Agrotechniques in Industrial Crops

Journal Homepage: https://atic.razi.ac.ir

Assessment of *Camelina sativa* Performance under Deficit Irrigation with Application of Animal Manure and Micronutrients Nano-Fertilizers

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ARTICLE INFO

Original paper

Article history:
Received: x Month 202x
Revised: x Month 202x
Accepted: x Month 202x

Keywords:
Chlorophyll content
Drought stress
Field capacity
Oil percentage
Semi-arid region
Vegetative growth

ABSTRACT

Camelina sativa as a relatively new oilseed crop has a relatively favorable adaptation to semi-arid and warm conditions. This study was conducted to evaluate the effects of different irrigation regimes (FI: full irrigation, 100% field capacity, DI: deficit irrigation, 60% field capacity) and the application of varying levels of animal manure and foliar application of iron and zinc nano-fertilizers on the growth and yield of camelina under deficit irrigation conditions during the vegetative growth. A field trial was carried out in the Bileh-Savar region of Ardabil. The animal manure levels were 0, 10 and 20 t ha^{-1} which are displayed as the abbreviations FYM_0, FYM_{10} and FYM_{20}, respectively. The highest leaf chlorophyll content (55.86) was recorded under FI+FYM_{20}+Zn conditions. DI reduced lateral canopy growth (LCG) by 33% compared to FI conditions. With increasing FYM application specifically under FI, significantly increased LCG. The effect of nano-iron foliar application on LGC was greater than that of zinc. The application of FYM_{10} and FYM_{20} increased biomass by 7% and 16% compared to FYM_0. DI reduced the number of siliquae by 34% compared to FI. The highest seed yield was recorded under FI+FYM_{20}+Zn conditions (1782 kg ha^{-1}), and the lowest seed yield was related to DI+FYM_0+FI conditions (1165 kg ha^{-1}). The highest seed oil content was achieved under FI+FYM_{20} conditions (35.10%) and the lowest was recorded in plants grown under DI+FYM_0 (31.55%). Overall, the DI with irrigation up to 60% FC does not seem to be an ideal irrigation option in the studied area for camelina production systems. These results could provide valuable insights for farmers in regions with limited water resources, helping them optimize irrigation and fertilization strategies for *C. sativa* production.

DOI: 10.22126/ATIC.2025.11812.1198

1. Introduction

Camelina (*Camelina sativa*) is an oilseed crop and it is one of the relatively new introduced crops from the Brassicaceae family that improved by the plant breeding process during the past decades. Camelina has relatively acceptable adaptation to the conditions of semi-arid regions (Zanetti *et al*., 2021). However, the trend of climate change such as increasing air temperature and decreasing precipitation has significantly accelerated in the mentioned regions in recent years. This has exacerbated the shortage of available water resources and increased the occurrence of drought stress (Furtak and Wolińska, 2023). Camelina is a plant that is adaptable to low-input farming conditions such as chemical fertilizers and has lower water requirements than many other oilseed crops. This high adaptability makes it a potential candidate as a climate-smart crop. Its high oil content could also be used as a valuable source for biodiesel production (Agarwal *et al*., 2021). The average yield of camelina in Europe is estimated to be between 1 and 3 tons per hectare. Factors such as genotype, soil conditions, rainfall, and restricted or unrestricted growth can have a significant impact on the yield of the grain (Zanetti *et al*., 2024). However, it has been found that the quantitative characteristics of the grain yield as well as the quality of the extracted oil are affected by environmental and edaphic conditions. Statistics on the area under camelina cultivation indicate that this plant has not yet been well received by farmers. This plant

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can be cultivated as a winter or spring crop; however, the yield of winter genotypes is estimated to be up to about 3.3 tons. Camelina can also be cultivated as a rainfed crop in areas with a suitable and significant rainfall distribution (Zanetti *et al*., 2017). It has been estimated that the minimum water requirement for camelina under a semi-arid condition is 330-420 mm. However, in semi-arid regions, due to low organic matter in the soil, water holding capacity is relatively low, and special management measures must be taken to improve the soil to conserve water (Hazrati *et al*., 2024). The relatively favorable drought tolerance of camelina will make this plant's position in rotations more prominent over the coming decades. The adaptability of the camelina growth cycle to different climatic conditions and the lack of need to design and build special equipment and machinery are other advantages of this plant. This plant is capable of producing crops with low fertilizer inputs, but only if the soil conditions meet the plant's nutritional needs to some extent (Rostami Ahmadvandi *et al*., 2021).

The reproductive stages of most crops represent the period of highest vulnerability to water stress (Yu *et al*., 2019). On the other hand, in the semi-arid regions of Iran, the majority of precipitation is concentrated between October and February. Some of the rainfall occurs during the growing season when the plant is not actively growing (Saeed *et al*., 2021). In such circumstances, by implementing efficient irrigation scheduling and reducing water consumption during the vegetative stages, water resources can be saved for sensitive reproductive stages (Hunsaker *et al*., 2013). Limited irrigation (water supply up to 75% of crop evapotranspiration) in camelina improved water use efficiency and mild water deficit stress activates improved tolerance to hot and dry periods at the end of the growth period (Khemmouli *et al*., 2023; Yang *et al*., 2021). In semi-arid regions, due to specific climatic conditions, high temperatures, and low rainfall, soils usually have little development and evolution and low fertility (Chenchouni and Neffar, 2022). Soils in these regions often have high pH, shallow depth, little organic matter, low water retention capacity, low CEC, and unfavorable physical and chemical properties (Baranian Kabir *et al*., 2017). Soil health and micronutrient dynamics are strongly associated with build-up of organic matter. Application of manure and improving the soil organic matter by adjusting the pH in the rhizosphere environment may release micronutrients from the soil and increase their uptake by the roots (Dhaliwal *et al*., 2019). However, foliar application of micronutrients can also be an alternative method in such situations (Haq *et al*., 2022). Given the development of the livestock industry in northwest Iran, caw manure is one of the cheapest and most abundant organic soil amendments that is easily available to farmers. The use of manure in the soil improves soil structure and increases the proportion of micro-pores, improving the penetration of precipitation into the soil and increasing the soil water retention capacity (Singh *et al*., 2022). On the other hand, the solubility and availability of micronutrients strongly depend on soil properties such as pH, soil organic matter content, and clay content and composition (Moreno-Jiménez *et al*., 2019). The unfavorable chemical and physical conditions of semi-arid soils have caused severe micronutrient deficiencies. In recent years, with the advancement of nanoparticle science and its efficient introduction into various agricultural sectors such as fertilizers, the efficiency of using these inputs has increased significantly (Gupta *et al*., 2023). Due to their very small dimensions (less than 100 nanometers) and high contact surface, nanoparticles have high capabilities in absorption processes, passage through membranes, and playing a role in the target site (Yadav *et al*., 2023). However, there is still no comprehensive information on reducing irrigation during the growing season and saving water for the reproductive season, as well as organic soil amendments and foliar application of Fe and Zn nanoparticles on camelina in the warm and semi-arid region. The present experiment simultaneously investigated the effects of irrigation regimes and the application of manure and micronutrients in Bileh-Savar, Ardabil, Iran.

2. Materials and methods

2.1. Site description

A field experiment was carried out in the semi-arid area of Bile Savar, Ardebil, in the Northwest of Iran from 2023 to 2024. Bile-Savar has a temperate and humid climate in winter and is relatively hot during the summer. The geographical location of the farm was 39°37' N 48°35' E and the height from sea level was 120 m. According to De Martonne's climate classification, the region has a temperate-warm and semi-arid climate. Despite being located in the northwest of Iran, this region is relatively different from neighboring regions due to its low altitude, specific air temperatures, and different precipitation patterns. The average annual temperature was 26˚C, the average maximum annual temperature was 37.3˚C, the minimum average annual temperature was 11˚C, and the average annual precipitation was 471 mm. Some important meteorological characteristics in the study area are shown in Table 1. To analyze the soil of the experimental site, soil samples were gathered and mixed from six points of the field from a depth of 0-30 cm before the utilization of fertilizers. The soil was a silty-clay loam (silt: 49.6%, clay: 33%, and sand: 17.4%) and contained 376.9 mg kg^{-1} of potassium, 6.5 mg kg^{-1} of absorbable phosphorus, 0.078% of total nitrogen, 0.885% of organic carbon, and other chemical properties of the soil were pH: 7.60, percentage of neutralizing materials: 11.20, and electrical conductivity: 1.72 ds m^{-1}.

Table 1. Meteorological data collected from the Bileh-Savar region during the implementation of the field experiment during in 2024.

	February	March	April	May	June	July	August
Minimum temperature (˚C)	1	6.9	11.5	17	20.4	20.9	17.5
Maximum temperature	11	20	25	32.1	33.8	32.6	31.7
Average temperature	6	13.5	18.3	24.5	27.1	26.7	24.6
Average humidity (%)	77	74	69	63	59	65	59
Maximum wind speed (km h^{-1})	15	17	16	18	14	14	13
Total monthly precipitation (mm)	29.6	32.3	38.4	8.7	33.3	10.4	0
Total monthly evaporation (mm)	-	60.4	142.8	203.7	259.4	217.3	196.9

2.2. Implementation of experimental treatments

The present research was conducted as a spilt-split plot experiment based on an arbitrary complete block design with 3 replications. The main factor includes irrigation regimes at two levels, full irrigation regime: irrigation at recommended intervals according to the appearance of plant symptoms before wilting and water supply up to 100% field capacity (FC)as full irrigation (FI), and deficit irrigation (DI): water supply up to 60% FC during the irrigation. The total water consumption was 620 mm in FI conditions and 400 mm in DI conditions. A distance of one meter was considered as a boundary between the main plots to prevent moisture leakage between the main plots. The sub-plots assigned to different levels of organic amendments include 0, 10, and 20 t ha^{-1} of decomposed farmyard manure (FYM), which are shown as abbreviations FYM_0, FYM_{10}, and FYM_{20} respectively. Sub-sub plots were assigned to foliar application of nano-structured micronutrient fertilizer (0: control, Fe, and Zn). Foliar application of nanostructured micronutrient fertilizers at a concentration of 300 ppm was repeated four times during stem elongation to full flowering. Foliar application was done with the help of a motorized sprayer in the early morning and all parts of the plant's shoots were sprayed with the solution. The initial soil tillage was carried out in October 2023, and the secondary tillage, the preparation of experimental plots, and the use of animal manure were done in February 2024. Irrigation was done through polyethylene pipes equipped with a volume meter. A time-domain reflectometer (TDR-200, Campbell Scientific, USA) was used to measure soil moisture during different development periods. The soil moisture content at the field capacity point was 33.41% v/v and at the permanent wilting point was 18.6% v/v. Irrigation was repeated when soil reached 60% of available soil water under full irrigation and 45% under deficit irrigation conditions. Surface irrigation was carried out through polyethylene pipes equipped with water volume meters for the experimental plots. Irrigation requirement was calculated according to Hasanuzzaman et al. (2016). Camelina seeds of cv. Soheil as an intermediate cultivar was obtained from Pakan Seed Company, Isfahan, Iran, and was manually planted on the ridge with inter and intra-row spacing of 20×3 cm on March 4.

2.3. Collecting agronomic and morphological data

At the early stage of flowering (BBCH= 60; First flowers open), the chlorophyll of the upper and developed leaves of Camelina was measured using a manual chlorophyll meter (SPAD 502, Konica Minolta, USA). In the physiological maturity stage of Camelina (BBCH= 89; when nearly all siliquae were ripe the crop was ready to be harvested) using arbitrarily 1-m2 quadrate from each experimental unit, main stem height was measured. The lateral growth of the canopy was calculated by measuring the diameter of the canopy from left to right. To evaluate morphological characteristics, measurements were taken from 10 plants per plot. After harvesting camelina plants and drying them in the oven, seed yield components such as the number of total siliquae per plant, number of seeds per siliquae, weight of 1000 seeds, yield per unit area, biomass, and harvest index (ratio of grain yield to biological yield) were calculated. A Soxhlet apparatus was used to calculate the oil percentage in the seeds of the harvested plants. For this purpose, ten grams of camelina seeds were ground and then mixed with 600 ml of hexane. After 6 hours of extraction, the solvent was separated from the oil by rotary evaporation and stored at refrigerator temperature until chemical analysis. The oil yield was obtained by multiplying the oil percentage by the seed yield.

2.4. Software used in statistical analysis

Before statistical analysis, a data normality test was performed. Data normality test ensures accurate statistical results. Statistical analysis was performed through SAS software. Spilt-split plot design and the applied statistical methods are appropriate for analyzing field experiments of this nature. The least significant difference test was used to compare the means. Box plots were drawn through SPSS Statistics. Component analysis (PCA), and boxplots were executed by Minitab software.

3. Results and discussion

3.1. Vegetative growth components

Evaluation of lateral canopy growth showed that reducing irrigation frequency reduced this component by 18%. The triple interaction effect of I×FYM×M was significant at the 5% level (Table 2). The lowest lateral growth was recorded under DI conditions without manure application (20-19 cm). While the highest lateral growth was observed in plants grown under FI+FYM_{20}+Fe (39.36 cm). Under FYM_0 and full irrigation conditions, the effect of micronutrient application was significant compared to the control. The iron application had a greater effect on lateral canopy growth. However, under FYM_{10}, the effect of foliar application of various micronutrients was not significantly different. Under FYM_{20}, the application of iron nano-fertilizer was superior to zinc, and the highest lateral growth was recorded under the aforementioned conditions. Under DI conditions, the effect of foliar application was visible only under the condition of manure application. At both levels of manure application, the effect of foliar application with nano-iron fertilizers was greater than that of zinc fertilizer (Fig. 1). This indicates a severe iron deficiency in the plants cultivated in the region. In addition, the application of manure probably made the effect of foliar application on lateral growth more pronounced due to the provision of other plant nutritional needs. The interaction of manure and micronutrients can be due to the improvement of soil conditions and better absorption of plant nutrients in the rhizosphere environment, improved water retention in the soil, pH adjustment, and improved soil physical conditions. In the process of cell growth, water is the main stimulus providing trigger pressure and cell elongation. This in turn stimulates growth-stimulating plant hormones such as auxin and gibberellin (Sosnowski *et al*., 2023).

Chlorophyll content analysis showed that deficit irrigation reduced chlorophyll content by 20% compared to optimal moisture conditions (Table 2). Interaction effects of I×M showed that iron and zinc application increased chlorophyll content by 4 and 5%, respectively, compared to the control, but no significant difference was observed between these two micronutrients. Micronutrients, with their key roles as cofactors in many biological enzymes, can affect the biosynthesis of pigments. In addition, iron is a structural component of chlorophyll. Given the severe deficiency of micronutrients in semi-arid regions, this increase was expected. These findings confirmed previous results obtained by Janmohammadi et al. (2018).

Plant biomass analysis showed that the interaction effects of I×FYM and the interaction effects of I×M and FYM×M were significant (Table 2). Means comparison for I×FYM effects showed that the highest biomass was recorded in plants grown under FI + FYM_{20} conditions (7188.89 kg ha^{-1}), followed by FI + FYM_{10} (6939.56 kg ha^{-1}). By reducing the use of animal manure, the plant biomass decreased significantly in both irrigation regimes, and the lowest amount of biomass was obtained under the DI+FYM_0 conditions (5002 kg ha^{-1}).

Table 2. The effects of farmyard and nano-micronutrient fertilizer on seed yield and morphological traits of *C. sativa* under deficit and full irrigation regimes in Bileh-Savar region of Ardabil.

	LGC	CHL	DB	NSP	SY	SOP	OY
Irrigation (I)							
FI	33.27^a	48.23^a	6831.43^a	147.03^a	1597.09^a	34.61^a	553.26^a
DI	23.96^b	38.41^b	5470.98^b	96.23^b	1268.60^b	32.57^b	413.72^b
Farmyard manure							
FYM_0	24.44^c	40.12^c	5684.06^c	111.73^c	1346.50^c	32.83^c	443.88^c
FYM_{10}	28.87^b	42.06^b	6165.42^b	117.08^b	1428.75^b	33.58^b	481.62^b
FYM_{20}	32.54^a	47.78a	6604.14^a	136.08^a	1523.28^a	34.36^a	524.98^a
Micronutrient							
0	27.57^c	42.00^b	5989.20^c	116.27^b	1398.08^c	33.33^c	468.11^c
Nano-Fe	29.65^a	43.87^a	6206.00^b	124.38^a	1440.10^b	33.59^b	485.87^b
Nano-Zn	28.62^b	44.10^a	6258.42^a	124.24^a	1460.36^a	33.84^a	496.28^a
F value in ANOVA							
I	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
FYM	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
I×FYM	0.0003	0.49	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
M	<0.0001	0.002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
I× M	0.76	0.033	0.014	0.45	0.012	0.0006	0.0561
FYM×M	0.27	0.45	0.0032	0.03	<0.0001	0.0036	<0.0001
I×FYM×M	0.047	0.85	0.45	<0.0001	<0.0001	0.059	<0.0001
CV (%)	3.24	4.95	6.93	7.26	8.13	1.33	3.86

FI: full irrigation, DI: deficit irrigation during the vegetative growth stages, FYM_0, FYM_{10}, and FYM_{20}: application of 0, 10, and 20 t ha^{-1} animal manure, micronutrient $_0$: no use of micronutrient fertilizer, nano-Zn, and nano-Fen: the foliar application of nano-structured zinc or iron fertilizers during stem elongation. LGC: lateral growth of canopy (cm), CHL: chlorophyll content in upper leaves (SPAD unit) during siliques formation, DB: total dry matter or biomass of plant (kg ha^{-1}), NSP: total number of siliquae per plant, SY: seed yield (kg ha^{-1}), SOP: seed oil percentage, OY: seed oil yield (kg ha^{-1}) F values less than 0.05 *(*p<0.05) and 0.01 (p<0.01) are statistically significant at 95% and 99% levels, respectively. The means with similar letters in each trait are not statistically different.

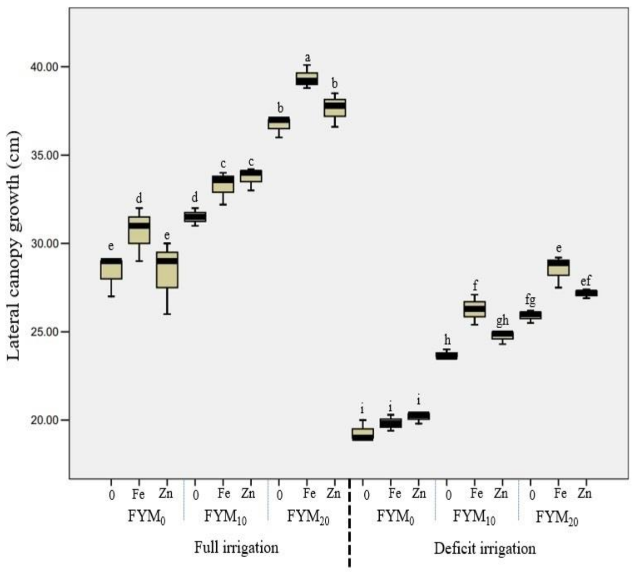

Figure 1. The assessment of the effect of different irrigation regimes, farmyard manure and nanostructured iron and zinc fertilizers on lateral canopy growth of *C. sativa* in the Bileh-Savar region - northwest of Iran. FYM_0, FYM_{10}, and FYM_{20}: application of 0, 10, and 20 t ha^{-1} animal manure, micronutrient $_0$: no use of micronutrient fertilizer, nano-Zn, and nano-Fe: foliar application of nano-structured zinc or iron fertilizers during stem elongation. Similar letters above the boxes indicate no statistically significant difference at the 5% level.

It seems that depending on the region, the application of farmyard manure, in addition to improving water permeability in the soil, increased the retention of water in the microtubules, and thus provided more water for absorption in the rhizosphere environment (Nouraein *et al.*, 2019; Fattahi *et al.*, 2023). Means comparison of biomass for the interaction effects of I×M showed that the highest biomass was obtained under FI+Zn conditions (6935 kg ha^{-1}) and the lowest biomass was obtained under DI+0 conditions (5377.5 kg ha^{-1}). Interestingly, no significant difference was observed for the effect of Fe or Zn under DI conditions. It seems that under water deficit stress conditions, the absorption of foliar applied elements by the shoots decreases due to structural changes in the outer parts of the leaves, such as increased cuticle thickness and waxiness, as well as the closure of stomata (Yang *et al.*, 2021). Means comparisons biomass for the interaction effects of FYM×M showed that the highest biomass was obtained under the conditions of FYM_{20} + Zn (6722 kg ha^{-1}), followed by the application of iron with high levels of manure (6647 kg ha^{-1}). The lowest biomass was associated with the condition of no manure utilization (FYM_0). However, the foliar application of nanostructured zinc micronutrient fertilizers, even under FYM_0 application (5841 kg ha^{-1}), had a greater effect on biomass production than the application of nanostructured iron fertilizers (5697 kg ha^{-1}).

3.2. Seed yield components

The results showed that the number of siliquae in camelina was affected by the triple effects of I×FYM×M. The highest number of siliquae was obtained under the conditions of FI+FYM_{20}+Zn (167.33) and plants grown with iron application under the conditions of FYM_{20} and FI was in second place in terms of the number of siliquae. However, the effect of manures did not have the same trend, which is probably due to the high competition between yield components and the compensatory relationship between them (Fig. 2). In this regard, it has been reported that the application of manure and micronutrients in semi-arid regions increased the number of siliquae (Martinez *et al*., 2021). Changes in the number of siliquae indicate the source-sink relationship. It seems that applying deficit irrigation during the vegetative stage has reduced the conversion of primordia to siliquae by reducing the supply of photoassimilates (Pavlista *et al*., 2016).

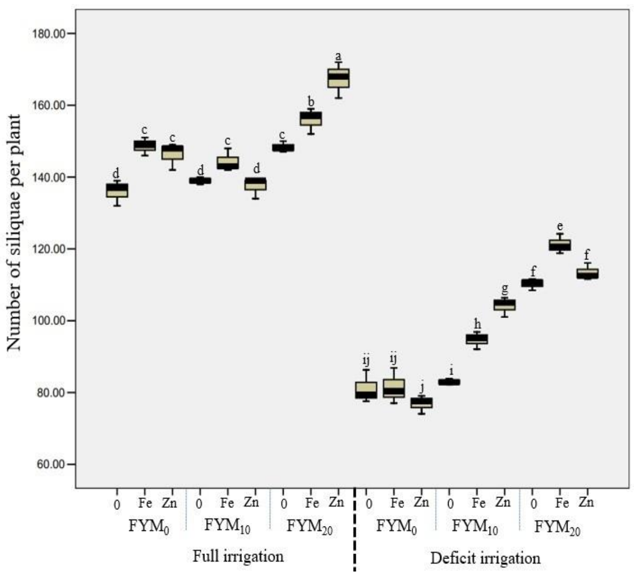

Figure 2. Evaluation of the effect of applying different levels of animal manure and nanostructured iron and zinc fertilizers on the number of siliquae in camelina plants under different moisture conditions in the Bileh-Savar region - northwest of Iran. FYM_0, FYM_{10}, and FYM_{20}: application of 0, 10, and 20 t ha^{-1} animal manure, micronutrient $_0$: no use of micronutrient fertilizer, nano-Zn, and nano-Fe: foliar application of nano-structured zinc or iron fertilizers during stem elongation.

Seed yield analysis showed that the triple effects of I×FYM×M were significant for this agronomic component. Applying water deficit stress reduced grain yield by about 26% compared to full irrigation conditions. The highest grain yield was obtained under FI+FYM_{20}+Zn (1782 kg ha^{-1}) and FI+FYM_{20}+Fe (1721 kg ha^{-1}). A comparison of FYM levels under full irrigation conditions showed that FYM application by 20 t ha^{-1} could meet the initial requirement of macronutrients and micronutrients for the plant, which significantly increased yield. However, under DI conditions, the most important factor determining yield was the level of FYM application, and no significant difference was observed between micronutrients (Fig. 3). The seed yield in camelina plant is the result of various plant processes and is a reflection of the plant growth during the vegetative stage and root system development, absorption rate, photosynthesis rate, photoassimilates reserve before entering the reproductive phase, genotype, climatic and edaphic conditions. In general, the results showed that the soil of the mentioned area was poor and the application of animal fertilizers was necessary. However, the application of DI in the mentioned area caused a significant decrease in yield compared to FI conditions.

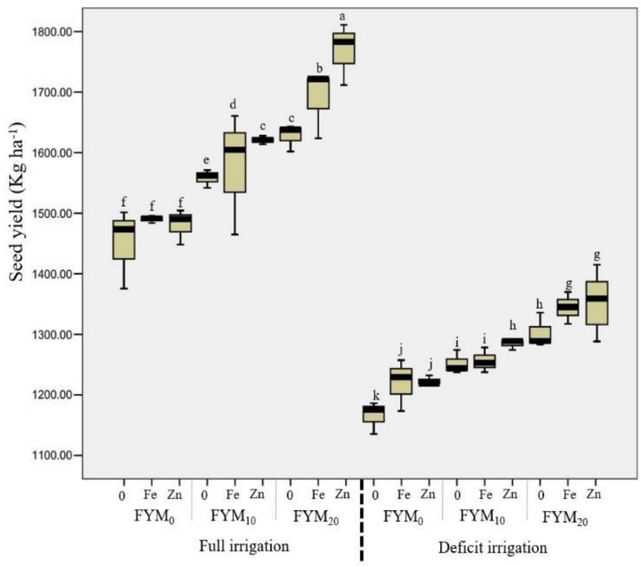

Figure 3. Mean comparison of seed yield of *C. sativa* under different irrigation regimes and application of nanostructured animal and micronutrient fertilizers in the Bile Savar region of Iran.

The irrigation regime and the amount of available water can affect the ion exchange capacity of the soil. Increasing the amount of available water increases the rate of nutrient replacement at the surface of soil particles. Increasing the release of nutrients from soil particles increases their availability to the root system and improves their absorption (Ding *et al*., 2023). In addition, increasing soil moisture increases the rate of dissolution of elements in soil solutions. However, this may also increase the likelihood of leaching of these elements to some extent. However, in semi-arid regions, due to the low water supply during irrigation, the rate of leaching of elements from the soil is not very high. Water shortage can lead to an imbalance in the supply of nutrients, especially micronutrients, and exacerbate their deficiency.

3.3. Oil seed

Applying drought stress during the growing season reduced the seed oil content by 2% compared to full irrigation. However, the use of 10 and 20 t ha^{-1} of animal manure increased the seed oil content by 1% and 2%, respectively. This indicates that the soil conditions of the region were relatively poor, so the process of oil biosynthesis in the seed was limited. Among micronutrients, the greatest effect was achieved with the application of zinc nanostructure fertilizers. In this context, it has been reported that reduced soil moisture content reduced oil biosynthesis in cottonseed kernel during flowering. This is due to the inhibitory effects of drought stress on the expression and the activities of phosphoenolpyruvate carboxylase and diacylglycerol acyltransferase, which together reduce the oil content by reducing the photosynthetic carbon supply for the oil biosynthesis pathway (Li *et al*., 2022). In addition to the role of zinc as a cofactor in many enzymes of the oil biosynthesis pathway, zinc appears to play a very important role in regulating oil production by playing a structural role in zinc-finger proteins (Kong *et al*., 2020). The evaluation of oil yield showed that the highest oil yield was obtained under FI+FYM$_{20}$+Zn (631.49 kg ha^{-1}), and the oil yield also decreased with the decrease in the use of animal manure (Fig. 4).

Under full irrigation conditions, the effect of nanostructured zinc fertilizer on oil yield was more evident than that of iron. The lowest oil yield was recorded under DI+FYM$_0$+0 conditions (365.44 kg ha^{-1}). Applying deficit irrigation reduced oil yield by 25% compared to full irrigation conditions. The effect of animal manure application was much more evident than foliar application of micronutrients. These findings were consistent with previous results by Haghaninia et al. (2024) in the northwestern region of Iran, and the application of micronutrients significantly improved grain yield. However, plants use some adaptive mechanisms in conditions of soil moisture deficiency. Among them are changes in root morphology and hydraulic conductivity. In this context, the application of animal manures increases rooting depth, increases root density, and increases water retention capacity in the soil (Ankenbauer and Loheide, 2017).

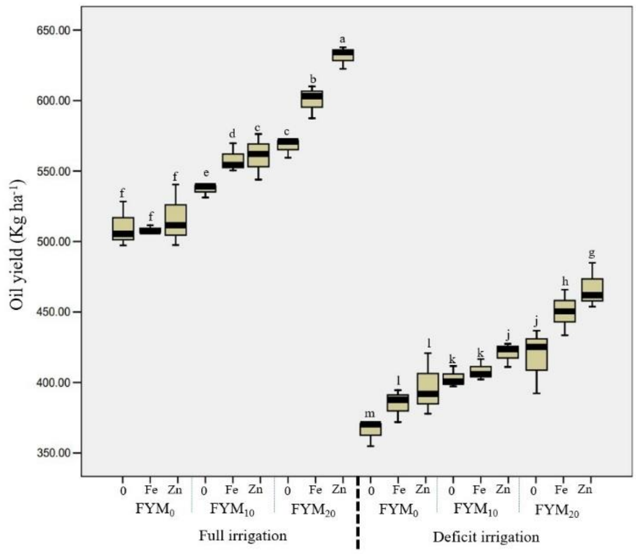

Figure 4. Yield of oil extracted from *C. sativa seeds* affected by deficit irrigation and application of animal manure and nanostructured iron and zinc fertilizers.

It seems that part of the better growth of camelina plants under FYM-applied conditions is due to these factors. However, plants may also reduce their photosynthesis rate by closing their stomata under water deficit conditions, and this in turn can affect the rate of nutrient absorption because nutrients enter the root system by the suction force caused by transpiration. In addition, under DI conditions, plants may allocate photoassimilable materials differently compared to FI conditions and prioritize the absorption of specific nutrients that are essential for survival (Hnilicka *et al*., 2023). The relationship between soil moisture and nutrient availability is a complex and dynamic interaction that can be influenced by other factors such as soil organic matter content and physical and chemical properties of the soil, ultimately affecting plant growth and development with different intensities. Soil moisture affects nutrient solubility, microbial activity, ion exchange, and root uptake. Understanding these interactions requires more detailed assessments of root systems and the rhizosphere environment. Amending soil properties with organic matter and carefully managing soil moisture by balancing the provision of adequate water for plant growth and increasing the availability of nutrients and micronutrients required for growth can improve grain yield as well as the allocation of photoassimilable materials to oil production in the grain.

3.4. Principal component analysis

The spatial distribution of traits based on the angles between them was used to estimate angular correlations through PCA (Fig. 5). The results showed that under the conditions studied, grain yield had small angles and positive and significant correlations with agronomic and morphological traits such as oil yield, siliquae number, chlorophyll content, lateral growth, biomass, and main stem height. These traits can be considered as biomarkers for evaluating grain yield. The difference in the angle of seed number per silique with other yield components is probably due to the compensatory relationship between yield components in *C. sativa*, so that with the application of manure and favorable irrigation conditions, the number of seeds per silique decreased with the increase in the number of siliquae per plant, due to the low source strength of for providing the requested photoassimilate for seed formation.

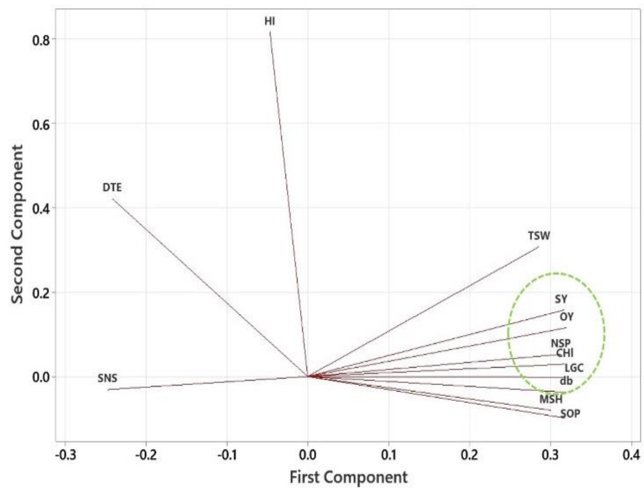

Figure 5. Principal component analysis (PCA) plot prepared with Statistica software to show the angular correlation between agronomic and morphological traits in *C. sativa* under different moisture conditions and application of animal and micronutrient fertilizers in the Bile Savar region of Iran. DTE: day to seedling emergence, MSH: main stem height, LGC: lateral growth of canopy, CHI: chlorophyll content, NSP: number of siliquae per plant, SNS: seed number per siliquae, TSW: thousand seed weight, DB: dry biomass, SY: Seed yield, HI: harvest index, SOP: seed oil percentage, OY: oil yield.

PCA plot divided the treatment combinations through the first and second components (Fig. 6). The results showed that the L component was able to separate the irrigation regimes well, so FI was located far from DI in terms of location and distribution. The second component focused on separating the manure levels and was able to separate FYM20 from the rest of the manure application levels well. Under optimal moisture conditions, the best effect was achieved with the application of FYM20 and zinc nano fertilizers. However, under deficit irrigation conditions, the manure factor had a greater effect compared to micronutrient fertilizers, and the effect of nanostructured micronutrient fertilizers was not very evident.

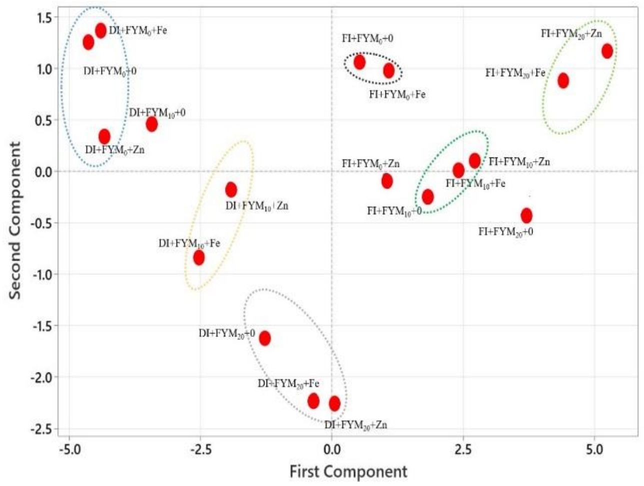

Figure 6. Principal component analysis to show the distribution of combined treatment. Combinations that are close together have relatively similar effects on the evaluated agronomic traits of *C. sativa* grown in the Bile Savar region of Iran. FI: full irrigation, DI: deficit irrigation during the vegetative growth stages. FYM$_0$, FYM$_{10}$, and FYM$_{20}$: application of 0, 10, and 20 t ha^{-1} animal manure, micronutrient $_0$: no use of micronutrient fertilizer, nano-Zn, and nano-Fen: foliar application of nano-structured zinc or iron fertilizers during stem elongation.

4. Conclusion

The results indicated that in the Bile Savar region of Ardabil, due to the low elevation of the open water, the temperature was relatively high during the spring months and sometimes faced hot and dry periods. Therefore, deficit irrigation for spring camelina during the growing season could not be considered a suitable solution for water saving and reduced the yield by about 25%. Due to the relatively high temperature of the region, the potential evapotranspiration was about 810 mm. Therefore, the deficit irrigation of about 400 mm could not adequately meet the water needs of the plant. Soil texture and low water retention capacity in the soil of the region could also be other possible reasons. The high rate of evapotranspiration and poor soil conditions in the studied area could be among the reasons for the failure of deficit irrigation. The use of animal manure, especially at high levels (20 t ha^{-1}), was able to somewhat reduce the destructive effects of deficit irrigation. However, due to the high rate of water loss through evaporation and transpiration in the region, the short-term effects of manure application were not able to mitigate the effects of irrigation deficit. It is possible that the long-term effect of manure application could have a positive effect by improving the water-holding capacity of the soil. Soil analysis results indicated a severe deficiency of micronutrients. Nanostructured micronutrient fertilizers were able to improve growth and yield characteristics. However, the positive and improving effect of micronutrients was more pronounced in plants fed with manure. The application of manure, by improving soil conditions and meeting some of the plant's nutritional needs, paved the way for a better effect of micronutrients. The highest grain and oil yields were achieved under full irrigation conditions with the application of high levels of animal manure and zinc foliar application. According to the findings of this experiment, winter cultivation of *C. sativa* can be economically preferable to other plants due to the greater synchronization of growth stages with rainfall and reduced irrigation requirements. The impact of long-term use of livestock manure with milder deficit irrigation (70% FC) and application of micronutrient fertilizers to the soil can be evaluated in the future.

Conflict of interests

The authors have no conflicts of interest to declare.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors hereby provide consent for the publication of the manuscript.

Availability of data and material

The authors confirm that the data supporting the findings of this study are available within the article.

Authors' contributions

Conception and design; Mohsen Janmohammadi (MJ); Acquisition of data: Abbas Mohsenpour (AM); Analysis and interpretation of data: Naser Sabaghnia (NS), MJ; Drafting of the manuscript: MJ; Critical revision of the manuscript for important intellectual content: MJ; Statistical analysis: NS; Obtaining funding: MJ, Fariborz Shekari (FS); Administrative, technical, or material support: AM, FS; Supervision: NS, FS.

Informed consent

The authors declare not to use any patients in this research.

Funding/Support

This study was supported by the University of Maragheh, Maragheh, Iran.

Acknowledgement

This article was achieved based on the material and equipment of Department of Plant Production and Genetics, Faculty of Agriculture, University of Maragheh, that the authors thanks it.

References

Agarwal A., Prakash O., Bala M. 2021. *Camelina sativa*, a short gestation oilseed crop with biofuel potential: Opportunities for Indian scenario. Oil Crop Science 6(3): 114-121. https://doi.org/10.1016/j.ocsci.2021.07.001

Ankenbauer K.J., Loheide S.P. 2017. The effects of soil organic matter on soil water retention and plant water use in a meadow of the Sierra Nevada, CA. Hydrological Processes 31(4): 891-901. https://doi.org/10.1002/hyp.11070

Baranian Kabir E., Bashari H., Mosaddeghi M.R., Bassiri M. 2017. Soil aggregate stability and organic matter as affected by land-use change in central Iran. Archives of Agronomy and Soil Science 63(13): 1823-1837. https://doi.org/10.1080/03650340.2017.1308492

Chenchouni H., Neffar S. 2022. Soil organic carbon stock in arid and semi-arid steppe rangelands of North Africa. Catena 211: 106004. https://doi.org/10.1016/j.catena.2021.106004

Dhaliwal S.S., Naresh R.K., Mandal A., Singh R., Dhaliwal M.K. 2019. Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. Environmental and Sustainability Indicators 1-2: 100007. https://doi.org/10.1016/j.indic.2019.100007

Ding B., Bai Y., Guo S., He Z., Wang B., Liu H., Zhai J., Cao H. 2023. Effect of irrigation water salinity on soil characteristics and microbial communities in cotton fields in southern Xinjiang, China. Agronomy 13(7): 1679. https://doi.org/10.3390/agronomy13071679

Fattahi M., Janmohammadi M., Abasi A., Sabaghnia N. 2023. The Effects of farmyard manure and nitrogen fertilizer on the performance of safflower. Agrotechniques in Industrial Crops 3(4): 162-169. https://doi.org/10.22126/ATIC.2023.9604.1114

Furtak K., Wolińska A. 2023. The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture –A review. Catena 231: 107378. https://doi.org/10.1016/j.catena.2023.107378

Gupta A., Rayeen F., Mishra R., Tripathi M., Pathak N. 2023. Nanotechnology applications in sustainable agriculture: An emerging eco-friendly approach. Plant Nano Biology 4: 100033. https://doi.org/10.1016/j.plana.2023.100033

Haghaninia M., Javanmard A., Kahrizi D., Bahadori M.B., Machiani M.A. 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: 100374. https://doi.org/10.1016/j.stress.2024.100374

Haq E., Hassan F., Iqbaal M., Ahmed M., Ghffar S., Ahmed J., Ahmed R., Shahbaz M., Rehman A., Hamzah A. 2022. Effects of micronutrients (boron and zinc) as foliar application on growth and yield of *Camelina sativa* L. Plant Cell Biotechnology and Molecular Biology 23(33-34): 1-11. https://doi.org/10.56557/PCBMB/2022/v23i33-347809

Hasanuzzaman M.D., Shabala L., Brodribb T.J., Zhou M., Shabala S. 2016. Assessing the suitability of various screening methods as a proxy for drought tolerance in barley. Functional Plant Biology 44(2): 253-266. https://doi.org/10.1071/FP16263

Hazrati S., Rostami N., Mohammadi H., Ebadi M.T. 2024. Improving the growth parameters, yield, and oil quality of camelina in rainfed farming due to the combined use of biochar and supplementary irrigation. Journal of Agriculture and Food Research 16: 101160. https://doi.org/10.1016/j.jafr.2024.101160

Hnilicka F., Lysytskyi S., Rygl T., Hnilickova H., Pecka J. 2023. Effect of short-term water deficit on some physiological properties of wheat (*Triticum aestivum* L.) with different spike morphotypes. Agronomy 13(12): 2892. https://doi.org/10.3390/agronomy13122892

Hunsaker D.J., French A.N., Thorp K.R. 2013. Camelina water use and seed yield response to irrigation scheduling in an arid environment. Irrigation Science 31: 911-929. https://doi.org/10.1007/s00271-012-0368-7

Janmohammadi M., Abdoli H., Sabaghnia N., Esmailpour M., Aghaei A. 2018. The effect of iron, zinc and organic fertilizer on yield of chickpea (*Cicer artietinum* L.) in Mediterranean climate. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 66(1): 49-60. https://doi.org/10.11118/actaun201866010049

Khemmouli A., Houria C., Abderrahmane H., Samir M., Azzdine C., Fouad R. 2023. Monitoring of limited water supply on oilseed crop (*Camelina sativa* L. Crantz) under semi-arid environment in the Algerian aures region. Sustainable Development 13(2): 389-406. https://doi.org/10.31924/nrsd.v13i2.142

Kong Q., Yang Y., Guo L., Yuan L., Ma W. 2020. Molecular basis of plant oil biosynthesis: Insights gained from studying the WRINKLED1 transcription factor. Frontiers in Plant Science 11: 24. https://doi.org/10.3389/fpls.2020.00024

Li Y., Hu W., Setter T.L., He J., Zou J., Zhu H., Zheng G., Zhao W., Wang Y., Chen B., Meng Y., Wang S., Zhou Z. 2022. Soil drought decreases oil synthesis and increases protein synthesis in cottonseed kernel during the flowering and boll formation of cotton. Environmental and Experimental Botany 201: 104964. https://doi.org/10.1016/j.envexpbot.2022.104964

Martinez S., Gabriel J.L., Alvarez S., Capuano A., Delgado M.D.M. 2021. Integral assessment of organic fertilization on a *Camelina sativa* rotation under Mediterranean conditions. Agriculture 11(4): 355. https://doi.org/10.3390/agriculture11040355

Moreno-Jiménez E., Plaza C., Saiz H., Manzano R., Flagmeier M., Maestre F.T. 2019. Aridity and reduced soil micronutrient availability in global drylands. Nature Sustainability 2(5): 371-377. https://doi.org/10.1038/s41893-019-0262-x

Nouraein M., Skataric G., Spalevic V., Dudic B., Gregus M. 2019. Short-term effects of tillage intensity and fertilization on sunflower yield, achene quality, and soil physicochemical properties under semi-arid conditions. Applied Sciences 9(24): 5482. https://doi.org/10.3390/app9245482

Pavlista A.D., Hergert G.W., Margheim J.M., Isbell T.A. 2016. Growth of spring camelina (*Camelina sativa*) under deficit irrigation in Western Nebraska. Industrial Crops and Products 83: 118-123. https://doi.org/10.1016/j.indcrop.2015.12.017

Rostami Ahmadvandi H., Zeinodini A., Ghobadi R., Gore M. 2021. Benefits of adding camelina to rainfed crop rotation in Iran: A crop with high drought tolerance. Agrotechniques in Industrial Crops 1(2): 91-96. https://doi.org/10.22126/ATIC.2021.6410.1007

Saeed F.H., Al-Khafaji M.S., Al-Faraj F.A.M. 2021. Sensitivity of irrigation water requirement to climate change in arid and semi-arid regions towards sustainable management of water resources. Sustainability 13(24): 13608. https://doi.org/10.3390/su132413608

Singh V.K., Malhi G.S., Kaur M., Singh G., Jatav H.S. 2022. Use of organic soil amendments for improving soil ecosystem health and crop productivity. Ecosystem Services (pp. 259-277). Nova Science Publishers, Inc. https://doi.org/10.52305/PFZA6988

Sosnowski J., Truba M., Vasileva V. 2023. The impact of auxin and cytokinin on the growth and development of selected crops. Agriculture 13(3): 724. https://doi.org/10.3390/agriculture13030724

Yadav N., Garg V.K., Chhillar A.K., Rana J.S. 2023. Recent advances in nanotechnology for the improvement of conventional agricultural systems: A review. Plant Nano Biology 4: 100032. https://doi.org/10.1016/j.plana.2023.100032

Yang X., Lu M., Wang Y., Wang Y., Liu Z., Chen S. 2021. Response mechanism of plants to drought stress. Horticulturae 7(3): 50. https://doi.org/10.3390/horticulturae7030050

Yu J., Jiang M., Guo C. 2019. Crop pollen development under drought: from the phenotype to the mechanism. International Journal of Molecular Sciences 20(7): 1550. https://doi.org/10.3390/ijms20071550

Zanetti F., Alberghini B., Marjanović Jeromela A., Grahovac N., Rajković D., Kiprovski B., Monti A. 2021. Camelina, an ancient oilseed crop actively contributing to the rural renaissance in Europe. A review. Agronomy for Sustainable Development 41: 2. https://doi.org/10.1007/s13593-020-00663-y

Zanetti F., Eynck C., Christou M., Krzyżaniak M., Righini D., Alexopoulou E., Stolarski M.J., Van Loo E.N., Puttick D., Monti A. 2017. Agronomic performance and seed quality attributes of camelina (*Camelina sativa* L. Crantz) in multi-environment trials across Europe and Canada. Industrial Crops and Products 107: 602-608. https://doi.org/10.1016/j.indcrop.2017.06.022

Zanetti F., Peroni P., Pagani E., von Cossel M., Greiner B.E., Krzyżaniak M., Stolarski M.J., Lewandowski I., Alexopoulou E., Stefanoni W., Pari L., Facciolla E., Monti A. 2024. The opportunities and potential of camelina in marginal land in Europe. Industrial Crops and Products 211: 118224. https://doi.org/10.1016/j.indcrop.2024.118224

HOW TO CITE THIS ARTICLE

Mohsenpour A., Janmohammadi M., Shekari F., Sabaghnia N. 202x. Assessment of *Camelina sativa* Performance under Deficit Irrigation with Application of Animal Manure and Micronutrients Nano-Fertilizers. *Agrotechniques in Industrial Crops* x(x): xx-xx. 10.22126/ATIC.2025.11812.1198