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ORIGINAL PAPER

Enhancing canola yield and quality through nitrogen and sulfur fertilization: an analysis of cultivar traits and grain elements*

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Abstract

Canola cultivation is highly dependent on nutritional management. This study was conducted in 2016-2017 and 2017-2018, as a factorial experiment with three factors, based on a randomized block design. The experiment was established in the Shast-Kalate region of Gorgan city, Iran. The experimental treatments included nitrogen (N) application (25, 50, 75, and 100 kg ha^{-1}), sulfur (S) fertilization (0 and 200 kg ha^{-1}), and three canola cultivars (Hyola 50 hybrid, Hyola 401 and ARGS 003). The results revealed that the highest grain yield (2701 kg ha^{-1}) was obtained with 100 kg ha^{-1} of N + 200 kg ha^{-1} of S fertilization applied to the Hyola 50 variety in the second year (Y). Conversely, the lowest seed yield was harvested in the same year from ARGS 003 and Hyola 401 cultivars (1577 and 1580 kg ha^{-1}, respectively) with 25 kg ha^{-1} of N and without S fertilization. Besides, Hyola 50 and Hyola 401 cultivars produced higher grain yields than ARGS 003 cultivar. Notably, the grain yield increased at higher N concentrations. The results showed that cv. ARGS 003 contained a higher seed oil percentage than Hyola 50 and Hyola 401 cultivars. Furthermore, an increased percentage of seed oil was observed at higher N fertilizer application. The seed oil percentage of rapeseed cultivars increased with the S fertilizer treatment. Furthermore, increasing the dose of nitrogen from 25 to 50 kg ha^{-1} in both years enhanced N percentage, whereas exceeding than the latter amount decreased the seed N content. Overall, it can be concluded that N and S play an essential role in enhancing the quality performance of canola cultivars.

Keywords: canola, seed elements, oil yield, protein yield, saturated fatty acids

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INTRODUCTION

Oilseeds are a superior source of calories and energy for humans, as well as a valuable source of nutritional value. Canola (*Brassica napus* L.), one of the most important oilseeds, is planted over a wide area of farmland in Iran (Ezati et al. 2020). Various factors, such as the weather conditions, plant variety, soil type, cultivation methods, and genetic traits, determine plant growth and thus also seed yield (Ezati et al. 2020). In addition, the management of plant nutrition is another key factor in the growth and production of crops (Karami et al. 2018). For instance, N can be considered a vital nutritional element for plant growth, development and yield, hence its deficiency drastically limits crop production (Taheri et al. 2021). N contributes mainly to the formation of chlorophyll, amino acids, and vitamins. When a sufficient amount of N is available to the plant, it increases the growth rate of the plant and the storage of seed proteins (Fathi, Zeidali 2021).

The best way to improve the efficiency of N fertilization of canola is to apply a nutrient balance approach that takes into account the synergistic and antagonistic interactions between macro- and micronutrients in soils and plants (Ma et al. 2019). When plant growth is limited by an excess or deficiency of another nutrient, focusing on plant response to N fertilizer inputs alone is unlikely to improve N fertilizer use efficiency. The phenomenon of concealed nutrient deprivation emerges as a prominent contributor to the diminished efficiency observed in the utilization of N-based fertilizers (Gao, Ma 2015). S is one of the six macronutrients needed for proper plant development, and it is found in various concentrations ranging from 0.1 to 1.5% of dry weight (Islam 2016). The need of plants for this microelement differs depending on the stage of development and species. Brassicas have higher S requirements than other major crops, such as wheat or maize, and are therefore particularly susceptible to S deficiency due to their high S requirement (Anjum et al. 2011, Islam 2016). S deficiency also can reduce the quality and quantity of canola yield by 40% (Abdallah et al. 2010, D'Hooghe et al. 2013).

S is an essential component of cysteine and methionine amino acids, and S-containing glucosinates, are the secondary metabolites (Capaldi et al. 2015, Castro et al. 2023). The interactive effects of N and S on canola yields have been demonstrated. It has been shown that N fertilizers stimulate plant S uptake and that N and S additions must be in balance to achieve optimal seed yields of canola grown on S-deficient soils (Malhi et al. 2007, Ma et al. 2019).

However, there is a significant research gap in understanding the intricate interactions between N and S nutrition concerning canola growth and yield. Existing literature has focused on individual nutrient effects, neglecting the synergistic and antagonistic dynamics between N and S in canola cultivation, emphasizing the need for comprehensive investigations in this regard. Besides, considering that N and S are the most utilized elements, this study was conducted to investigate following objectives: 1) to examine the combined effects of different N and S fertilization levels on canola growth and development; 2) to identify the optimal N and S application rates that maximize grain yield and oil content in canola.

MATERIALS AND METHODS

Study area

This study was conducted in the Shast-Karate region (36° 49′ 48″ N, 54° 28′ 48″ E) in Gorgan city, during the 2016-2017 and 2017-2018 years. The climate of the experimental area is humid subtropical with an annual rainfall of 450 mm.

Experimental design

This study was performed as a factorial arrangement with three factors based on a completely randomized block design. The experimental treatments included N at four levels (25, 50, 75, and 100 kg ha^{-1}), S at two levels (0 and 200 kg ha^{-1}), and three canola cultivars (Hyola 50 hybrid, Hyola 401 and ARGS 003). N and S were supplied from a urea source, and S powder was obtained from potassium sulfate (K_2SO_4) with 99.50% purity. Seeds were provided by the Agriculture Research Center and Natural Resources of Golestan province, Iran.

Field preparation and treatments

To determine the physicochemical properties of the field soil, several soil samples were taken from 0 to 30 cm depth before the experiment. The results of the soil analysis are shown in Table 1. Each experimental plot had

Table 1

Results of physicochemical analysis of soil in the study area

Depth (cm)	pH	Clay (%)	Silt (%)	Sandy (%)	N (%)	P (ppm)	K (ppm)	Lime (%)	EC (dS m^{-1})
0-30	7.7	41	45	11	0.13	9.5	380	13	0.8

an area of 2.7 m^2 and dimensions of 2.4×3 m^2. There were 16 plots in each replicate; the distance between repetitions and treatments was 2 and 1 m, respectively. Field preparation operations such as plowing and disking were carried out conventionally before sowing. Based on the results of the soil test, it was not necessary to use potassium (K) fertilizer, while phosphorus (P) fertilizer was applied before planting. Additionally, S fertilization was applied before planting. N fertilizer was added to the soil during three phases, i.e. before planting, stemming, and flowering. Treflan herbicide was applied for weed control at a dose of 1.5 L ha^{-1} before planting. Weeding was done manually before flowering. Initially, irrigations were performed every four to six days/once.

Morphological and physiological traits

After the physiological maturation of the seeds, the final harvest took place. From each plot, 10 plants were selected and their characteristics were measured. For grain yield measurement, we removed all plants from the central area of 1 m^2 in each plot to eliminate the edge effect.

Physiological measurements

A Soxhlet apparatus was used to measure the oil content of the canola seeds using the AOCS method after they were milled with hexane. In the harvesting stage, to measure the mineral elements in the grain, first, the digested extract was prepared from the ground samples. Then, N, P and K elements were evaluated (Waling et al. 1989). The Kjeldahl method was used to measure N amounts after digesting the samples. Seed protein was obtained from the product as the N percentage multiplied by the plant coefficient of 6.25% (Ezati et al. 2020). We obtained oil and protein yield by multiplying seed yield by oil and protein percentages. To measure grain P, 5 mL of the digested sample were mixed with same quantity of yellow reagent. The volume was increased to 25 mL. Then, the absorbance was measured on a spectrophotometer at 430 nm. The K concentration in seeds was determined by the flame photometer method on a film photometer (Eyni et al. 2023).

Data analysis

Data were analyzed using SAS v9.1 statistical software. The Duncan's multiple tests at a 5% probability level were used to compare the means.

RESULTS AND DISCUSSION

Grain yield

Analyses of variance showed that Y× variety, Y×S× variety, Y×N, Y× variety × N, Y×S×N and the interaction effect of Y×N× variety ×S had a significant effect on grain yield (Table 2). The highest grain yield was observed in the second Y with the application of 100 kg ha^{-1} N fertilizer + 200 kg ha^{-1} S fertilizer at 2701 kg ha^{-1} for the variety Hyola 50 (Table 3). The lowest seed yield in the first Y was obtained with 25 kg ha^{-1} of N + fer-

Table 2

Analysis of variance of measured traits of canola under the effects of N and S sources

S.O.V	df	MS				
		grain yield	protein percentage	protein yield	oil percentage	oil yield
Year (Y)	1	3243 ns	10.43 ns	38024.68**	12.45 ns	61560.53 ns
Block(Y)	4	2133	4.84	1335.88	8.39	33509.38
Cultivar (C)	2	964 ns	0.95 ns	3810.07 ns	227.54 ns	1742.79 ns
C×Y	2	4534*	5.45 ns	1891.35 ns	315.84**	14123.06 ns
Sulfur (S)	1	13083 ns	1.94 ns	251242.37*	6.65 ns	995838.88 ns
Y×S	1	1572 ns	3.37 ns	124.71 ns	5.41 ns	33499.59
C×S	2	6323 ns	2.64 ns	1525.8 ns	31.94 ns	3467.85 ns
C×Y×S	2	9475**	5.43 ns	1484.18 ns	45.08**	5333.87 ns
Nitrogen (N)	3	24323 ns	17.94 ns	195089.91 ns	86.75 ns	1241015.3**
Y×N	3	8452**	14.84**	29350.76**	72.56**	31955.23*
C×N	6	483 ns	4.53 ns	198.07 ns	17 ns	1391.13 ns
S×N	3	1554 ns	3.84 ns	24484.41 ns	21.6 ns	107873.63 ns
C×Y×N	6	3425**	7.53*	2878.02 ns	25.54 ns	17715.56*
S×Y×N	3	4284.54**	9.65*	6652.37*	32.82**	20091.1*
C×S×N	6	2434.8 ns	3.23 ns	623.53 ns	36.75 ns	1127.67 ns
S×C×Y×N	6	3874.49**	11.69**	5950.24*	45.83**	19033.68*
Error	92	802.5	3.3	2320.65	4.75 ns	7379.57
CV (%)	-	11.4	6.84	13.23	10.67	12.01

ns, * and ** show non-significant and significant differences between groups at $p<0.05$ and $p<0.01$, respectively

tilizer applied without S fertilizer to ARGS 003 and Hyola 401 cultivars, respectively (1577 and 1580 kg ha^{-1}). Grain yields were higher in Hyola 50 and Hyola 401 cultivars than in ARGS 003. Also, grain yield increased with increasing N (Table 3).

Our results show that the application of N and S significantly increases seed yield. Our findings are consistent with previous studies regarding the effects of N on the yield of *Brassica carinata* and sesame (Bhattarai et al. 2021, Mehmood et al. 2021). It has been reported that N application increases seed yield by affecting growth parameters as well as by enhancing assimilation capacity (Ghanahi, Chegeni 2019). The increase in N application is attributed to the mitigation of flower abscission, associated with increased panicle proliferation within a given cropping area, which is further enhanced by the beneficial effects on various physiological parameters. This complicated interplay of factors results in an overall noticeable increase in total yield. Maafpourian et al. (2010) reported an increase in rape seed yield under the influence of S fertilizer application. The highest yield of rapeseed was achieved with N fertilizer of 180 kg and S fertilizer of 50 kg. The use of N fertilizer in rapeseed cultivation has also been found to increase seed yield

Table 3

Comparison of the average effect of N and S fertilizers on the yield of canola varieties

Year	N (kg ha^{-1})	S (kg ha^{-1})	C	Grain yield (kg ha^{-1})	Seed protein (%)	Protein yield (kg ha^{-1})	Seed oil (%)	Oil yield (kg ha^{-1})
First year	25	control	Hyola 50	1594.96 *y*	14.76 *y*	233.31 *z*	29.7 *o*	469.75 *vwx*
	25	control	Hyola 401	1580.33 *z*	14.93 *y*	235.39 *xyz*	28.69 *p*	452.78 *wx*
	25	control	ARGS 003	1577.79 *z*	15.3 *xy*	243.94 *xy*	28.08 *pq*	448.08 *x*
	25	200	Hyola 50	1680.9 *v*	16.87 *rstu*	283.7 *vw*	31.54 *n*	531.37 *s*
	25	200	Hyola 401	1752.48 *st*	16.81 *stuv*	294.67 *tu*	31.65 *mn*	555.85 *rs*
	25	200	ARGS 003	1853.26 *n*	17.04 *qrstu*	315.59 *rs*	32.31 *m*	600.07 *q*
	50	control	Hyola 50	1734.48 *u*	18.21 *klmn*	316.16 *rs*	27.48 *q*	477.13 *uvw*
	50	control	Hyola 401	1760.59 *s*	18.19 *klmno*	320.46 *rs*	28.48 *p*	502.32 *t*
	50	control	ARGS 003	1821.91 *op*	18.52 *jklm*	337.79 *pq*	30.05 *o*	548.84 *rs*
	50	200	Hyola 50	1899.1 *l*	18.98 *hijk*	359.33 *mn*	37.09 *hi*	701.86 *mn*
	50	200	Hyola 401	2115.33 *e*	19.35 *ghij*	407.98 *gh*	37.02 *hij*	780.35 *ij*
	50	200	ARGS 003	2366.43 *d*	20.05 *defg*	472.98 *c*	37.58 *gh*	886.51 *de*
	75	control	Hyola 50	1993.05 *jk*	16.36 *uvw*	325.05 *qr*	36.16 *k*	718.3 *lm*
	75	control	Hyola 401	2043.47 *h*	17.12 *pqrstu*	351.62 *no*	36.38 *jk*	740.14 *kl*
	75	control	ARGS 003	1869.46 *m*	16.51 *tuv*	308.46 *st*	36.53 *ijk*	682 *no*
	75	200	Hyola 50	2055.41 *g*	18.01 *lmnop*	370.42 *l*	38.54 *ef*	787.46 *ij*
	75	200	Hyola 401	2058.24 *g*	18.36 *klmn*	378.36 *kl*	39.06 *e*	798.83 *i*
	75	200	ARGS 003	2094.62 *f*	19.01 *hijk*	398.93 *ij*	40.24 *d*	837.42 *gh*
	100	control	Hyola 50	1991.16 *jk*	16.62 *tuv*	329.72 *qr*	33.82 *l*	672.8 *o*
	100	control	Hyola 401	2009.39 *ij*	16.63 *tuv*	333.41 *pq*	33.48 *l*	672.77 *o*
	100	control	ARGS 003	2060.49 *g*	16.91 *rstu*	348.21 *o*	33.72 *l*	694.67 *mno*
	100	200	Hyola 50	2637.06 *bc*	16.99 *rstu*	448.44 *d*	36.65 *ijk*	968.36 *bc*
	100	200	Hyola 401	2625.25 *c*	17.29 *opqrst*	454.45 *d*	36.5 *ijk*	959.84 *c*
	100	200	ARGS 003	2665.94 *ab*	17.94 *lmnopq*	478.79 *c*	37.1 *hi*	990.5 *b*
Second year	25	control	Hyola 50	1792.83 *qr*	15.39 *xy*	273.52 *wx*	25.57 *r*	458.15 *wx*
	25	control	Hyola 401	1800.25 *q*	15.56 *wxy*	278.16 *wx*	24.96 *rs*	448.81 *x*
	25	control	ARGS 003	1830.82 *o*	15.94 *vwx*	290.24 *uv*	24.69 *s*	451 *x*
	25	200	Hyola 50	1684.05 *v*	17.62 *nopqrs*	296.78 *tu*	29.79 *o*	500.31 *tu*
	25	200	Hyola 401	1646.28 *w*	17.58 *nopqrs*	289.23 *uv*	29.51 *o*	486.72 *tuv*
	25	200	ARGS 003	1630.74 *x*	17.78 *mnopqr*	291.31 *uv*	29.64 *o*	483.98 *tuv*
	50	control	Hyola 50	1962.81 *k*	18.7 *ijkl*	362.02 *m*	37.38 *gh*	733.61 *l*
	50	control	Hyola 401	1758.16 *s*	18.73 *ijkl*	329.84 *qr*	36.68 *ijk*	644.59 *p*
	50	control	ARGS 003	1577.13 *z*	19.02 *hijk*	306.02 *st*	36.46 *ijk*	571.37 *r*
	50	200	Hyola 50	2069.77 *fg*	19.84 *efgh*	405.26 *hi*	38.77 *e*	802.74 *i*
	50	200	Hyola 401	1903.84 *l*	20.26 *defg*	385.67 *k*	38.48 *ef*	732.29 *l*
	50	200	ARGS 003	1763.39 *s*	20.95 *cd*	375.11 *l*	38.7 *e*	680.26 *no*
	75	control	Hyola 50	1755.14 *st*	17.06 *qrstu*	299.28 *tu*	41.8 *bc*	731.98 *l*
	75	control	Hyola 401	1850.67 *n*	17.02 *rstu*	315.17 *rs*	41.64 *bc*	770.43 *j*
	75	control	ARGS 003	1971.31 *k*	17.21 *pqrstu*	339.59 *p*	42.03 *bc*	828.82 *h*
	75	200	Hyola 50	1969.19 *k*	19.47 *fghi*	383.48 *k*	43.46 *a*	855.19 *fg*
	75	200	Hyola 401	2009.58 *ij*	19.69 *fgh*	395.66 *j*	42.85 *b*	866.65 *ef*
	75	200	ARGS 003	2076.82 *fg*	20.17 *defg*	418.74 *f*	43.07 *ab*	900.9 *d*
	100	control	Hyola 50	2023.19 *i*	20.35 *def*	411.11 *fgh*	38 *fg*	769.07 *j*
	100	control	Hyola 401	2011.33 *ij*	20.7 *cde*	415.47 *fg*	37.95 *fg*	763.28 *jk*
	100	control	ARGS 003	2026.61 *i*	21.32 *c*	430.76 *e*	38.41 *ef*	778.25 *ij*
	100	200	Hyola 50	2701.78 *a*	22.41 *b*	603.84 *b*	40 *d*	1080.48 *a*
	100	200	Hyola 401	2647.16 *b*	22.92 *ab*	606.51 *b*	40.16 *d*	1045.88 *ab*
	100	200	ARGS 003	2627.9 *c*	23.73 *a*	624.39 *a*	41.01 *c*	1039.16 *ab*

Means with same letters in each row in each index do not have a significant difference at the one percent level based on the Duncan's test.

(Moradi Telavat et al. 2007). This research supports findings reported by Mazloum et al. (2009). Furthermore, it was documented that S has a positive effect on grain yield because it increases the leaf area index and dry matter production (Ur Rehman et al. 2013, Ramezanpour et al. 2022). The effects of S on chloroplast synthesis, fatty acid synthesis, and photosynthesis enhanced seed yield (Shah et al. 2022). This phenomenon can be attributed to the multiple functions that S performs in facilitating important metabolic pathways and ultimately contributing to the optimization of seed production. The interplay of these molecular and physiological mechanisms underscores the nuanced relationship between S availability and the resulting agronomic outcomes, leading to some significance to the observed increase in seed yield.

Protein percentage and yield

The results of the analysis of variance showed that the effect of Y × N, Y × N × S and the quadruple effect of Y × N × variety × S on protein percentage and grain protein yield were significant (Table 2). Based on the results, the highest seed protein percentage was observed in the second Y with the application of 100 kg ha^{-1} of N + 200 kg ha^{-1} of S fertilizer in ARGS 003 at a dose of 23.73% (Table 3). The lowest percentage of seed protein in the first Y was obtained by applying 25 kg ha^{-1} of N + without S fertilizer in Hyola 50 and 401 cultivars at doses of 14.76 and 14.93%, respectively (Table 3). The ARGS 003 cultivar had a higher seed protein percentage than the Hyola 50 and Hyola 401 cultivars. Also, the seed protein percentage was enhanced at higher N fertilizer application. Furthermore, this trait increased with the application of S fertilizer (Table 3). The results showed that in the second Y, the highest yield of seed protein was observed with the application of 100 kg ha^{-1} of N fertilizer + 200 kg ha^{-1} of S fertilizer in ARGS 003 cultivar at a dose of 624 kg ha^{-1}. In the first Y, the lowest yield of seed protein was obtained with the application of 25 kg ha^{-1} of N + fertilizer without S fertilizer in the variety Hyola 50 at a dose of 233 kg ha^{-1} and then at 235 kg ha^{-1} in the variety Hyola 401. Hyola 50 and Hyola 401 cultivars had lower seed protein yield than ARGS 003 cultivar. Also, with increasing application of N and S, grain protein yields increased (Table 3).

The enhanced nitrogen fertilization leads to a noticeable increase in the protein content of canola. This phenomenon is due to the increased availability of nitrogenous proteins, which in turn translates into a decrease in the substrates available for fatty acid synthesis. As a result of this complicated metabolic modulation, the balance between protein and fatty acid biosynthesis within canola is disturbed, leading to a noticeable enhancement of protein composition. According to Bonnet et al. (2016), optimal N consumption leads to an increase in seed protein levels. Similarly, Fazili et al. (2008) found that the use of S combined with N increased the protein content of rapeseed, which is consistent with these results. Using a combination of N and S fertilizers increases the protein content of rapeseed. The increase in N utilization is directly related to an enhancement in seed protein content, and this correlation between nitrogen consumption and seed protein content has a recognizable and predictable pattern. Due to the fact that N is the main component of amino acids and proteins, increasing its absorption will also increase protein synthesis. This study's results are consistent with Ahmad et al. (2007), who found that increasing N consumption enhanced canola protein yield.

The results also exhibited that the effects of a cultivar and N on protein yield were significant, which was in agreement with previous studies (Nehe et al. 2020, Ghimire et al. 2021). Protein synthesis is dependent on N content; hence, an increased concentration of this element can lead to higher grain production and protein synthesis (Fathi, Zeidali 2021). The results also showed that the application of S significantly increased protein yield. Our findings are in agreement with Younis et al. (2020), and Kandil and Gad (2012). Different cultivars reacted differently to the S application. Increased levels of S may have resulted in a greater accumulation of carbohydrates and protein and their translocation to the productive organs, leading to greater yields of seeds (Pachauri, Trivedi 2012). Canola's quality is primarily determined by its seed protein content (%). Younis et al. (2020). reported that S levels showed a positive influence on protein content (%), and 60 kg ha^{-1} S application resulted in higher seed protein content (24.8%) in canola. Our results revealed that the protein content increased from 22.4% to 24.8% when S levels increased from 15 to 60 kg ha^{-1}, while this trait decreased (23.6%) when the S level was further increased up to 75 kg ha^{-1} (Younis et al. 2020). Similar results were reported by S Kandil and Gad (2012), who found that canola seed protein and oil content increased at higher doses of S fertilizer. Younis et al. (2020) also found that the S application of up to 60 kg ha^{-1} enhanced the protein content of canola seeds.

Percentage and yield of seed oil

The results of the analysis of variance showed that the effect of Y×N, Y×N×S and the interaction effect of Y×N×Variety×S on yield and seed oil percentage were significant (Table 2). The results showed that the highest percentage of seed oil in the second Y was observed with the application of 75 kg ha^{-1} of N fertilizer + 200 kg ha^{-1} of S fertilizer in Hyola 50 by 43.46% and then in ARGS 003 by 43.07% (Table 3). The lowest percentage of seed oil in the second Y was obtained with the application of 25 kg ha^{-1} of N + fertilizer without S fertilizer in ARGS 003 and Hyola 401 cultivars at doses of 24.69 and 24.96%, respectively (Table 3). ARGS 003 cultivar had higher seed oil percentage than Hyola 50 and Hyola 401 cultivars. Also, the increase in the percentage of seed oil increased with the increase in the use of N fertilizer. The seed oil percentage of canola cultivars was enhanced with the application of S fertilizer (Table 3). The results showed that the highest yield of seed oil was observed with the application of 100 kg ha^{-1} of N fertilizer + 200 kg ha^{-1} of S fertilizer in the Hyola 50 cultivar at a dose of 1080 kg ha^{-1} in the second Y. Hyola 50 and Hyola 401 cultivars had higher seed oil yield than ARGS 003. Also, with the increasing application of N and S, seed oil yield increased (Table 3).

In conditions of the application of 100 kg ha^{-1} of N fertilizer, seed yield significantly impacted oil yield increase. Based on the results, oil percentage increased with a 75% increase in N consumption, but decreased with a 100 kg ha^{-1} N fertilizer application. As a result of an increase in N, especially at 100 kg of N per hectare, the decline in oil percentage can be interpreted as an increase in N. Protein precursors are increasing during the preparation of photosynthetic materials, whereas the materials available for fatty acid synthesis are decreasing, thus lowering the percentage of oil (Ahmad et al. 2007). Alternatively, researchers have found that an increase in N consumption enhances rapeseed oil yield (Moradi Telavat et al. 2007, Eyni et al. 2023). Previous studies have presented that N application increased oil yield (Sifola, Barbieri 2006, Aminpanah 2013). Furthermore, the S application enhanced the oil content, which is in agreement with previous studies (Kumar et al. 2016, Lakshman et al. 2017). Oil yield increased significantly from 0 to 200 kg ha^{-1}. Kumar et al. (2016) and Lakshman et al. (2017) also documented a positive relationship between heightened S content and amplified oil yield.

High economic performance can be achieved by using higher amounts of N than the conventional limit. The decrease in grain yield and, consequently, the reduced oil yield cannot be compensated by reducing N and increasing oil percentages (Eyni et al. 2023). S fertilizer has affected seed oil percentages in rapeseed production, and generally the oil percentages were higher in treatments containing S fertilizer. In their study, Shah et al. (2022) established that S exerts a substantial influence on the proportion of seed oil, primarily attributed to its pivotal role in the constitution of fatty acids and its indispensable contribution to the biosynthetic pathways of associated metabolites. According to Ahmed et al. (2007), increasing S treatment by 20 kg ha^{-1} increased seed oil production. Additionally, adding S to rapeseed cultivation increases its oleic acid content, which prevents the conversion of oleic acid to erucic and reduces its amount (Shoja et al. 2018). This study's results are consistent with those of Malhi et al. (2007). With S application to rapeseed, researchers found that the percentage of oil and protein increased (Malhi et al. 2007).

Seed N content

The results of the variance analysis of the data showed that the interaction effect of Y×S and Y×N on the seed N content was significant. Also, the interaction effect of the treatments on this trait was significant at the 5% level (Table 4). The highest seed N content was obtained in the second Y and the application of 50 kg of N along with the consumption of 200 kg ha^{-1} of S in the ARGS 003 cultivar at a dose of 3.39%, which showed an increase of 34.8% compared to the treatment of 25 kg ha^{-1} of N fertilizer and no S consumption in the Hyola 50 cultivar (Table 5). Also, the results showed that

Table 4

Analysis of variance of measured traits of canola under the effects of N and S sources

S.O.V	df	MS				
		seed N content	seed K content	seed P content	saturated fatty acid	unsaturated fatty acid
Year (Y)	1	0.186 ^{ns}	0.0014 ^{ns}	0.0447*	14.412*	113.96**
Block(Y)	4	0.094	0.0221	0.0062	1.814	3
Cultivar (C)	2	0.195 ^{ns}	0.0102 ^{ns}	0.0014 ^{ns}	0.428 ^{ns}	0.27
C×Y	2	0.003 ^{ns}	0.012**	0.039**	0.011 ^{ns}	0.11
Sulfur (S)	1	0.475 ^{ns}	0.006 ^{ns}	0.0211 ^{ns}	0.576 ^{ns}	0.94
Y×S	1	0.15*	0.04 ^{ns}	0.0126 ^{ns}	1.949*	0.66
C×S	2	0.004 ^{ns}	0.0081 ^{ns}	0.0014 ^{ns}	0.006 ^{ns}	0.03
C×Y×S	2	0.002 ^{ns}	0.05**	0.0044 ^{ns}	0.008 ^{ns}	16.01*
Nitrogen (N)	3	2.341 ^{ns}	0.0139 ^{ns}	0.0023 ^{ns}	0.3 ^{ns}	0.84
Y×N	3	0.22*	0.121**	0.0156*	1.981*	0.74
C×N	6	0.052 ^{ns}	0.0003 ^{ns}	0.0018 ^{ns}	0.269 ^{ns}	0.19
S×N	3	0.041 ^{ns}	0.0013 ^{ns}	0.001 ^{ns}	1.758 ^{ns}	0.37
C×Y×N	6	0.131*	0.06**	0.0006 ^{ns}	0.008 ^{ns}	13.02*
S×Y×N	3	0.017 ^{ns}	0.0008 ^{ns}	0.002 ^{ns}	1.851*	0.01
C×S×N	6	0.03 ^{ns}	0.0005 ^{ns}	0.0008 ^{ns}	0.081 ^{ns}	0.42
S×C×Y×N	6	0.14*	0.017*	0.019*	1.45*	11.22*
Error	92	0.054	0.006	0.007	0.571	4.76
CV (%)	-	8.11	12.56	16.47	10.25	9.89

^{ns}, * and ** show non-significant and significant differences between groups at $p<0.05$ and $p<0.01$, respectively

increasing the consumption of 25 to 50 kg ha^{-1} of N in both Y increased the percentage of N, but increasing it above this value decreased the percentage of seed N content. In addition, cv. ARGS 003 has shown a better response to fertilizer consumption than the other two cultivars in both Y (Table 5).

Both N and S fertilizers are important as plant nutrients. N is very important as the main element in plant protein production and in plant seeds such as rapeseed (Eyni et al. 2023). Also, N fertilizer can help improve plant growth and development (Fathi 2022). In contrast, S can affect the amount of N. It can reduce the plant's ability to absorb N and consequently decrease the plant's N content (Shabani et al. 2015).

Seed K content

The results of the variance analysis of the data showed that the interaction effect of Y× variety and Y×N was significant at the level of 5% on the seed K content (Table 4). The results showed that the interaction effect of

Table 5

Comparison of the average effect of N and sulfur fertilizers on the studied traits of canola cultivars

Year	N (kg ha-1)	S (kg ha-1)	C	N content (%)	K content (%)	P content (%)	Saturated fatty acid (%)	Unsaturated fatty acid (%)
First year	25	control	Hyola 50	2.25*op*	1.27*bcdefghij*	0.47*abc*	4.96*kl*	87.87*efghi*
	25	control	Hyola 401	2.42*nop*	1.27*bcdefghij*	0.48*abc*	5.29*ijkl*	87.44*fghi*
	25	control	ARGS 003	2.63*jklmno*	1.28*abcdefghij*	0.49*abc*	5.68*defghijkl*	88.19*defghi*
	25	200	Hyola 50	2.49*mnop*	1.3*abcdefghi*	0.53*abc*	5.35*ghijkl*	88.93*cdefghi*
	25	200	Hyola 401	2.55*lmnop*	1.31*abcdefgh*	0.53*abc*	5.57*efghijkl*	88.36*defghi*
	25	200	ARGS 003	2.65*jklmn*	1.33*abcdefg*	0.54*abc*	5.89*defghijk*	89.28*bcdefghi*
	50	control	Hyola 50	2.91*cdefghijkl*	1.37*abc*	0.53*abc*	5.95*defghijk*	90.09*bcdefg*
	50	control	Hyola 401	2.91*cdefghijkl*	1.35*abcdef*	0.53*abc*	5.95*defghijk*	89.13*cdefghi*
	50	control	ARGS 003	2.96*bcdefghij*	1.35*abcde*	0.54*abc*	6.06*bcdefghijk*	89.95*bcdefgh*
	50	200	Hyola 50	3.04*abcdefghi*	1.39*ab*	0.55*ab*	6.2*abcdefghij*	90.38*bcdef*
	50	200	Hyola 401	3.1*abcdefgh*	1.38*ab*	0.56*ab*	6.1*bcdefghijk*	90.41*bcdef*
	50	200	ARGS 003	3.21*abcd*	1.4*a*	0.57*ab*	6.11*bcdefghijk*	91.96*abc*
	75	control	Hyola 50	2.62*jklmno*	1.19*hij*	0.41*c*	4.63*l*	86.43*hi*
	75	control	Hyola 401	2.69*ijklmn*	1.22*ghij*	0.44*bc*	5.31*hijkl*	86.67*ghi*
	75	control	ARGS 003	2.7*ijklmn*	1.2*hij*	0.48*abc*	5.52*efghijkl*	87.9*defghi*
	75	200	Hyola 50	2.72*hijklmn*	1.22*ghij*	0.48*abc*	5.82*defghijkl*	88.23*defghi*
	75	200	Hyola 401	2.75*hijklmn*	1.26*cdefghij*	0.48*abc*	5.83*defghijkl*	87.59*fghi*
	75	200	ARGS 003	2.83*efghijklm*	1.31*abcdefgh*	0.5*abc*	5.93*defghijk*	88.4*defghi*
	100	control	Hyola 50	2.66*jklmn*	1.18*ij*	0.44*bc*	5.09*jkl*	86.7*ghi*
	100	control	Hyola 401	2.66*jklmn*	1.18*j*	0.45*bc*	5.25*ijkl*	86.39*i*
	100	control	ARGS 003	2.71*ijklmn*	1.19*hij*	0.46*abc*	5.5*fghijkl*	87.53*fghi*
	100	200	Hyola 50	2.72*ijklmn*	1.21*hij*	0.51*abc*	6.08*bcdefghijk*	88.26*defghi*
	100	200	Hyola 401	2.77*ghijklmn*	1.23*efghij*	0.51*abc*	6*defghijk*	87.73*efghi*
	100	200	ARGS 003	2.87*cdefghijklm*	1.28*bcdefghij*	0.52*abc*	6.03*cdefghijk*	88.96*cdefghi*
Second year	25	control	Hyola 50	2.21*p*	1.22*fghij*	0.59*a*	5.46*fghijkl*	89.44*bcdefghi*
	25	control	Hyola 401	2.45*nop*	1.22*fghij*	0.55*ab*	5.82*defghijkl*	89.04*cdefghi*
	25	control	ARGS 003	2.71*ijklmn*	1.24*defghij*	0.51*abc*	6.25*abcdefghij*	89.83*bcdefghi*
	25	200	Hyola 50	2.53*mnop*	1.26*cdefghij*	0.55*ab*	5.89*defghijk*	90.72*bcdef*
	25	200	Hyola 401	2.61*jklmno*	1.27*bcdefghij*	0.55*ab*	6.14*abcdefghijk*	90.33*bcdef*
	25	200	ARGS 003	2.73*hijklmn*	1.29*abcdefghij*	0.55*ab*	6.48*abcdefghi*	91.13*abcde*
	50	control	Hyola 50	3.15*abcdef*	1.23*fghij*	0.55*ab*	6.55*abcdefg*	92.11*abc*
	50	control	Hyola 401	3.14*abcdefg*	1.22*fghij*	0.52*abc*	6.56*abcdefg*	91.42*abcd*
	50	control	ARGS 003	3.18*abcde*	1.24*defghij*	0.49*abc*	6.66*abcdef*	91.94*abc*
	50	200	Hyola 50	3.25*abc*	1.24*cdefghij*	0.51*abc*	6.82*abcd*	92.45*abc*
	50	200	Hyola 401	3.3*ab*	1.26*bcdefghij*	0.52*abc*	6.73*abcde*	92.79*ab*
	50	200	ARGS 003	3.39*a*	1.3*abcdefghij*	0.54*abc*	6.73*abcde*	94.36*a*
	75	control	Hyola 50	2.84*defghijklm*	1.31*abcdefgh*	0.46*abc*	5.1*jkl*	87.71*efghi*
	75	control	Hyola 401	2.69*ijklmn*	1.3*abcdefghij*	0.47*abc*	5.55*efghijkl*	88*defghi*
	75	control	ARGS 003	2.57*klmnop*	1.3*abcdefghij*	0.48*abc*	6.07*bcdefghijk*	89.48*bcdefghi*
	75	200	Hyola 50	2.61*jklmno*	1.32*abcdefgh*	0.49*abc*	6.4*abcdefghi*	89.88*bcdefghi*
	75	200	Hyola 401	2.63*jklmn*	1.34*abcdefg*	0.51*abc*	6.42*abcdefghi*	89.38*bcdefghi*
	75	200	ARGS 003	2.68*ijklmn*	1.39*ab*	0.54*abc*	6.52*abcdefgh*	90.08*bcdefg*
	100	control	Hyola 50	2.74*hijklmn*	1.3*abcdefghi*	0.54*abc*	5.6*defghijkl*	88.04*defghi*
	100	control	Hyola 401	2.74*hijklmn*	1.3*abcdefghij*	0.53*abc*	5.79*defghijkl*	87.95*defghi*
	100	control	ARGS 003	2.78*fghijklmn*	1.31*abcdefgh*	0.53*abc*	6.05*bcdefghijk*	89.04*cdefghi*
	100	200	Hyola 50	2.79*fghijklmn*	1.33*abcdefg*	0.55*ab*	7.34*a*	89.91*bcdefghi*
	100	200	Hyola 401	2.85*defghijklm*	1.34*abcdefg*	0.55*ab*	7.26*abc*	89.73*bcdefghi*
	100	200	ARGS 003	2.94*bcdefghijk*	1.36*abcd*	0.56*ab*	7.27*ab*	90.75*bcdef*

ns, * and ** show non-significant and significant differences between groups at $p<0.05$ and $p<0.01$, respectively the four treatments on this trait was significant at the 5% level (Table 5). The highest seed K content was obtained in the first Y and the application of 50 kg of N along with the consumption of 200 kg ha^{-1} of S in ARGS 003 variety at a dose of 1.4%. which showed an increase of 15.7% compared to the treatment of 100 kg ha^{-1} of N fertilizer and no S consumption in Hyola 50 and Hyola 401 cultivars (Table 5).

In the study, the seed K content was slightly affected by increasing N fertilizer consumption from 50 to 100 kg. As a basic element, N fertilizer is vital to plant growth and development, and it can enhance canola growth and development. The excessive fertilizer application, however, may result in reduced K absorption by this crop (Rezvani Moghaddam, Seyyedi 2014). Consequently, these results emphasize the importance of careful consideration in the selection and application of N fertilizers. In sunflowers, 200 and 100 kg ha-1 of urea and P fertilizers significantly increased thee K content compared to no fertilizer application (Yadavi and Yuosefpur 2015). It was found that the results of this investigation are consistent with those of Eyni et al. (2023) as well.

Seed P content

The results of the analysis of variance table show that the quadruple interaction of the treatments was significant at the 5% level on the seed P content (Table 4). The results showed that the highest seed P content was obtained in the first Y and the application of 25 kg N and no S consumption in Hyola 50 variety at a dose of 0.59%, which showed an increase of 30.5% compared to the application of 75 kg ha^{-1} of N fertilizer and no S consumption in the Hyola 50 variety (Table 5). Our research shows interesting results when N and S fertilizers are used, canola cultivars indicate better responses than when S is not used. However, more consumption of N and S had a significant effect on the percentage of grain P (Table 5).

Increasing fertilizer N and S application to different cultivars showed different their reactions in termns of the seed absorption of P. According to researchers, the mutual effect of S and N is highly correlated with the amount of fertilizer consumed, indicating that an excessive increase in fertilizer consumption affects the absorption of the other elements (Shabani et al. 2015). With the increased use of N fertilizer, P absorption in both Y increased initially and then decreased. N fertilizer increases P absorption in rapeseed. But the use of S has also affected the amount of P in the seeds. It seems that excessive use of N fertilizer may reduce P uptake by the plant. On the other hand, using S fertilizer as a regulatory element can improve P absorption in rapeseed.

Saturated fatty acids

The results of the analysis of variance table show that the interaction of the treatments was significant at the 5% level on saturated fatty acids

(Table 4). The highest amount of saturated fatty acids was obtained in the second Y and the application of 100 kg N and consumption of 200 kg ha^{-1} S in Hyola 50 at a dose of 34.7%, which increased by 36.9% compared to the application of 75 kg ha^{-1} of N fertilizer and no S consumption in Hyola 50 (Table 5). With the increase of N consumption from 25 to 50 kg ha^{-1} with or without using S fertilizer, the saturated fatty acid content was enhanced. Also, the results show that in the first Y, an excessive increase in N fertilizer consumption (more than 50 kg ha^{-1}) caused a decrease in saturated fatty acids. Conversely, in the second Y at all levels with the increase of N and S, the amount of saturated fatty acids was enhanced in the three different cultivars (Table 5).

The results showed that the impact of the application of N and a cultivar increased saturated fatty acids. Our findings are in agreement with previous studies on the effects of N (Ahmed 2018, Szpunar-Krok et al. 2021). Different cultivars responded differently to fertilizers in terms of this trait, which could be attributed to their genetic structures.

Unsaturated fatty acids

The results of the analysis of variance table show the interaction of the treatments was significant at the 5% level for unsaturated fatty acids (Table 4). The highest amount of unsaturated fatty acids was obtained in the second Y and the application of 50 kg N and consumption of 200 kg ha^{-1} S in ARGS 003 at a dose of 94.36%, indicating an 8.4% increase compared with the 100 kg ha^{-1} of N fertilizer and no S consumption in the Hyola 401 cultivar (Table 5). The results show that with the increase of S and N fertilizers, amounts of unsaturated fatty acids increased in canola, so that the optimal use of N and S fertilizer had a positive effect on unsaturated fatty acids (Table 5).

In terms of improving the quality of unsaturated fatty acids, N fertilizer seems to have a relatively limited role. It is possible to increase the growth and productivity of the canola plant by using N fertilizer, but by increasing the amount of N in the soil, it is possible to decrease the amount of unsaturated fatty acids. Eyni et al. (2023) have reported similar results. Furthermore, comparable findings were documented in previous studies for N fertilizer (Ahmed 2018, Szpunar-Krok et al. 2021), and for S application (Shoja et al. 2018, Shokri et al. 2022). Different cultivars responded differently to fertilizers in terms of unsaturated fatty acids. This phenomenon can be explained by genetic structure.

CONCLUSIONS

Based on the results, a significant interaction was observed for all studied traits. The Hyola 50 and Hyola 401 cultivars had higher grain yields than the ARGS 003 cultivar. Also, grain yield increased with increasing N. The results showed that the ARGS 003 cultivar had a higher seed oil percentage than Hyola 50 and Hyola 401. Also, the seed oil percentage increased with the increase in N fertilizer use. The practical aspects of these results are that farmers and agricultural practitioners can use them to make informed decisions about the choice of canola varieties for their specific conditions. Selecting high-yield varieties such as Hyola 50 and Hyola 401, or the ARGS 003 cultivar if seed oil content is a priority, can lead to more profitable outcomes. Overall, it can be concluded that nutrients N and S were critical for improving the quality performance of canola varieties. It is recommended that future studies focus more on the application of higher concentrations of S fertilizer to other varieties. Furthermore, with changing climate patterns, exploring how different canola varieties respond to environmental stressors and whether nutrient management can improve crop resilience is a promising avenue for future study. This could contribute to the development of more resilient canola varieties in the face of climate change.

Author contributions

Data curation, investigation, writing – original draft, project administration – Hossein Ali Ebrahimi Badashiani, supervision, conceptualization, review and editing – Abolfazl Faraji, supervision, review and editing – Morteza Samdeliri, review and editing – Amirabbas Mousavi Mirkalaei

Conflicts of interest

The authors declare that they have no conflicts of interest.

Data availability statement

Not applicable.

Disclosure statement

No potential conflict of interest was reported by the authors.

Ethics approval and consent to participate

Not applicable.

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