhlet extraction method. Fuel 116:103–108. https://doi.org/10.1016/j.fuel.2013.07.118

Rengasamy KR, Kulkarni MG, Pendota SC, Van Staden J (2016) Enhancing growth, phytochemical constituents and aphid resistance capacity in cabbage with foliar application of eckol—A biologically active phenolic molecule from brown seaweed. New Biotechnol J 33:273–279. https://doi.org/10.1016/j.nbt.2015.11.002

Righini D, Zanetti F, Martínez-Force E, Mandrioli M, Gallina Toschi T, Monti A (2019) Shifting sowing of camelina from spring to autumn enhances the oil quality for bio-based applications in response to temperature and seed carbon stock. Ind Crop Prod 137:66–73. https://doi.org/10.1016/j.indcrop.2019.05.009

Sanoie A, Tohidi-Moghadam HR, Nasri M, Oveysi M, Ghooshchi F (2024) Responses of Canola cultivars to cpplication of micronutrients upon late-season drought stress. Commun Soil Sci Plant Anal 13:2028–2041. https://doi.org/10.1080/00103624.2024.2336578

Sasan SK, Shende PV, Manapure PR, Baviskar S, Pokale SS, Barde SR, Ingle SV (2023) Physiological responses of ferrous sulphate and zinc sulphate on biochemical parameters, yield and yield contributing parameters of mung bean. Pharm Innov Int J 12:486–490

Seadh SE, EL-Metwally MA (2015) Influence of antioxidants on wheat productivity, quality and seedborne fungi management under NPK fertilization levels. Asian J Crop Sci 7:87–112. https://doi.org/10.3923/ajcs.2015.87.112

Seyyedi SM, Tavakkol Afshari R, Daneshmandi MS (2018) The relationships between fatty acids and heterotrophic seedling growth in winter Canola cultivars during accelerated seed aging process. S Afr J Bot 119:353–361. https://doi.org/10.1016/j.sajb.2018.09.034

Shao Q, Wang H, Guo H, Zhou H, Huang A, Sun Y, Li M (2014) Effects of shade treatments on photosynthetic characteristics, Chloroplast ultrastructure, and physiology of *Anoectochilus Roxburghii*. PLoS ONE 9:e85996. https://doi.org/10.1371/journal.pone.0085996

Tavakkol Afshari M, Tavakkol Afshari R, Seyyedi SM (2024) The effect of sowing date and deficit irrigation on Quinoa seed (Chenopodium Quinoa Willd.): Understanding the morphology of embryo-cotyledons and germination characteristics based on image analysis. Arid Land Res Manag 39:49–64. https://doi.org/10.1080/15324982.2024.2368665

Ul Haq E, Ul Hassan F, Iqbal M, Ahmed M, Ghuffar S, Ahmed J, Ahmed R, Shahbaz M, Ur Rehman A, Hamzah AM (2022) Effect of micronutrients (B and Zn) as foliar application on growth and yield of *Camelina sativa* L. Plant Cell Biotechnol Mol Biol 23:1–11. https://doi.org/10.56557/PCBMB/2022/v23i33-347809

Urbaniak SD, Caldwell CD, Zheljazkov VD, Lada R, Luan L (2008) The effect of seeding rate, seeding date and seeder type on the performance of *Camelina sativa* L. in the maritime provinces of Canada. Can J Plant Sci 88:501–508

USDA (2015) National Agricultural Statistics Service. USDA. http://www.nass.usda.gov/ (accessed Dec. 2015)

Vaghar MS, Sayfzadeh S, Zakerin HR, Kobraee S, Valadabadi SA (2020) Foliar application of iron, zinc, and manganese nano-chelates improves Physiological indicators and soybean yield under water deficit stress. J Plant Nutr 43:2740–2756. https://doi.org/10.1080/01904167.2020.1793180

Vollmann J, Moritz T, Kargl C, Baumgartner S, Wagentristl H (2007) Agronomic evaluation of camelina genotypes selected for seed quality characteristics. Ind. Crops and Prod 26, 270–277. https://doi.org/10.1016/j.indcrop.2007.03.017

Walia MK, Zanetti F, Gesch RW, Krzyzaniak M, Eynck C, Puttick D, Alexopoulou E, Royo-Esnal A, Stolarski MJ, Isbell T, Monti A (2021) Winter camelina seed quality in different growing environments across Northern America and Europe. Ind Crops Prod 169:113639. https://doi.org/10.1016/j.indcrop.2021.113639

Wang Y, Shi A, Ravelombola WS, Yang W, Qin J, Motes D, Moseley DO, Chen P (2017) A rapid method for measuring seed protein content in Cowpea (*Vigna unguiculata* (L.) Walp). Am J Plant Sci 8:2387–2396

Watts JL (2016) Using caenorhabditis elegans to uncover conserved functions of omega-3 and omega-6 fatty acids. J Clin Med 5(19). https://doi.org/10.3390/jcm5020019

Yadav GS, Dinesh K, Subhash B (2013) Enhancing iron density and uptake in grain and straw of aerobic rice through mulching and rhizo-foliar fertilization of Fe. Afr J Agric Res 8:5447–5454

Yantai G, Harker KN, Kutcher HR, Gulden RH, Irvine B, May WE, O'Donovan JT (2015) Canola seed yield and phenological responses to plant density. Can J Plant Sci 96:151–159. https://doi.org/10.1139/cjps-2015-0093

Zaluski D, Tworkowski J, Krzyżaniak M, Stolarski MJ, Kwiatkowski J (2020) The characterization of 10 spring camelina genotypes

grown in environmental conditions in North-Eastern Poland. J Agron 10(64). https://doi.org/10.3390/agronomy10010064
Zulfiqar U, Hussain S, Ishfaq M, Ali N, Ahmad M, Ihsan F (2021) Manganese supply improves bread wheat productivity, economic returns and grain biofortification under conventional and no-tillage systems. Agriculture 11:142. https://doi.org/10.3390/agriculture11020142
Rad AS, Naeimi M, Esfahani SN (2010) Evaluation of terminal drought tolerance in spring and winter rapeseed genotypes. Iranian J Agric Sci 12:112–126