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Effect of Sulfur, Boron, Zinc and Iron on Canola under Salt Affected Soils

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THE POSSIBILITY of canola achieving self-sufficiency in oil production in Egypt is feasible due to its adaptability to different climates and potential for cultivation in the country. With proper investment in research, infrastructure, and agricultural practices, Egypt can increase canola production and reduce its dependence on imported oils. So, two field trials were carried out during sequential winter seasons of 2021/2022 and 2022/2023 aiming to study the influence of four rates of elemental sulfur (ES) soil applications as main plots [control (ES_0), 100, 150 and 200 kg S fed^{-1}] and five micronutrient treatments as foliar application [control (without spraying), boron (B), zinc (Zn), iron (Fe) and mixture of them] as sub-plots on growth, yield and its components of canola plants. The values of available N, P, K, S and pH were measured in the experimental soil after harvest. The results of the study demonstrated that increasing the level of elemental sulfur fertilizer to 200 kg S fed^{-1} resulted in the highest vegetative growth values, effective yield, and its constituent parts compared to the control (ES_0). Applying foliar treatment with a mixture of B, Zn, and Fe also had a significant positive effect on all growth parameters, yield, oil yield and protein yield. Moreover, the interaction between applying 200 kg S fed^{-1} of elemental sulfur and foliar treatment with the mixture of B, Zn, and Fe caused the highest values for canola plant development, yield, and its components. Additionally, the control treatment (ES_0 x without spraying) led to the highest remaining N and K concentrations in the soil, while the applying 200 kg S fed^{-1} of elemental sulfur without foliar treatment resulted in the highest remaining P and S concentrations.

Keywords: Canola, Elemental Sulfur, Boron, Zinc and Iron.

Introduction

Canola is an important and healthy oil crop that grown under different agro- climatic zones (**Shaaban *et al*. 2023**). Its seeds contain about 40% oil content with low glycosylates (an anti-nutritive factor) and low erucic acid (**Aram *et al*. 2021**). Recently, canola was introduced to Egypt as a new vegetable oil crop where Egypt suffers from a gap between production and oil consumption reached 1.251 million tons (**El-Hamdi *et al.* 2020**). Canola as well as other crops needed balanced nutrients to produce a high yield with high quality (**El-shahawy *et al*. 2022**). Canola farming is successful in salty soils, according to **El Habasha *et al*. (2020)**; where canola cultivar Serw 4 is thought to be a highly salt tolerant crop till 8 dsm^{-1} **(Al-Thabet, 2003)**

Sulfur is a vital element for growth and development of plants where it is necessary for the production of chlorophyll, proteins, vitamins and oil. Sulfur is an important macronutrient for canola production more than other cereals (**Younis *et al.* 2020**). The application of sulfur is vital for methionine and cysteine (a vitamin A component) synthesis, enhances some enzymes in the plant and chlorophyll synthesis (**Waraich *et al.* 2022**). Also, it increases oil concentration in canola seeds as well as glycosylate content (**Rameeh *et al*. 2021).**

On the other hand, sulfur application significantly decreases soil pH which respectively improve nutrients availability in soil, enhance nutrients uptake by plant and finally improve yield productivity of plant **(Abou Hussien *et al.* 2020).**

Micronutrients are required in small amounts for plant growth and yield production and their deficiency affects negatively on physiological plant process (**Rahman and Schoenau 2020**). Foliar micronutrients application is more effective than soil application at causing the reaction of nutrients application to happen

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quickly and easily, as well as it addresses the deficiency of the elements (**Emam and Mahdi 2020**). Foliar micronutrients feeding is typically inexpensive, more efficient at utilizing nutrients, and significantly reduces environmental pollution by reducing the amount of fertilizers added **(Aziz et al. 2021).** Foliar spraying is the greatest solution for supplying nutrients to growing plants since the salt of the soil makes it difficult for plants to absorb nutrients from the soil **(Dhaliwal et al. 2021).**

Boron (B) is a micronutrient that necessary for plant growth, meristematic activity, carbon metabolism and flower pollination (**Dinh *et al.* 2022**). Canola is frequently more sensitive to boron levels (**Manaf *et al.* 2019).** The principal uses of boron include cell division, enhancing strength and rigidity of cell wall structure, as well as it involved in carbohydrates metabolism, protein synthesis and pollen germination (**Shoja *et al*. 2018**).

Zinc (Zn) is responsible for seedling growth and germination (**Afashi *et al.* 2020**). Also, it plays a necessary role in the activation of over 300 enzymes that important for cell division and protein synthesis (**Manaf *et al.* 2019**). On the other hand, deficiency of zinc affects negatively the metabolism of carbohydrates, pollen formation and leads to yield decrease (**Shoja *et al*. 2018**).

Iron (Fe), as well as zinc, plays a significant part in a number of enzyme systems where haem or haemin serves as the prosthetic group. These haem enzyme systems include various cytochromes, peroxidases, and catalases (**Dhaliwal *et al*. 2021**). Also, it has a vital role in chlorophyll metabolism and photosynthesis process increasing (**Pourjafar *et al.* 2016**).

Therefore, the aim of this study was to investigate the impact of different rates of elemental sulfur (ES) soil applications and micronutrient foliar treatments in improving the growth, yield and its components of canola plants. Additionally, the study aimed to evaluate the influence of these treatments on the remaining concentrations of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) in the soil after harvest.

Materials and methods

Two field trails were performed over the course of two subsequent winter seasons in 2021/2022 & 2022/2023 at Tag El-Ezz farm, Agricultural Research Station, Dakahlia Governorate, ARC, Egypt, (located at 31^{o} 58\ E longitude,´30^{o} 59\ N latitude) to study the effect of different rates of sulfur fertilizer and foliar application of some micronutrients on growth, yield and productivity of canola plants. Before planting, random disturbed soil samples were gathered from the soil surface (depth 0-30 cm). The experimental soil's physical and chemical properties were determined according to **Klute (1986) and Page *et al*. (1982)** as displayed in **Table (1)**.

Experimental setup.

The experiment contained twenty treatments resulting from the combinations of four Sulfur fertilizer rates as elemental sulphur (98% S) [control (ES0), 100, 150, & 200 kg fed^{-1}] as the main plots and five micronutrient treatments [control (without spraying), boron (B) as boric acid, 17.4% B (0.3 g l^{-1}), zinc (Zn) as zinc sulphate, 22.8% Zn (2 g l^{-1}), iron (Fe) as ferrous sulphate, 20% Fe (2 g l^{-1}) and the mixture of them (B+ Zn+ Fe)] as the sub plots on growth, yield, its ingredients and chemical constituents of canola plants (*Brassica napus* L.) var. Serw 4. A split-plot design with 3 replicates was employed for the experiment. The experiment layout is shown in Table 2.

The entire experimental area included 60 plots. The sub plot measured 12 m^2 (3m ×4m). Seeds of canola were sown on 10th November during the two growing winter seasons at amount of 4 kg fed^{-1}. Elemental sulfur (98% S) was added to the soil with four rates (control, 100, 150 and 200 kg S fed^{-1}) and Mono calcium phosphate (15% P_2O_5) was added with the soil preparation at an average of 200 kg fed^{-1}. Urea (46.5% N) was applied at an average of 65 kg fed^{-1} for canola plants after 25 and 45 days from sawing. Potassium sulfate (48% K_2O) was added with the second dose of N fertilizer at an average of 50 kg fed^{-1}. Canola plants were sprinkled with micronutrients in the form of mineral after 30 and 60 days from sawing. These micronutrients were obtained from Al - Gomhoria Company for medicines and medical supplies. All other cultural practices were carried out in accordance with the Ministry of Agriculture and Soil Reclamation's (MASR) recommendations.

Table 1. The properties of the experimental field during two seasons before planting (the combined data over both studied seasons).

Particle size distribution (%)				Textural class	EC, soil past, (dSm^{-1})	pH (1:2.5, soil: water Susp.)	Organic matter (%)
C. sand	F. sand	Silt	Clay				
5.12	14.11	35.74	45.03	Clayey	4.31	8.10	1.42

Soluble ions ($mmol\ L^{-1}$)								Available elements, $mg\ Kg^{-1}$		
Soluble cations				Soluble anions						
K^+	Na^+	Mg^{++}	Ca^{++}	HCO_3^-	CO_3^{--}	SO_4^{--}	Cl^-	N	P	K
4.10	23.10	7.31	8.59	2.00	0.00	21.48	19.62	42.62	9.65	200.35

Table 2. The experiment layout.

Main factor	Sub main factor	Replicates		
Control (ES0)	Cont.	R_1	R_2	R_3
	Boron (B)	R_1	R_2	R_3
	Zinc (Zn)	R_1	R_2	R_3
	Iron (Fe)	R_1	R_2	R_3
	B+ Zn + Fe	R_1	R_2	R_3
Elemental sulfur 100	Cont.	R_1	R_2	R_3
	Boron (B)	R_1	R_2	R_3
	Zinc (Zn)	R_1	R_2	R_3
	Iron (Fe)	R_1	R_2	R_3
	B+ Zn + Fe	R_1	R_2	R_3
Elemental sulfur 150	Cont.	R_1	R_2	R_3
	Boron (B)	R_1	R_2	R_3
	Zinc (Zn)	R_1	R_2	R_3
	Iron (Fe)	R_1	R_2	R_3
	B + Zn + Fe	R_1	R_2	R_3
Elemental sulfur 200	Cont.	R_1	R_2	R_3
	Boron (B)	R_1	R_2	R_3
	Zinc (Zn)	R_1	R_2	R_3
	Iron (Fe)	R_1	R_2	R_3
	B + Zn + Fe	R_1	R_2	R_3

Data recorded

Pigments and chemical composition

At the maximum vegetative growth stage, i.e., 70 days from sawing, five fresh leaves of plants were taken randomly from each plot to determine chlorophyll a, b and a+b ($mg\ g^{-1}$ FW) according to the method of **Nayek *et al.* (2014)**. The leaves samples were dried at 70 ^{0}c to determine N, P, K, S (%), B, Zn and Fe ($mg\ kg^{-1}$) using the methods described by **Walinga *et al.* (2013).**

Yield and yield parameters:

- Plants were collected from each plot randomly at harvesting (after 170 days from planting) to measure some yield parameters i.e.: plant height (cm), branches No. $plant^{-1}$, pods No. $plant^{-1}$, weight of 1000 seed (g) and seed yield ($kg\ fed^{-1}$).

- N, P, K, S (%), B, Zn and Fe ($mg\ kg^{-1}$) in seeds were measured as formerly mentioned with leaves.

- Macro and micronutrients uptake were calculated according to formula:

$$\text{Nutrients uptake in mature seeds} = \frac{\text{Nutrient concentration x seeds yield kg fed}^{-1}}{100}$$

- Protein content (%) was calculated by multiplication N% x 6.25 **(Kelly and Bliss 1975).** Protein yield ($kg\ fed.^{-1}$) calculated by multiply protein % x seed yield.

- Oil content (%) was determined by soxhelt apparatus using petroleum ether as a solvent as described by **A.O.A.C. (1995).** Oil yield ($kg\ fed.^{-1}$) calculated by multiply oil % x seed yield.

Soil analyses

- Available nutrients in the soil as N, P, K and S (mg kg^{-1}) as well as soil pH were measured after canola plants harvest.

Statistical Analyses

Data from two years of identical experiments were pooled for analysis. The LSD test and Duncan's Multiple Comparisons Test were used to evaluate whether there were significant differences in treatment means at P 0.05. According **to Gomez and Gomez (1984)** and **Snedecor and Cochran (1980),** data from the current study were statistically analyzed using COSTATE Computer Software.

Results

1- Chlorophyll Content after 70 days from sawing.

The mean results observed in Table (3) showed the impact of elemental sulfur (ES) application rates and foliar application of some micronutrients as well as their interactions on chlorophyll content of canola plants. The results manifested that all treatments have a significant effect on chl. a, chl. b and chl. a+b contents. ES application at rate of 200 kg fed^{-1} has a positive effect on chlorophyll contents, the values increased by 4.46 , 17.99 and 8.33 % for chl. a, chl. b and chl. a+b, respectively comparing with the control.

Table 3. Mean effect of different elemental sulfur rates and some micronutrients foliar application and their interactions on chlorophyll content (mg g^{-1} FW) of canola after 70 day from sawing.

Treatments	Chlorophyll content (mg g^{-1} Fw)		
	Chl. A	**Chl. B**	**Chl. a+b**
Main: elemental sulfur rates (kg fed^{-1})			
Control. (ES0)	0.873^{d}	0.339^{d}	1.212^{d}
Elemental sulfur 100	0.889^{c}	0.358^{c}	1.247^{c}
Elemental sulfur 150	0.896^{b}	0.376^{b}	1.273^{b}
Elemental sulfur 200	0.912^{a}	0.400^{a}	1.313^{a}
F test	***	***	***
LSD at 0.05%	0.002	0.001	0.003
Sub main: foliar micronutrient treatments			
Cont. (without spraying)	0.885^{d}	0.359^{e}	1.244^{e}
Boron (B)	0.889^{c}	0.363^{d}	1.252^{d}
Zinc (Zn)	0.893^{b}	0.368^{c}	1.262^{c}
Iron (Fe)	0.897^{ab}	0.374^{b}	1.271^{b}
B+ Zn+ Fe	0.899^{a}	0.378^{a}	1.278^{a}
F test	***	***	***
LSD at 0.05%	0.003	0.003	0.005
Interactions			
LSD at 0.05%	0.007	0.007	0.010

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

On the other hand, the foliar application with the mixture of (B+ Zn+ Fe) gave the highest values of chlorophyll content with increments 1.58, 5.29 and 2.73% for chl. a, chl. b and chl. a+b, respectively than control (without foliar application treatments). Furthermore, it appeared that interaction between application of ES at 200 kg fed^{-1} and foliar application with the mixture of (B+ Zn+ Fe) indicated the highest values of chlorophyll content of canola plants.

1- Vegetative Nutrient Contents after 70 days from sawing.

It is clear from the average data in Table (4) that the application of elemental sulfur gave the highest values of the studied macro and micronutrients contents i.e. N, P, K, S, Fe, Zn and B compared to the absence of sulfur treatment. The highest values of nutrients (3.51% of N, 0.395% of P, 3.61% of K, 1.04% of S, 69.05 mg. g^{-1} of Fe, 45.83 mg. g^{-1} of Zn and 21.99 mg. g^{-1} of B) were recorded at the application of ES 200 kg fed^{-1}. Macronutrients increased by 19.80% for N, 20.42% for P, 21.14% for K and 61.49% for S while micronutrients increased by13.10% for Fe, 15.82% for Zn and 35.57% for B comparing with the control (ES0).

On the other hand, micronutrients foliar application increased N, P, K and S content of canola leaves by 7.34%, 7.40%, 8.12% and 18.47, respectively as well as Fe, Zn and B content by 5.00%, 5.92% and 12.96% compared with the control treatment, where foliar application with the mixture of (B+ Zn+ Fe) foliage recorded the highest significant values of all studied nutrients of canola leaves.

The interaction of elemental sulfur application at 200 kg fed^{-1} with foliar application with the mixture of (B+ Zn+ Fe) recorded the highest values of macro and micronutrients i.e., N, P, K, S, Fe, Zn and B concentration in canola leaves.

Table 4. Mean effect of different elemental sulfur rates and some micronutrients foliar application and their interactions on nutrients content of canola leaves after 70 day from sawing.

Treatments	Macronutrients %				Micronutrients mg kg $^{-1}$		
	N	P	K	S	Fe	Zn	B
Main: elemental sulfur rates (kg fed^{-1})							
Control. (ES0)	2.93^{d}	0.328^{d}	2.98^{d}	0.644^{d}	61.05^{d}	39.57^{d}	16.22^{d}
Elemental sulfur 100	3.15^{c}	0.353^{c}	3.24^{c}	0.795^{c}	64.24^{c}	41.84^{c}	18.37^{c}
Elemental sulfur 150	3.4^{b}	0.385^{b}	3.53^{b}	0.978^{b}	67.73^{b}	45.66^{b}	21.02^{b}
Elemental sulfur 200	3.51^{a}	0.395^{a}	3.61^{a}	1.040^{a}	69.05^{a}	45.83^{a}	21.99^{a}
F test	***	***	***	***	***	***	***
LSD at 0.05%	0.004	0.005	0.027	0.015	0.393	0.130	0.075
Sub main: foliar micronutrient treatments							
Cont. (without spraying)	3.13^{e}	0.351^{e}	3.20^{e}	0.785^{e}	63.78^{d}	41.56^{d}	18.12^{e}
Boron (B)	3.19^{d}	0.358^{d}	3.27^{d}	0.824^{d}	64.59^{c}	43.16^{c}	20.05^{d}
Zinc (Zn)	3.27^{c}	0.367^{c}	3.36^{c}	0.877^{c}	65.85^{b}	43.74^{b}	18.76^{c}
Iron (Fe)	3.31^{b}	0.372^{b}	3.41^{b}	0.907^{b}	66.38^{ab}	43.61^{b}	19.61^{b}
B+Zn+Fe	3.36^{a}	0.377^{a}	3.46^{a}	0.930^{a}	66.97^{a}	44.02^{a}	20.47^{a}
F test	***	***	***	***	***	***	***
LSD at 0.05%	0.040	0.004	0.040	0.019	0.799	0.151	0.0059
Interactions							
LSD at 0.05%	0.105	0.008	0.081	0.038	1.59	0.302	0.127

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

2- Yield and yield components

Data tabulated in Table (5) indicated that the sulfur fertilization and micronutrients foliar application affected positively on yield and yield attributed i.e. plant height (cm), No of branches plant^{-1}, No. of pods Plant^{-1}, 1000 seed weight (g) and seed yield ton.fed^{-1} of canola plant.

Elemental sulfur application treatments increased the yield of canola comparing with the control treatment. Elemental sulfur application at 200 kg fed^{-1} recorded the highest values of yield (1538 kg fed^{-1}) with relative increment 22.19%. Also, it increased yield attributes by 11.20% for plant height, 18.50% for No. of branches plant^{-1}, 24.54% for No. of pods plant^{-1} and 18.23% for 1000 seed weight.

On the other hand, the foliar application of the mixture of (B+ Zn+ Fe) treatment increased all studied treatments, For example, the value of the yield increased by 7.89% comparing with the non-foliar application.

The interaction of elemental sulfur 200 kg fed^{-1} application and foliar application with the mixture of (B+ Zn+ Fe) achieved the highest values of yield and yield parameters of the canola plant.

4- Nutrients content in canola seeds

Nutrients content of canola seeds as affected by elemental sulfur applications with or without micronutrients foliar application was indicated in Tables (6 and 7). Elemental sulfur applications positively affected the nutrients and their uptake by seeds and the values increased by increasing elemental sulfur rate to 200 kg fed^{-1}. The macronutrients uptake increased by 15.63 % for N, 27.10% for P, 28.13 % for K and 89.97% for S as well as uptake of micronutrients increased by 53.10% for Fe, 19.93% for Zn and 23.34% for B.

Micronutrients foliar application increased values of the nutrients and their uptake by canola seeds. B+ Zn+ Fe foliar application achieved the highest values of nutrients (3.79 % for N, 0.315% for P, 2.70% for K, 0.585% for S, 46.49 mg. kg^{-1} for Fe, 29.51 mg. kg^{-1} for Zn and 16.36 mg. kg^{-1} for B) . Otherwise, their uptake increased by 33.08, 18.93, 18.76 and 39.49 % for N, P, K and S as well as 27.11, 16.00 and 17.56% for Fe, Zn and B, respectively.

Table 5. Mean effect of different elemental sulfur rates and some micronutrients foliar application and their interactions on yield and yield parameters of canola.

Treatments	Plant height (cm)	Branches No. plant^{-1}	Pods No. plant $^{-1}$	1000 seed weight (g)	seed yield (kg fed^{-1})
Main: elemental sulfur rates (kg fed^{-1})					
Control. (ES0)	132.49^{d}	6.16^{d}	144.62^{d}	3.18^{d}	1259.19^{d}
Elemental sulfur 100	138.47^{c}	6.66^{c}	163.77^{c}	3.39^{c}	1398.59^{c}
Elemental sulfur 150	145.37^{b}	6.73^{b}	176.02^{b}	3.54^{b}	1501.35^{b}
Elemental sulfur 200	147.33^{a}	7.30^{a}	180.12^{a}	3.76^{a}	1538.59^{a}
F test	***	***	***	***	***
LSD at 0.05%	0.515	0.039	0.049	0.023	0.349
Sub main: foliar micronutrient treatments					
Cont. (without spraying)	128.15^{e}	4.89^{e}	138.34^{e}	3.14^{e}	1380.07^{e}
Boron (B)	137.35^{d}	6.75^{d}	155.15^{d}	3.38^{d}	1408.41^{d}
Zinc (Zn)	139.90^{c}	6.93^{c}	169.37^{c}	3.53^{c}	1432.75^{c}
Iron (Fe)	146.65^{b}	7.30^{b}	181.43^{b}	3.59^{b}	1456.78^{b}
B+Zn+Fe	152.53^{a}	7.69^{a}	186.37^{a}	3.70^{a}	1488.89^{a}
F test	***	***	***	***	***
LSD at 0.05%	0.841	0.022	0.034	0.041	0.328
Interactions					
LSD at 0.05%	1.68	0.045	0.068	0.083	0.656

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

The interaction of elemental sulfur at 200 kg fed^{-1} and foliar application with the mixture of (B+ Zn+ Fe) improved N, P, K, S, Zn, B & Fe concentrations and their uptake.

5- Yield quality

As shown in Table (8) oil and protein contents (%) and yields (kg fed^{-1}) in canola seeds were increased significantly with increasing elemental sulfur rates. Sulfur application at rate 200 kg fed^{-1} improved oil and protein contents of canola seeds where oil yield increased by 44.99% and protein yield increased by 37.18 % as compared to control.

It is evident from tabulated statistics that (B+ Zn+ Fe) as a foliar application improved oil concentration (36.17%) and protein concentration (23.69 %) and yields increased by 17.42 and 14.82% for oil and protein, respectively of canola seeds followed by Fe> Zn> B and lately control treatment.

The interaction of elemental sulfur at 200 kg fed^{-1} and foliar application with the mixture of (B+ Zn+ Fe) enhanced quality i.e. oil and protein yield of canola.

Table 6. Mean effect of different elemental sulfur rates and some micronutrients foliar application and their interactions on nutrients concentration of canola seeds.

Treatments	Macronutrients Concentration (%)				Micronutrients Concentration (mg kg^{-1})		
	N	P	K	S	Fe	Zn	B
Main: elemental sulfur rates (kg fed^{-1})							
Control. (ES0)	3.39^{d}	0.262^{d}	2.24^{d}	0.349^{d}	33.35^{d}	25.74^{d}	13.97^{d}
Elemental sulfur 100	3.59^{c}	0.289^{c}	2.49^{c}	0.463^{c}	40.31^{c}	27.61^{c}	15.13^{c}
Elemental sulfur 150	3.83^{b}	0.322^{b}	2.77^{b}	0.614^{b}	48.34^{b}	30.00^{b}	16.67^{b}
Elemental sulfur 200	3.92^{a}	0.333^{a}	2.87^{a}	0.663^{a}	51.06^{a}	30.87^{a}	17.23^{a}
F test	***	***	***	***	***	***	***
LSD at 0.05%	0.023	0.004	0.015	0.015	0.061	0.052	0.085
Sub main: foliar micronutrient treatments							
Cont. (without spraying)	3.56^{e}	0.285^{e}	2.46^{e}	0.451^{e}	39.45^{e}	27.46^{e}	15.02^{e}
Boron (B)	3.62^{d}	0.294^{d}	2.53^{d}	0.492^{d}	41.31^{d}	27.99^{d}	16.12^{d}
Zinc (Zn)	3.70^{c}	0.304^{c}	2.61^{c}	0.528^{c}	43.88^{c}	29.10^{c}	15.38^{c}
Iron (Fe)	3.74^{b}	0.310^{b}	2.65^{b}	0.555^{b}	45.20^{b}	28.72^{b}	15.89^{b}
B+Zn+Fe	3.79^{a}	0.315^{a}	2.70^{a}	0.585^{a}	46.49^{a}	29.51^{a}	16.36^{a}
F test	***	***	***	***	***	***	***
LSD at 0.05%	0.028	0.003	0.030	0.013	0.156	0.100	0.181
Interactions							
LSD at 0.05%	0.057	0.006	0.092	0.026	0.312	0.201	0.360

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 7. Mean effect of different elemental sulfur rates and some micronutrients foliar application and their interactions on nutrients uptake of canola seeds.

Treatments	Macronutrients Uptake (Kg fed^{-1})				Micronutrients Uptake (g fed^{-1})		
	N	**P**	**K**	**S**	**Fe**	**Zn**	**B**
Main: elemental sulfur rates (kg fed^{-1})							
Control. (ES0)	44.01^{d}	3.40^{d}	29.04^{d}	4.54^{d}	432.87^{d}	333.59^{d}	181.13^{d}
Elemental sulfur 100	50.24^{c}	4.05^{c}	34.87^{c}	6.48^{c}	564.18^{c}	386.29^{c}	211.76^{c}
Elemental sulfur 150	57.68^{b}	4.84^{b}	41.70^{b}	9.25^{b}	727.16^{b}	450.75^{b}	250.51^{b}
Elemental sulfur 200	60.37^{a}	5.13^{a}	44.21^{a}	10.22^{a}	787.02^{a}	475.38^{a}	265.39^{a}
F test	***	***	***	***	***	***	***
LSD at 0.05%	0.317	0.076	0.212	0.266	1.05	0.849	1.12
Sub main: foliar micronutrient treatments							
Cont. (without spraying)	49.33^{e}	3.96^{e}	34.16^{e}	6.33^{e}	550.04^{e}	380.61^{d}	208.37^{e}
Boron (B)	51.21^{d}	4.17^{d}	35.84^{d}	7.04^{d}	587.53^{d}	395.75^{c}	228.27^{d}
Zinc (Zn)	53.33^{c}	4.39^{c}	37.70^{c}	7.70^{c}	636.31^{c}	419.10^{b}	221.47^{c}
Iron (Fe)	54.85^{b}	4.54^{b}	38.98^{b}	8.22^{b}	665.96^{b}	420.53^{b}	232.89^{b}
B+Zn+Fe	56.65^{a}	4.71^{a}	40.57^{a}	8.83^{a}	699.20^{a}	441.51^{a}	244.98^{a}
F test	***	***	***	***	***	***	***
LSD at 0.05%	0.424	0.045	0.440	0.178	2.25	1.47	2.64
Interactions							
LSD at 0.05%	0.849	0.091	0.881	0.357	4.50	2.95	5.29

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 8. Mean effect of different elemental sulfur rates and some micronutrients foliar application and their interactions on oil and protein content of canola seeds.

Treatments	**Oil (%)**	**Oil yield (kg fed^{-1})**	**Protein (%)**	**Protein yield (kg fed^{-1})**
Main: elemental sulfur rates (kg fed^{-1})				
Control. (ES0)	31.11^{d}	403.19^{d}	21.22^{d}	275.07^{d}
Elemental sulfur 100	33.50^{c}	467.83^{c}	22.45^{c}	314.02^{c}
Elemental sulfur 150	36.77^{b}	552.67^{b}	23.99^{b}	360.51^{b}
Elemental sulfur 200	37.99^{a}	584.61^{a}	24.50^{a}	377.35^{a}
F test	***	***	***	***
LSD at 0.05%	0.046	2.09	0.145	1.98
Sub main: foliar micronutrient treatments				
Cont. (without spraying)	33.29^{e}	460.39^{e}	22.26^{e}	308.36^{e}
Boron (B)	34.03^{d}	481.37^{d}	22.66^{d}	320.10^{d}
Zinc (Zn)	35.11^{c}	506.01^{c}	23.16^{c}	333.32^{c}
Iron (Fe)	35.62^{b}	522.01^{b}	23.43^{b}	342.82^{b}
B+Zn+Fe	36.17^{a}	540.60^{a}	23.69^{a}	354.07^{a}
F test	***	***	***	***
LSD at 0.05%	0.106	2.62	0.180	2.65
Interactions				
LSD at 0.05%	0.212	5.25	0.360	5.30

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

6- Available Nitrogen, Phosphorus, Potassium, Sulfur and pH in soil post harvesting

Available nutrients i.e. N, P, K and S (mg kg^{-1}) status in the soil as well as pH after canola harvesting were shown in Figs. 1, 2, 3, 4 and 5, respectively. It's clear that available N, K and pH in the soil decreased with the addition of elemental sulfur applications comparing with untreated. While, the available P and S values were increased in the soil treated with elemental sulfur applications than that untreated.

Regarding to the foliar micronutrient treatments, they reduce the average of available nitrogen, phosphorus, potassium and Sulfur (mg kg^{-1}) in the soil post harvesting compared to the without foliar application treatment (control) and they aren't significantly affected on soil pH values.

The interaction of ES and micronutrients recorded the lowest values of the available N, K and pH of the soil, while it increased values of available P and S nutrients.

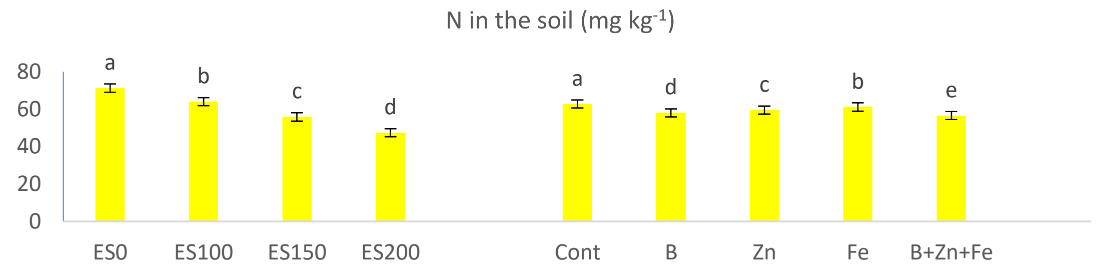

Fig. 1. Individual mean effect of different elemental sulfur rates and some micronutrients foliar application on available N (mg kg^{-1}) in the soil after harvesting.

ES0: Without sulfur addition (as control); **ES100:** Sulfur addition at a rate of 100kg S fed^{-1}; **ES150:** Sulfur addition at a rate of 150 kg S fed^{-1}); **ES200:** Sulfur addition at a rate of 200kg S fed^{-1}**;Cont:** without spraying; **B:** Foliar spraying with boron; **Zn:** Foliar spraying with **zinc; Fe:** Foliar spraying with iron.

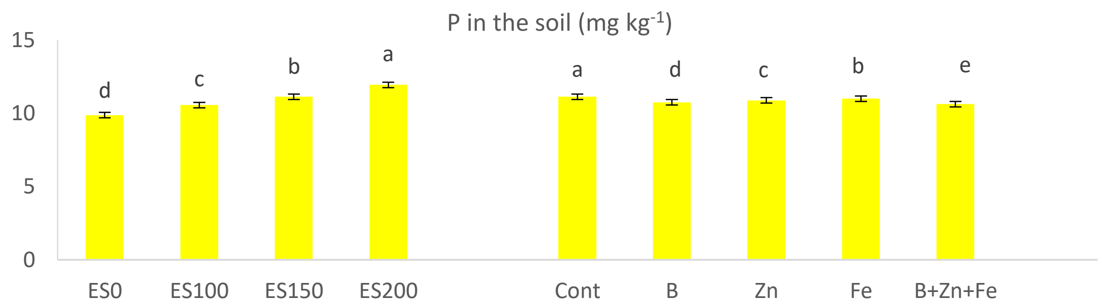

Fig 2. Individual mean effect of different elemental sulfur rates and some micronutrients foliar application on available P (mg kg^{-1}) in the soil after harvesting.

ES0: Without sulfur addition (as control); **ES100:** Sulfur addition at a rate of 100kg S fed^{-1}; **ES150:** Sulfur addition at a rate of 150 kg S fed^{-1}); **ES200:** Sulfur addition at a rate of 200kg S fed^{-1}**;Cont:** without spraying; **B:** Foliar spraying with boron; **Zn:** Foliar spraying with **zinc; Fe:** Foliar spraying with iron.

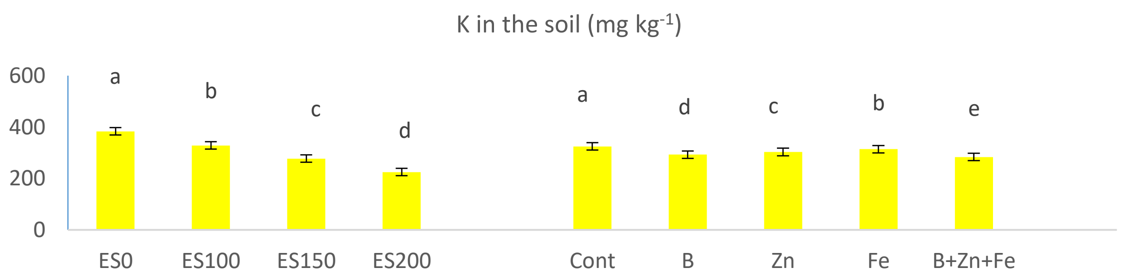

Fig. 3. Individual mean effect of different elemental sulfur rates and some micronutrients foliar application on available K (mg kg^{-1}) in the soil after harvesting.

ES0: Without sulfur addition (as control); **ES100:** Sulfur addition at a rate of 100kg S fed^{-1}; **ES150:** Sulfur addition at a rate of 150 kg S fed^{-1}); **ES200:** Sulfur addition at a rate of 200kg S fed^{-1}**;Cont:** without spraying; **B:** Foliar spraying with boron; **Zn:** Foliar spraying with **zinc; Fe:** Foliar spraying with iron.

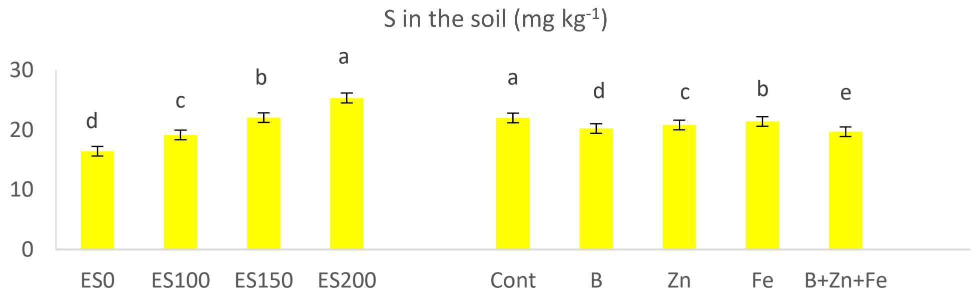

Fig. 4. Individual mean effect of different elemental sulfur rates and some micronutrients foliar application on available S (mg kg^{-1}) in the soil after harvesting.

ES0: Without sulfur addition (as control); **ES100:** Sulfur addition at a rate of 100kg S fed^{-1}; **ES150:** Sulfur addition at a rate of 150 kg S fed^{-1}); **ES200:** Sulfur addition at a rate of 200kg S fed^{-1}**;Cont:** without spraying; **B:** Foliar spraying with boron; **Zn:** Foliar spraying with **zinc; Fe:** Foliar spraying with iron.

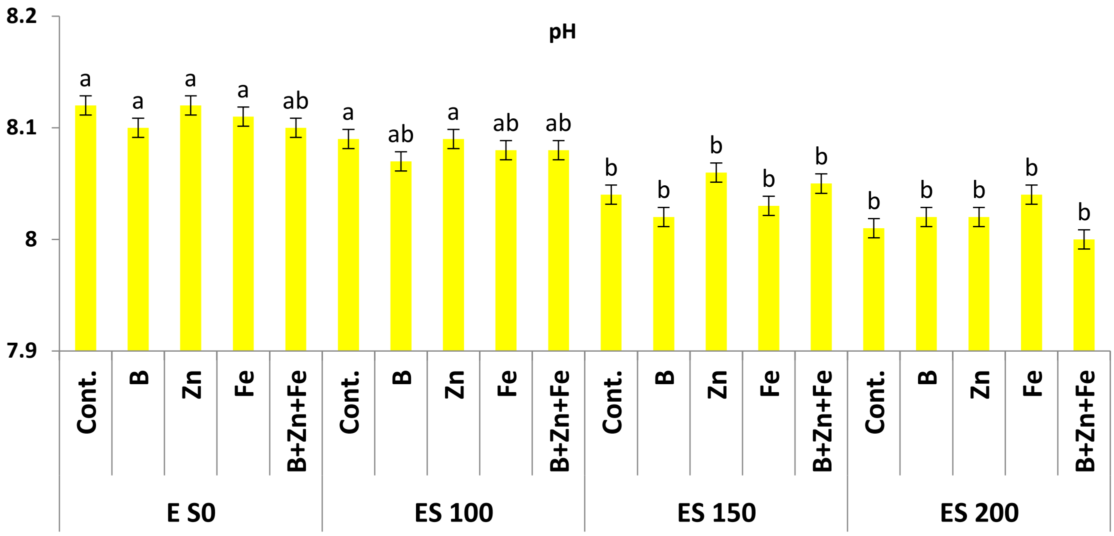

Fig. 5. Interaction mean effect of different elemental sulfur rates and some micronutrients foliar application on pH in the soil after harvesting.

ES0: Without sulfur addition (as control); **ES100:** Sulfur addition at a rate of 100kg S fed^{-1}; **ES150:** Sulfur addition at a rate of 150 kg S fed^{-1}); **ES200:** Sulfur addition at a rate of 200kg S fed^{-1}**;Cont:** without spraying; **B:** Foliar spraying with boron; **Zn:** Foliar spraying with **zinc; Fe:** Foliar spraying with iron.

Discussion

Numerous environmental challenges like drought, salt, severe temperatures and nutrient deficiency have a significant impact on the production and cultivation of agricultural crops **(Latef *et al*. 2021).** Although the soil in which the experiment carried out is affected by salts, it doesn't negatively affect canola, as it is a salinity-tolerant plant up to 8 dsm^{-1} (**Al-Thabet 2003**).

1- Effect of the elemental sulfur (ES) application rates:

Increasing the level of elemental sulfur fertilizers to 200 kg S fed^{-1} resulted the highest vegetative growth values compared to the control (ES0) due to the sulfur is an essential nutrient for plant growth, and canola requires an adequate supply of sulfur for optimal development. By providing with higher levels of sulfur through fertilizer applications, the plants had improved nutrient uptake, enhanced metabolic processes, and increased biomass accumulation, leading to better vegetative growth.

In addition to these results may be due to the importance of sulfur for chlorophyll production where it has a vital role in cell division aided leaf growth and improved light absorption. (**Rameeh *et al*. 2021**). Also, it promotes releasing nutrients which involved in synthesis of enzymes that are responsible for chlorophyll synthesis (**Younis *et al*. 2020**).

For increments of nutrients content in canola leaves may be attributed to the decrements of soil pH by sulfur applications that increased some nutrients availability in the soil and thus increased nutrients uptake by plants (**Ma *et al.* 2019).**

Also, the higher level of elemental sulfur (200 kg S fed^{-1}) contributed to increase effective yield and its constituent parts and this may be due to the vital role of Sulfur in various physiological processes, including photosynthesis, protein synthesis, and oil production. By providing sufficient sulfur, the plants were able to maximize their yield potential, resulting in higher seed yield, oil yield, and protein yield.

Sulfur application increased yield, yield attributes and productivity of canola as a result of its vital role in synthesis of sulfur-amino acids as well as it promotes special enzyme systems in plants **(Balint and Rengel 2009)**. These results are in accordance with that recorded by **Ewees and El- Sowfy (2013) and Varényiová *et al*. (2017).**

Regarding to available nutrients status in the soil after canola harvesting as well as soil pH, it’s clear that the addition of elemental sulfur applications decreased available N and K as a result of the positive effect of ES in increasing nutrient soil availability that led to increasing nutrients uptake by plants from the soil (**Rameeh *et al*. 2021** and **Ali 2018)**.

While, available phosphorus and sulfur increased by increasing ES rates application where ES oxidized in soil forming sulfuric acid that reducing soil pH values, improving aggregation and boosting the availability of phosphorus nutrients to improve the relationship between soil and water (**Malhi *et al.* 2007**) and (**Blum *et al.* 2013**).

2- Effect of micronutrients foliar application

Applying foliar treatment with a mixture of micronutrients (B, Zn, and Fe) had a significant positive effect on all growth parameters, yield, oil yield, and protein yield. Micronutrients are essential for plant growth and development, albeit required in smaller quantities compared to macronutrients. The foliar application of micronutrients ensured their direct uptake by plant, addressing any potential deficiencies and improving overall nutrient balance, leading to enhanced growth and yield.

Foliar application of the mixture of (B+ Zn+ Fe) gave the highest values of chlorophyll content, nutrients content in leaves and seeds as well as highest values of yield productivity and quality. These results are in harmony with that recorded by (**Olama et al. 2014).**

Zinc has a vital role in regulating the concentration of auxin that increases the majority of plant's physiological and metabolic activities, which help plants absorb more nutrients from the soil **(Mian et al. 2021).** Zinc accelerated photosynthesis process, the movement of photo assimilates, and the production of proteins (**Shaaban *et al.* 2023).**

Iron is an important nutrient for cell metabolism, chlorophyll production, photosynthesis, respiration and enzymes activity **(Riki *et al.* 2014).** In addition to, both of iron and zinc act as a co-factor of most enzymes and also have an effective role in cell division and protein synthesis (**Dhaliwal *et al.* 2021).**

On the other hand, boron effects on transfer of water and nutrients from root to shoot, has a vital role in chlorophyll production and enhances the formation of carbohydrates (**Shoja *et al.* 2018**). Also, it’s responsible for carbohydrates metabolism, pollen germination, protein synthesis and seed & cell wall development. These results are in harmony with that concluded by **Manaf (2019).**

Foliar micronutrient treatments reduce the average amount of accessible nitrogen, phosphorus, potassium and Sulfur (mg kg^{-1}) in the soil after harvesting compared to the control treatment (without foliar applications) because of enhancing plant growth and nutrients uptake by canola. While micronutrient foliar applications doesn't effect on soil pH values significantly, these results are in accordance with that recorded by **Rahman and Schoenau (2020).**

3- Interaction effect

The interaction between applying 200 kg S fed^{-1} of elemental sulfur and foliar treatment with the mixture of B, Zn, and Fe resulted in the highest values for canola plant development, yield, and its components. This suggests that the combined application of sulfur in the soil and foliar-applied micronutrients had a synergistic effect, optimizing nutrient availability and utilization by the plants, thus maximizing their growth and productivity.

The control treatment (ES0 x without foliar) led to the highest remaining nitrogen (N) and potassium (K) concentrations in the soil as well as soil pH, indicating that these nutrients were not fully utilized by the canola plants. Conversely, applying 200 kg S fed^{-1} of elemental sulfur without foliar treatment resulted in the highest remaining phosphorus (P) and sulfur (S) concentrations. These observations suggest that the different treatments affected nutrient uptake and utilization by the plants, influencing the remaining nutrient concentrations in the soil.

Conclusion

Based on the results of the field trials, it can be concluded that achieving self-sufficiency in canola oil production in Egypt is feasible. Canola demonstrates adaptability to different climates and holds potential for cultivation in the country. The study highlighted the significance of elemental sulfur (ES) soil applications and micronutrient foliar treatments in promoting canola growth, yield, and its components. Increasing the level of sulfur fertilizer to 200 kg S fed^{-1} resulted in the highest vegetative growth and effective yield, while foliar treatment with a mixture of micronutrients positively influenced all growth parameters, yield, oil yield, and protein yield. The interaction between these treatments exhibited synergistic effects, further enhancing canola productivity. Proper nutrient management and the utilization of sulfur and micronutrients are key factors in maximizing canola production.

Generally, further research should be conducted to explore the optimal application rates of sulfur fertilizer and micronutrient foliar treatments for canola production in different regions of Egypt. This will help refine nutrient management practices and maximize crop productivity. By implementing these recommendations, Egypt can harness the potential of canola as an oil crop, reduce dependence on imported oils, and achieve self-sufficiency in canola oil production, contributing to improved food security and agricultural sustainability in the country.

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