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Exogenous Application of Growth-Stimulating Substances Alleviated the Effects of Water-Deficit Stress on the Spring *Camelina sativa*

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ABSTRACT

A field experiment aimed to evaluate the agronomic characteristics of the spring camellia plant in different soil moisture conditions (100% FC or well-watered and 50% FC or water-deficit stress) and foliar spraying with ascorbic acid (concentration of 10 and 20 mM) and salicylic acid (0.6 and 1.2 mM) in the semi-arid region of Maragheh in the northwest of Iran (47°53′ E, 37°93′ N; 1682 m above sea level). The results showed that water shortage stress caused a significant decrease in plant height (13%), canopy width (43%), seed yield (22%), number of days to maturity (13%), and number of siliques plan^{-1} (44%). However, external application of high concentrations of ascorbic acid and to some extent salicylic acid could improve vegetative growth in both irrigation conditions. The highest number of days to maturity (128 days) was recorded with the application of 1.2 mM salicylic acid solution under well-watered conditions. Foliar application of ascorbic acid under water-deficit stress conditions improved the chlorophyll content by 28% compared to the control (S0: spraying with distilled water). Foliar spraying with 10 mM ascorbic acid could increase the number of seeds silique^{-1} under both water-deficit stress (58%) and well-watered (36%) conditions when compared with control. The highest seed yield was obtained with foliar spraying of 20 mM ascorbic acid under well-watered conditions. This foliar treatment could improve the seed yield by 13% under well-watered conditions and 16% in water-deficit conditions compared to the control. Under water shortage conditions, high concentrations of ascorbic acid and to some extent, salicylic acid can alleviate the effects of drought stress. The results showed that the exogenous application of 10 mM ascorbic acid was very efficient under well-watered conditions. However, spray of growth-stimulating substances was able to alleviate the destructive effects of drought stress to some extent.

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1. Introduction

Camelina sativa L., also called gold-of-pleasure, false flax, or linseed dodder, is an unexplored oilseed crop belonging to the Brassicaceae family that has been cultivated since 4000 years before the Common Era (Berti *et al*., 2016). Historical review has shown that camelina was grown as an agricultural crop in European countries and Russia before the Second World War and up to the fifties (Waraich *et al*., 2020a). America, Canada, Slovenia, Ukraine, China, Finland, Germany, Austria, and New Zealand are the main producers of camelina (FAOSTAT, 2024). However, the official statistics regarding its production and cultivated area are not yet available. Due to potential of *C. sativa* for novel food, feed, and biofuel products also due to its adaptation to cultivation in cool, temperate regions with a short growing season (~80 days) and has relatively few reported insect or disease problems it can be included in crop rotations (Zhang and Auer, 2020). This plant is well adapted to cold semi-arid climates and its origin seems to be Southeast Europe, Southwest Asia, and Turkey (Larsson, 2013). However, due to the insufficient information regarding the agricultural management of this crop, including planting time, density, distance between rows, application of fertilizers, compatibility of its genotypes with different

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climates, and the uncertainty of its response to different moisture conditions and irrigation treatments, it has not been accompanied by much acceptance from the farmers for the development of its cultivation (Matteo *et al*., 2020). Camelina seeds contain 30-40% oil, and most of it includes unsaturated fatty acids such as linolenic acid (up to 40%), linoleic acid (up to 25%), and 15% oleic acid (Waraich *et al*., 2020a). On the other hand, due to the presence of health-improving substances in camelina oil, such as α-linolenic acid (omega-3), tocopherols, and other antioxidants, the quality of the oil extracted from this plant has a high nutritional value compared to other oilseed plants (Ibrahim and El Habbasha, 2015).

The major part of Iran has a semi-arid climate where plants are adversely affected by various limitations such as low precipitation, scattered and unpredictable rainfall, the predominant occurrence of precipitation during the cold months of the year (when the plant is in the inactive growth phase of the rosette), low winter temperature in high areas, lack of essential nutrients in the soil or their inaccessibility in the rhizosphere environment, low soil organic matter, high soil pH, long periods of dry and low rainfall during the spring season (Modarres and da Silva, 2007; Janmohammadi and Sabaghnia, 2023; Fattahi *et al*., 2023; Janmohammadi *et al*., 2024). Although some researchers have investigated the effects of water deficit on camelina plants and the results obtained indicate a significant decrease in the vegetative growth, seed yield, and oil quality (Borzoo *et al*., 2021; Bukhari *et al*., 2022; Hazrati *et al*., 2024), it still seems that by applying some precise agronomic management, this plant can be a suitable option for the development of cultivation in relatively susceptible rainfed areas in the west of Iran (Kahrizi *et al*., 2015). Despite the numerous benefits of *C. sativa* under current situation and its potential for future uses in semi-arid regions, the cultivation of this plant is still not very significant in Iran due to the weaknesses of promotion, and it is necessary to intensify efforts to develop its cultivation.

The results obtained by the researchers indicate that by using some agronomic management such as foliar spraying with natural alleviators of drought stress, the destructive effects of water-deficit stress can be alleviated (Askari and Ehsanzadeh, 2015; Bukhari *et al*., 2022). Drought stress often causes secondary oxidative stress and the production of reactive oxygen species (H_2O_2, superoxide radical, $^{\bullet}OH$, and singlet oxygen) during photosynthesis and in some other physiological pathways (Sachdev *et al*., 2021). However, plants can reduce the accumulation of reactive oxygen species through some enzymatic and non-enzymatic antioxidants such as ascorbic acid, proline, glutathione, carotenoids, etc. (Mishra *et al*., 2023). Hormone-like substances such as acid ascorbic and acid salicylic were found to play important roles in different processes throughout plant development. Recent studies indicate that, beyond their roles in stimulating internal defense systems, altering the ratios of other phytohormones, modulating root architecture, and promoting leaf senescence (Zahid *et al*., 2023), these substances may also function as positive regulators in plant responses to abiotic stresses, including drought. Foliar spray of hormone-like substances in semi-arid areas can improve growth characteristics and crop yield (Estaji and Niknam, 2020).

Salicylic acid as a hormone-like plays a central role in seed germination, seedling establishment, growth regulation, regulating and stimulating the activity of antioxidant enzymes, signaling, biosynthesis of chlorophyll and proteins, transpiration, photosynthesis, absorption of nutrients and nodule formation in roots (Lee *et al*., 2010). The increase in the internal concentration of salicylic acid in plants under environmental stress indicates the possibility of influencing the external application of this hormone-like substance as a foliar spray (Yang *et al*., 2023). The external application of salicylic acid in *Ammi visnaga* L. under drought stress conditions increased the scavenging capacity of reactive oxygen species and increased the yield and quality (Osama *et al*., 2019). Also, the exogenous application of ascorbic acid as a small water-soluble molecule with antioxidant properties under water-deficit stress conditions could increase the growth and yield of corn (Ghassemi *et al*., 2020), quinoa (Hosseini *et al*., 2021) and wheat (Hussein and Khursheed, 2014) by stimulating the defense systems and reducing the accumulation of hydrogen peroxide. However, there is still no comprehensive and sufficient information about the effect of the external use of hormone-like compounds on the camelina plant. The purpose of this experiment was to investigate the effect of different concentrations of ascorbic acid and salicylic acid on the agronomic and morphophysiological characteristics of camelina under water stress conditions in the semi-arid region of Maragheh in the northwest of Iran.

2. Materials and methods

2.1. Climatic and soil characteristics of the studied area

A field experiment was conducted during 2023-2024 in the Maragheh region (37° 23'N; 46° 16'E) in the northwest of Iran. The height of the farm is 1480 meters above sea level. The climate of region is semi-arid-cold with an average rainfall of 312 mm. The soil of the studied area was silty loam (23% clay, 49% silt, and 28% sand) and has a pH of 7.82, organic matter content of 0.24%, total nitrogen content of 0.12%, calcium carbonate of 11%, electrical conductivity (EC) was 0.92 ds m^{-1}, phosphorus 11.31 mg kg^{-1}, and potassium 282 mg kg^{-1}. About 70% of the total precipitation occurs as snow during the cold months of the year. During the growing season, about 284 mm of rain fell during October to February. The weather conditions during the Camelina growing season are shown in Table 1.

Table 1. Some meteorological parameters in the Maragheh region during the Camelina growing season

	tmin	tmax	tm	ff_max	dd_max	ffm	sshn	umin	umax	um	nm	tr	evapo
March	2.18	14.24	7.80	7.58	190.65	3.54	6.65	34.06	76.26	54.39	4.29	89.8	52.3
April	9.35	24.15	16.29	7.13	183.67	3.43	8.64	16.53	54.43	34.90	3.77	49.2	10.3.7
May	13.83	29.12	21.26	6.87	140.32	3.66	10.08	14.97	48.16	30.46	2.68	14.7	174.1
June	18.83	35.55	27.21	7.53	130.67	4.34	12.47	4.37	20.17	11.40	0.62	4.5	234.6
July	21.23	36.35	28.26	8.23	130.32	5.04	12.20	10.06	38.19	23.29	1.10	0	270.2

Tmin: minimum air temperature, tmax: maximum air temperature, tm: average temperature, ff max: maximum wind speed, ddmax: maximum wind direction, sshn: sunny hours, ffm: wind speed, umin: minimum relative humidity, umax: maximum relative humidity, um: average relative humidity, tr: total rain, evapo: average evapotranspiration,

2.2. Implementation of experimental treatments

The field was left fallow during the previous cropping season. The primary tillage of the field was done during the autumn of 2023 with a moldboard plow and 10 t ha^{-1} of farm yard manure was used. In early March 2024, secondary tillage was done using a disc, *rotavator*, and leveler. Then, using a Hiller-Furrower, the top soil was made into a ridge and furrow. The distance between the ridges was 45 cm. Before planting seeds, 60 kg of phosphorus was consumed through triple super phosphate fertilizer and 100 kg of nitrogen through urea based on suggested dose. Cultivar Soheil was obtained from the Pakan seed company, Isfahan, and used for this experiment. In the middle of March, the farm was divided into main and sub-plots. The experimental design was a spilt-plot (2×5) based on a randomized complete block design with three replications. The main factor was different levels of irrigation (up to 100% FC or well-watered and up to 50% FC or water-deficit stress), and the second factor comprised foliar spraying with distilled water (as check or control), ascorbic acid with 10 and 20 mM concentrations and salicylic acid with 0.6 and 1.2 mM concentrations. Ascorbic acid and salicylic acid, 99% pure synthetic powder, were provided from Merck, Germany. Before planting, the *seeds were* surface *sterilized* and disinfected with Vitavax fungicide. Seeds were sown manually on the ridge with 5 cm intra-row spacing on March 18. The seed planting depth was 2 cm.

During foliar spraying, the amount of spraying was such that the whole plant was wet with the desired solution. Each experimental plot consisted of 9 planting rows with a length of 4 meters. After planting the seeds, all the main plots were irrigated up to 100% of the field capacity to accelerate germination and improve seedling establishment. The onset of drought stress was adopted from the beginning of the shoot stage (Martinelli and Galasso, 2011). The foliar treatments were repeated during main stem elongation, inflorescence emergence, mid-flowering, and fruit development. Irrigation was carried out through polyethylene pipes and a drip tape system. To prevent moisture leakage between the main plots or between the experimental repetitions, a one-meter border was considered uncultivated. The soil moisture content at the point of 100% of the field capacity was 31%. Soil moisture monitoring was done through time domain reflectometry (TDR). The Equation 1 is used to calculate the water required to reach the field capacity.

$$I = (FC \times \theta) \times SBD \times R \quad (1)$$

Where I is the irrigation depth (mm), FC is the target field capacity, ɵ is soil moisture content before irrigation, SBD is soil apparent density g cm^{-3}, and R is the depth of rooting (Hasanuzzaman *et al.*, 2017). The other agronomic management including fertilizer application, thinning, and weed control similarly were done for all plots.

2.3. Measurement of agronomic traits

Leaf chlorophyll was measured using a portable chlorophyll meter (SPAD 502, Konica Minolta, USA) at the early flowering stage. To record the days to maturity, the experimental plots were daily monitored. At the end of the growing season, with the appearance of signs of ripening and browning of siliques (nearly all siliques are ripe and the crop is ready to be harvested), ten plants were randomly selected from each plot, and traits such as plant height (from the soil surface to the highest point of the plant), canopy width, number of branches, number of siliques $plant^{-1}$, number of seeds $silique^{-1}$ were measured. To measure the above-ground biomass, using a $1m^2$ quadrate, the plants in the mentioned area were cut above the ground. After placing the harvested plants in an oven at a temperature of 70°C for 48 h, their dry weight was measured. Then, by threshing the dried plants and separating the seed from the straw, the seed yield per unit area was calculated. The harvest index was calculated from the ratio of seed yield to aboveground biomass.

2.4. Statistical analysis

Data collected were subjected to the proper statistical analysis of variance using the SAS 9.1 statistical package (SAS Institute Inc., Cary). Mean comparison carried out by LSD test at 5% level. Principal component analysis (PCA) and related statistics and graphs provided by Minitab software (version 19.2). Box plots were prepared using GenStat software.

3. Results and discussion

3.1. Vegetative growth components

The results of analysis of variance showed that the main effects of moisture regime and foliar spraying as well as the mutual effects of moisture regime × foliar spraying for plant height were statistically significant at the 1% level (Table 2). The maximum height recorded in the plants grown under optimal irrigation conditions (WW) and with foliar spraying of 10 mM ascorbic acid (72.33 cm) and 1.2 mM salicylic acid (68.20 cm). Water-deficit stress (DS) reduced plant height by 24% compared to WW conditions, and the shortest plants were observed under DS conditions without foliar application of regulators (control) or foliar spray with a low concentration of ascorbic acid. The evaluation of the canopy width indicated the main effects of moisture regime and foliar spraying on this component were statistically significant ($P \leq 0.01$). Water-deficit stress reduced this component by 42% compared to WW conditions. A comparison of the canopy width among the foliar treatment levels showed that spraying with high concentrations of ascorbic acid and foliar spraying with both concentrations of salicylic acid produced the highest canopy width (Table 2).

The evaluation of the number of branches in the plant also showed that the mutual effects of moisture regime × foliar spraying for this trait were statistically significant at the 1% level. The highest number of branches was obtained in WW conditions and with 20 mM ascorbic acid spray (16.74), and the lowest number of branches was recorded under DS conditions with foliar spray of distilled water (control). Water-deficit stress reduced the number of branches by about 40% compared to WW conditions. On the other hand, foliar spraying with high concentrations of ascorbic acid improved this trait by 38%. This trend was also visible for the above-ground biomass so the highest biomass was recorded in plants sprayed with low concentrations of salicylic acid (0.6 mM) and high concentrations of ascorbic acid (20 mM). The lowest biomass was recorded for plants grown under DS conditions without foliar application of growth regulators (Fig. 1).

Under DS conditions, the highest above-ground biomass was obtained by spraying high concentrations of salicylic acid, which was about 17% higher than plants sprayed with distilled water under the same moisture regime. The obtained results showed that soil moisture status affected the effectiveness of foliar spraying treatments, so under WW conditions, low concentrations of ascorbic acid, and under DS conditions, low concentrations of hormone-like substances had a greater effect on improving vegetative growth.

Table 2. Effect of foliar application of ascorbic acid and salicylic acid the morphological traits of *Camelina sativa* under well water and drought stress conditions in the northwest of Iran.

	PH	CW	BN	DM	NSI	SW	TSW	HI
Well-irrigated (W)	63.65^{a}	64.00^{a}	14.23^{a}	119.53^{a}	99.53^{a}	1.24^{a}	0.861^{a}	26.85^{a}
Drought stress (D)	48.53^{b}	37.06^{b}	8.48^{b}	103.80^{b}	53.60^{b}	0.89^{b}	0.770^{b}	25.85^{b}
S_0	46.95^{d}	45.93^{c}	9.57^{c}	104.33^{c}	65.66^{d}	0.913^{c}	0.786^{a}	27.42^{a}
S_1	57.61^{bc}	48.70^{bc}	11.02^{b}	112.66^{a}	71.16^{cd}	1.005^{b}	0.830^{a}	25.41^{b}
S_2	59.15^{ab}	54.00^{a}	13.17^{a}	114.00^{a}	78.00^{bc}	1.043^{b}	0.836^{a}	26.67^{a}
S_3	54.98^{c}	53.66^{a}	11.37^{b}	110.83^{b}	79.50^{b}	1.203^{a}	0.831^{a}	25.07^{b}
S_4	61.67^{a}	50.36^{ab}	11.62^{b}	114.00^{a}	88.50^{a}	1.195^{a}	0.811^{a}	26.48^{a}
WS_0	53.90^{c}	59.20^{c}	12.55^{c}	112.33^{d}	87.66^{c}	1.063^{d}	0.849^{abc}	28.22^{a}
WS_1	72.23^{a}	62.40^{bc}	14.05^{b}	123.00^{b}	95.66^{bc}	1.216^{b}	0.867^{ab}	24.97^{cde}
WS_2	61.69^{b}	66.00^{ab}	16.74^{a}	128.00^{a}	100.66^{b}	1.190^{bc}	0.911^{a}	24.54^{de}
WS_3	62.92^{b}	70.00^{a}	14.35^{b}	116.66^{c}	100.66^{b}	1.456^{a}	0.861^{abc}	23.11^{e}
WS_4	68.20^{a}	62.40^{bc}	13.45^{bc}	117.66^{c}	113.00^{a}	1.300^{b}	0.815^{bcd}	26.38^{b}
DS_0	40.00^{e}	32.66^{f}	6.60^{g}	96.33^{g}	43.66^{f}	0.763^{g}	0.722^{e}	26.61^{b}
DS_1	43.00^{e}	35.00^{f}	8.00^{f}	102.33^{f}	46.66^{ef}	0.793^{fg}	0.794^{cd}	25.86^{bcd}
DS_2	56.33^{c}	42.00^{d}	9.60^{de}	100.00^{f}	55.33^{de}	0.896^{ef}	0.761^{cd}	28.80^{a}
DS_3	48.00^{d}	37.33^{def}	8.40^{ef}	105.00^{e}	58.33^{d}	0.950^{e}	0.801^{bcd}	26.33^{bc}
DS_4	53.33^{c}	38.33^{de}	9.80^{d}	110.33^{d}	64.00^{d}	1.090^{cd}	0.807^{bcd}	26.07^{b}
				Significance level				
I	**	**	**	**	**	**	**	**
S	**	**	**	**	**	**	NS	**
I×S	**	NS	**	**	NS	**	NS	**
CV%	5.71	6.34	7.02	1.31	7.55	6.07	5.07	3.11

Abbreviation S_0: control or sprayed with distilled water, S_1: foliar spray with 0.6 mM salicylic acid, S_2: foliar spray with 1.2 mM salicylic acid, S_3: foliar spray with 10 mM ascorbic acid, S_4: foliar spray with 20 mM ascorbic acid, PH: the height of plant (cm), CW: canopy spread (cm), BN: number of the lateral branch plant^{-1}, DM: days to full maturity, NSI: number of siliques plant^{-1}, SW: weight of silique (g), TSW: thousand seed weight (g), HI: harvest index (%), W: well-watered during the growth season, D: drought stress by deficit irrigation from branching stage, CV: The coefficient of variation (%), At the significance level, p values less than *0.05* ($p<0.05$) and 0.01 ($p<0.01$) which were significant at 95% and 99%, showed by * and **, respectively. NS: not significant. The means with various letters in each trait (column) are statistically different.

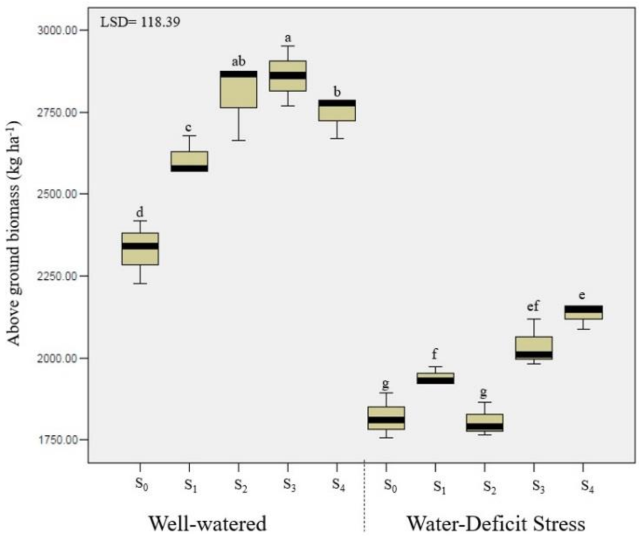

Figure 1. The response of above-ground biomass of spring camelina plant to irrigation regimes and foliar spraying treatments with ascorbic acid and salicylic acid in the Maragheh region. S_0: control or sprayed with distilled water, S_1: foliar spray with 0.6 mM salicylic acid, S_2: foliar spray with 1.2 mM salicylic acid, S_3: foliar spray with 10 mM ascorbic acid, S_4: foliar spray with 20 mM ascorbic acid.

Camelina is a relatively low-input crop, however, it appears that cultivation under water-deficit conditions has a negative impact on the productivity and oil quality of oil-seed crops (Chaturvedi *et al*., 2018), our results showed that drought stress caused by deficit irrigation from mid-vegetative stage caused a sharp decrease in vegetative growth characteristics. Considering the key role of water in growth by turgor pressure (cell acidic growth) and its important role in processes such as photosynthesis, the moisture regime of 50% FC could not adequately meet the plant's water requirement for the promotion of plant growth. One of the reasons for this can be the low precipitation during the active growing season, irregular distribution of rainfall, and insufficient storage of moisture in the soil due to unsuitable soil characteristics. Our findings were consistent with the results of Waraich et al. (2020b). These researchers reported that the reduction of water supply for camelina in the semi-arid region caused a significant decrease in plant height, leaf area index, and the number of lateral branches. Also, growth improvement with foliar spraying of hormone-like compounds can be attributed to facilitating the process of osmotic adjustment and the accumulation of small molecules such as free amino acids and helping to improve the state of cellular water (Askari and Ehsanzadeh, 2015).

3.2. chlorophyll content

The evaluation of leaf chlorophyll content showed that the mutual effects of moisture regime × foliar spraying were statistically significant at the 1% level. The highest chlorophyll content was recorded in plants grown under WW conditions with the foliar spray of 20 mM ascorbic acid. The spray of ascorbic acid increased the chlorophyll content by 33% compared to the foliar spray of distilled water under the same moisture regime. The lowest chlorophyll content (32.66 SPAD unit) was recorded in plants grown under DS conditions with foliar spraying of distilled water (Fig. 2). Under DS conditions, the highest chlorophyll content (52.33) was recorded in plants sprayed with 1.2 mM salicylic acid. The improving effect of hormone-like substances on chlorophyll content was more evident under DS conditions. The sharp decrease in chlorophyll content under drought stress conditions can be attributed to its increased decomposition (Hu *et al*., 2023). It seems that foliar spraying of 1.2 mM salicylic acid has stabilized photosynthetic pigments in drought-stress conditions by improving the internal conditions of the plant. This finding was consistent with previous results reported by Zahid et al. (2023).

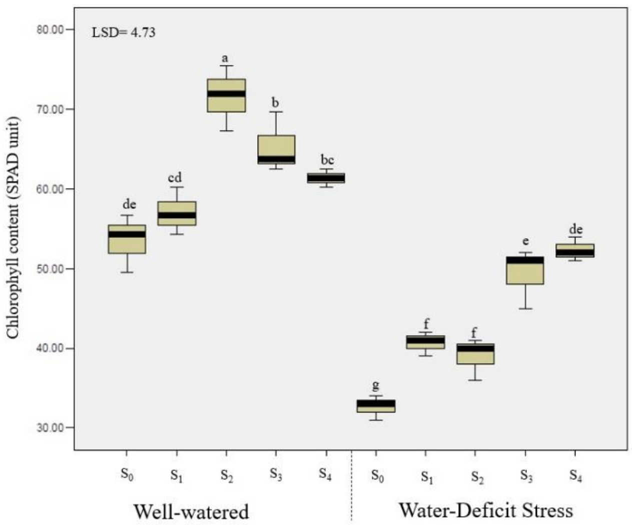

Figure 2. Investigating the amount of chlorophyll in the leaves of the spring camelina plant under different irrigation regimes with foliar spraying with different concentrations of salicylic acid and ascorbic acid in the Maragheh region. S_0: control or sprayed with distilled water, S_1: foliar spray with 0.6 mM salicylic acid, S_2: foliar spray with 1.2 mM salicylic acid, S_3: foliar spray with 10 mM ascorbic acid, S_4: foliar spray with 20 mM ascorbic acid. Boxes with the same letters do not have statistically significant differences at the 5% level.

3.3. Days to maturity

The results of the analysis of variance for days to maturity (DTM) indicated the significance of the mutual effects of moisture regime × foliar spraying on this phenological trait (P≤0.01). The comparison of means showed that the highest DTM was recorded for plants grown under WW conditions and with foliar spraying of high concentrations of ascorbic acid (Table 2). The earliest maturity was recorded for plants grown under DS conditions and with distilled water spray (96.3 days). The results showed that water-deficit stress reduced DTM by 15% compared to WW conditions. Foliar application of both concentrations of ascorbic acid and high concentrations of salicylic acid increased DTM more effectively. Acceleration in maturity under drought stress conditions is largely attributed to the changes in the ratio of phytohormones and especially the increase in abscisic acid (Waadt *et al*., 2022). It seems that the external application of salicylic acid and ascorbic acid, by affecting plant hormones and also optimizing the internal conditions of the cells, increases the growth period of the plant and delays the maturity (Hosseini *et al*., 2021).

3.4. Seed yield component

Silique number per plant was affected by the main effects of foliar spraying and moisture regime (P≤0.01). Water-deficit stress caused a 44% decrease in silique number compared to WW conditions. However, the spray of solutions with a high concentration of salicylic acid increased the silique number by about 35% compared to the control (Table 2). The highest silique number was recorded in plants grown under WW conditions with high concentrations of salicylic acid (113) and the lowest number was recorded for plants grown under DS conditions with distilled water spray (43.66).

The evaluation of silique weight indicated the presence of significant moisture regime × foliar spraying interaction effects on this component (P≤0.01). The lowest silique weight was recorded under DS conditions with distilled water spray (0.763 g) and the highest silique weight was recorded under WW conditions with 0.6 mM (1.45 g) salicylic acid spray. The improving effect of both concentrations of salicylic acid on this component was greater than that of ascorbic acid (Table 2).

The evaluation of the number of seeds silique^{-1} (NSS) showed that the main effects of moisture regime and foliar spraying on this component were statistically significant at the level of 1%. NSS under well-watered and water-deficit conditions was 11.5 and 7.68, respectively. The comparison of average NSS in the levels of foliar spraying treatments showed that the application of 0.6 mM salicylic acid resulted in the highest number of seeds silique^{-1} (11.48) and the application of 1.2 mM salicylic acid (10.58) and Ascorbic 20 mM (9.50) was in the next position. The lowest NSS (7.77) was recorded for plants grown under DS conditions without spraying growth regulators (Fig. 3). Evaluation of thousand seed weights showed that the effect of moisture regimes was statistically significant (P≤0.01). Drought stress caused an 11% decrease in thousand seed weight compared to plants grown in WW conditions.

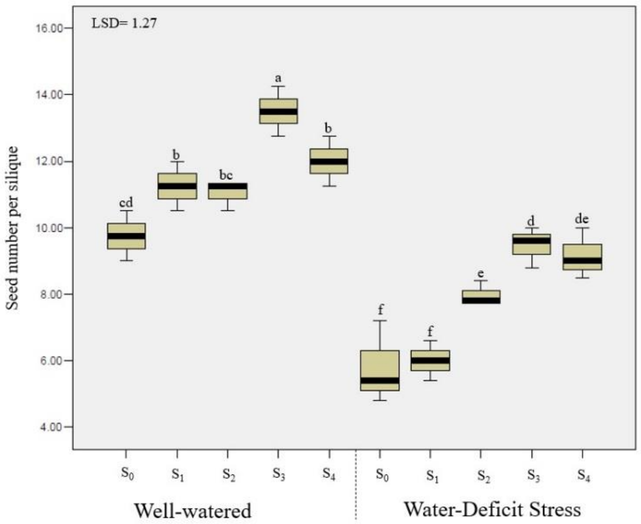

Figure 3. Mean comparison of seed number per silique in spring camelina plant under different conditions of irrigation and foliar spraying with ascorbic acid and salicylic acid in the Maragheh region in the North East of Iran. S_0: control or sprayed with distilled water, S_1: foliar spray with 0.6 mM salicylic acid, S_2: foliar spray with 1.2 mM salicylic acid, S_3: foliar spray with 10 mM ascorbic acid, S_4: foliar spray with 20 mM ascorbic acid.

The results showed that moisture regime × foliar spraying interaction effects on seed yield were statistically significant at 5%. The highest seed yield (723 kg ha^{-1}) was obtained under well-watered conditions and foliar spraying of 1.2 mM salicylic acid. Foliar application of ascorbic acid 20 mM with 686 kg ha^{-1}, and spray of salicylic acid 0.6 mM under WW conditions with 686 kg ha^{-1} seed yield were in the next place (Fig. 4). Under DS conditions, the highest seed yield was obtained with the foliar application of salicylic acid 1.2 mM (565 kg ha^{-1}), and the lowest yield (483 kg ha^{-1}) was recorded for plants grown without the use of growth regulators (sprayed with distilled water).

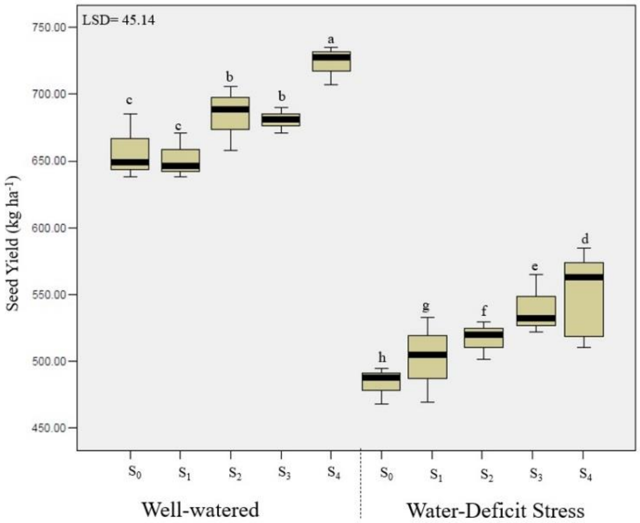

Figure 4. Mean comparison of seed yield in spring camelina plant under different conditions of irrigation and foliar spraying with ascorbic acid and salicylic acid in the Maragheh region in the North East of Iran. S_0: control or sprayed with distilled water, S_1: foliar spray with 0.6 mM salicylic acid, S_2: foliar spray with 1.2 mM salicylic acid, S_3: foliar spray with 10 mM ascorbic acid, S_4: foliar spray with 20 mM ascorbic acid.

Principal component analysis (PCA) for treatment combinations is shown in Fig. 5. The first component was able to distinguish the humidity regimes from each other. According to the time of applying drought stress and its drastic reduction effect on most of the investigated traits, the separation of irrigation levels has been facilitated by this analysis. On the other hand, the second component was able to separate the foliar spray treatments in terms of effectiveness in different humidity regimes. The highest improvement effect in WW conditions was recorded with foliar spraying of both concentrations of ascorbic acid (10 and 20 mM) and the low concentration of salicylic acid (0.6 mM). While under drought stress, salicylic acid had a better effect.The graphical analysis of the correlation between the evaluated traits using the trait vectors is shown in Fig. 6. Seed yield showed the most positive correlation (presented angles between traits) with the number of siliques plant^{-1}, seed number per silique, number of branches, canopy width, and plant height. This indicates that both vegetative growth traits and yield components play a significant role in determining seed yield.

Although there is not much information about the partitioning of photo-assimilates between the source and sink organs in the camelina plant, the results of the present experiment showed that the water-deficit stress from the middle of the vegetative growth period affected both the source (vegetative characteristics such as plant height, canopy width, chlorophyll content, branch number) and the sink (number of the silique, number of the seed per silique, silique weight). The obtained results showed that the effect of continuous water-deficit stress on yield components was much more evident than vegetative growth. The stages of flowering stage and seed-filling stage in the camelina in semi-arid regions were highly sensitive to drought stress, and supplemental irrigation in the mentioned stages in rain-fed cultivation caused a significant increase in seed yield (Hazrati *et al*., 2024). Although, silique shell and rachis are more important source organs for photosynthetic carbon supply to grains than the upper leaves, and they can sustain grain filling in necessity (Fujita *et al*., 2014), in the current study, despite the foliar sprays, the yield loss was not compensated. However, it seems that the application of high concentrations of ascorbic acid and low concentrations of salicylic acid increased the vegetative growth to some extent by improving the internal condition of the plant and possibly stimulating the defense systems. The present experiment to some extent indicated the greater effect of drought stress on the limitation of the sink.

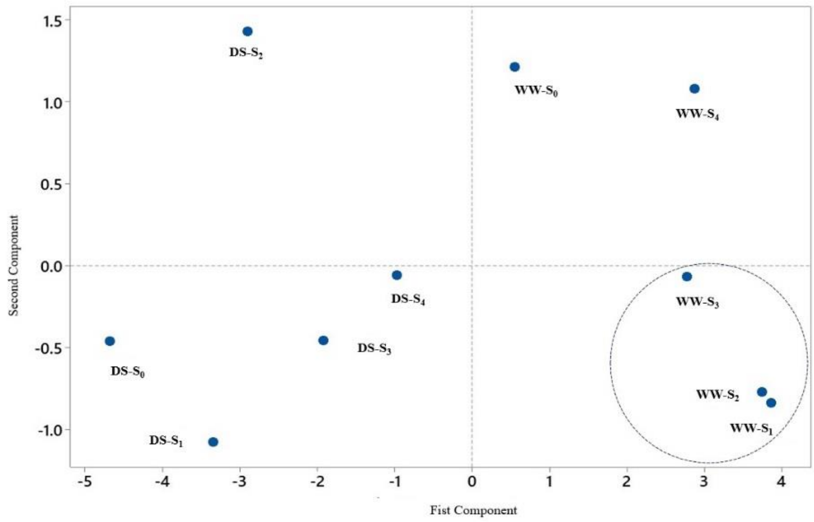

Figure 5. Principal component analysis (PCA) showing a plot of the first two PCs for all combined treatments (irrigation regimes and foliar spray treatment) on spring camelina grown in the Maragheh region. WW: well-watered condition, DS: water-deficit stress. S_0: control or sprayed with distilled water, S_1: foliar spray with 0.6 mM salicylic acid, S_2: foliar spray with 1.2 mM salicylic acid, S_3: foliar spray with 10 mM ascorbic acid, S_4: foliar spray with 20 mM ascorbic acid.

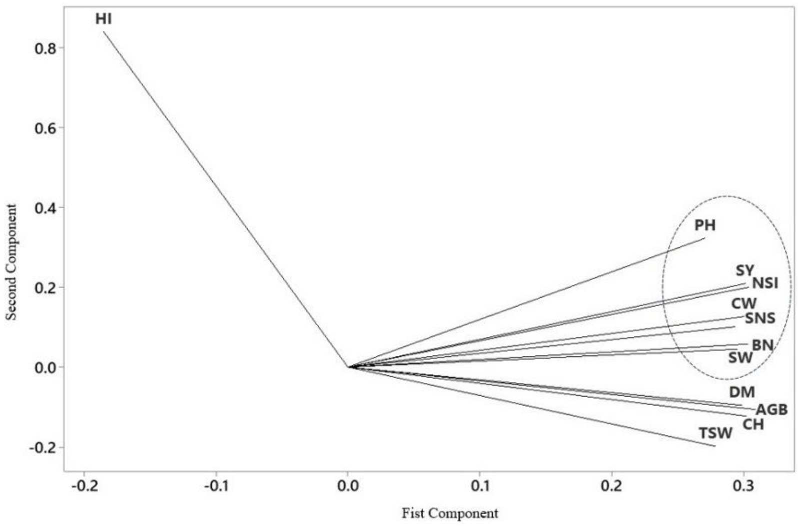

Figure 6. The plot of the first two PCAs showing the relation among various agronomical traits of spring camalina (*Camelina sativa*) grown under different irrigation regimes and foliar spray treatment. HI: harvest index, PH: plant height, SY: seed yield, NSI: number of siliques plant^{-1}, CW: canopy width, SNS: seed number per silique, BN: branch number per plant, SW: weight of silique, DM: days to maturity, AGB: above-ground biomass, CH: chlorophyll content (SPAD), TSW: thousand seed weight. Angles between traits show their correlation with each other.

4. Conclusion

The obtained results showed that water-deficit stress (Irrigation water supply up to 50% FC) from the initial stages of branching significantly reduced both vegetative growth and yield components. The spray of 20 Mm ascorbic acid and in some cases, salicylic acid was able to alleviate the negative effects of water-deficit stress to some extent. However, Due to insufficient rainfall and severe water shortage in the soil under water deficit-stress conditions, the decline of vegetative growth components and grain yield was still evident. Altogether, foliar sprays of 20 mM ascorbic acid were also effective treatments under both well-watered and water-deficit conditions. Foliar spray of of 20 mM ascorbic acid increased the seed yield by about 100 kg ha^{-1}. In future investigations, the internal influence of natural alleviators can be evaluated in winter camelina plants under mild to moderate water-deficit stress.

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: Mohadeseh Eskandarzadeh (ME), Nooshin Kheshtpaz (NK); 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; Administrative, technical, or material support: MJ, ME, NK; Supervision: NS, MJ.

Informed consent

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

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