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RESEARCH ARTICLE

Exploring the effects of nitrogen and zinc treatments on some agronomic parameters and zinc biofortification in sesame (*Sesamum indicum* L.)

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ABSTRACT

Biofortification appears to be the most appropriate strategy for nutrient enrichment in sesame (*Sesamum indicum* L.) Agronomic techniques in sesame, an important source of oil, protein, and nutrients, can have a significant impact on healthy nutrition. The research was conducted in Manavgat-Antalya, Türkiye, in 2022 and 2023. The experiment was designed with three replicates according to a factorial experimental design, with four different N doses (0, 30, 60, and 90 kg ha^{-1}; N_0-N_3, respectively) applied to the plots and four different Zn doses (0%, 0.15%, 0.30%, and 0.45% zinc sulphate, $ZnSO_4 \cdot 7H_2O$) applied to sesame plants. The results showed that N treatments had significant effects on number of capsules, seed yield, number of seeds per capsule, N and protein content in seeds, and oil content. The N_3 application (90 kg N ha^{-1}) resulted in the highest seed yield (14.5 and 18.4 g plant^{-1}, respectively), number of seeds per capsule (65.7 and 80.8 nr plant^{-1}), and protein content (28.4% and 26.9%, respectively) in both years compared to the control group (N_0). Zinc treatments resulted in an increase in Zn and oil content in seeds. The 0.45% $ZnSO_4$ treatments resulted in the maximum Zn concentration in seeds in both years (77.4 and 76.8 mg kg^{-1}, respectively). 0.15%-0.30% $ZnSO_4$ treatment doses resulted in the maximum oil content. In the N×Zn interaction, the highest number of seed per capsule (86.2 nr plant^{-1}) was obtained at the N_1Zn_1 treatment dose, while the highest oil content was obtained with N_0Zn_2 (59.4%) and N_3Zn_1 (59.2%). Considering their effects on capsules number, number of seeds per capsule, and seed oil content, it is also possible that the combined treatment of N and Zn significantly improves sesame quality. Foliar Zn treatment is effective in Zn accumulation in the seed and contributes to nutrient enrichment in sesame.

Key words: Biofortification, mineral nutrition, nitrogen, oil content, sesame, zinc.

INTRODUCTION

In societies whose diet is mostly based on cereals, micronutrient intakes have started to decrease due to the increase in the cultivation of cereals. The majority of cereal grains are deficient in micronutrients (Waqeel and Khan, 2022). Micronutrient malnutrition resulting from a lack of adequate micronutrients in the diet leads to serious but often invisible health consequences, known as hidden hunger. More than 2 billion people in the world are affected by micronutrient deficiency (Zaman et al., 2018). People with Zn malnutrition may experience symptoms such as impaired brain function, stunting, infections, poor mental development, weakness and anemia in infants (Kyle, 2025). Zinc is required for different biochemical processes in plants such as chlorophyll synthesis, auxin metabolism, carbohydrate, lipid and nucleic acid metabolism (Zaman et al., 2018; Nandal and Solanki, 2021). Zinc is effective in seed germination, seedling development, tryptophan synthesis, protection against soil pathogens and nematodes and provides more tolerance against abiotic stresses (Taiz et al., 2017). Due to the negative effects of the factors affecting Zn uptake in soils on Zn accumulation in plants, the necessity of agronomic practices rather than breeding studies is more important. In this context, agronomic biofortification appears to be the most effective method for nutrient enrichment in edible parts of plants. Since cell proteins are usually bound by available Zn^{2+} (Thompson, 2022), Zn needs to be applied externally, as foliar spray or soil application to increase Zn availability in cereals. Zinc solution spraying or biofortification is a convenient and effective practice to improve the Zn status and thus the quality of the grains produced. Some studies have shown that people fed with products enriched with Zn through biofortification practices have a more adequate Zn intake than those fed with traditional products (Qin et al., 2012). An effective biofortification strategy should aim to ensure that grain Zn concentrations are sufficient for human health, rather than for grain yield (Zou et al., 2012). Since Zn deficiency is usually associated with cereal-based diets and people in developing countries depend on cereal-based diets for various reasons (low purchasing power, cultural preferences and high food prices), biofortification of cereals with Zn can be considered as the most effective solution to increase Zn intake (Cakmak and Kutman, 2018).

Sesame (*Sesamum indicum* L.) is markedly superior to other oilseed crops due to its high drought tolerance and wide adaptation to a variety of agroclimatic conditions (Kurt et al., 2018). Sesame proteins are rich in essential S-containing amino acids (methionine and tryptophan) (Sharma et al., 2021). Sesame is one of the main plants used for producing oil. It contains 80% unsaturated fatty acids and small amounts of saturated fatty acids (Ozdemir et al., 2018). Raw sesame seeds contain various phytochemicals, including terpenoids, saponins, alkaloids, steroids, tannins, flavonoids, sesamin, sesamol, sesamolin, gamma-tocopherol, 3-coumaroylquinic acid, protocatechuic acid, quinic acid, hydroxybenzoic acid, ellagic acid pentoside and quercetin 3.4-diglucoside (Zeb et al., 2017).

Zinc plays a vital role in improving the production and quality of sesame and is considered an essential element for protein synthesis, biological N fixation and various enzymatic activities (Shehu, 2014). In sesame, Zn deficiency results in reduced growth hormone production, shortened internodes, shortened leaves and seed deformation with low yield (Prakash and Ganesan, 2000). Under Zn deficiency conditions, flowering and capsule development in sesame are reduced, the growth period is prolonged, resulting in delayed maturity, lower yield, poor quality and sub-optimal nutrient use efficiency (Suresh et al., 2013). Zinc treatment can lead to increased biomass, disease resistance, and better seed quality, which in turn increases productivity. Biofortification is a method of improving the nutritional value of sesame, addressing micronutrient deficiencies in human nutrition, and increasing agricultural production (Guwela et al., 2024).

The objective of this study was to improve the nutrient content in sesame seeds to improve some growth parameters and quality traits of sesame seeds, with particular focus on soil and foliar application of N and Zn in sesame plant grown as a second crop behind the pods.

MATERIALS AND METHODS

Experimental area, climatic conditions and materials

The experiments were conducted in Manavgat-Antalya (36°53'39.6" N, 31°12'43.9" E), Türkiye, between May and November in 2022 and 2023. Some soil properties (0-20 cm) in field were as follows: Clayey in texture, 2.18% organic matter, 24.73% $CaCO_3$, pH 6.92, electrical conductivity (EC) 0.29 dS m^{-1}, 0.104% total N, 14.06 mg kg^{-1} available P, 0.31 meq 100 g^{-1} extractable K, 19.77 meq 100 g^{-1} extractable Ca and 1.93 meq 100 g^{-1} extractable Mg, 0.30 mg kg^{-1} available Zn, 9.88 mg kg^{-1} available Mn and 2.20 mg kg^{-1} available Cu. The experiment soil was at a medium level in terms of N and low level in terms of Zn, especially in the elements where the applications were made.

'Muganlı-57' sesame (*Sesamum indicum* L.) seeds used as planting material were supplied by the Batı Akdeniz Agricultural Research Institute in Antalya. 'Muganlı-57' was determined to have two carpels, 81.2 capsules per plant, 1000 seed weight was 3.94 g, seed yield was 1445 kg ha^{-1}, protein content was 21.3% and oil content was 48.6%.

The research was carried out in the summer of 2022 and 2023, and during the 2 yr research period, the maximum temperature value in July 2023 was determined as 44.7 °C. This period was seen as the period when plant development began and was effective in plant development. Average meteorological data (maximum, minimum and average temperature; rainfall) during the crop growing periods of the experiment are presented in Figure 1.

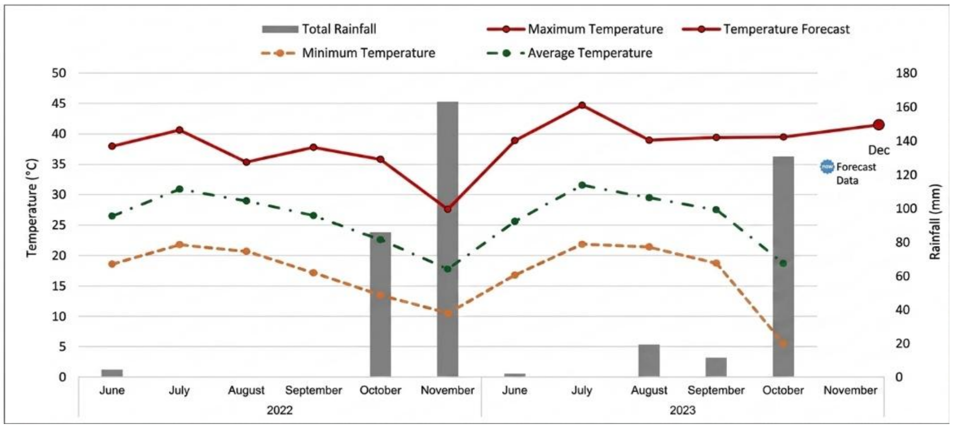

Figure 1. Average values of maximum, minimum and average air temperatures and rainfall for sesame crops in 2022-2023.

Experimental design and treatments

The experiment was designed as a factorial fitted into a randomized complete block design with three replicates. The factors were N rates (N_0: 0 kg N ha^{-1}, N_1: 30 kg N ha^{-1}, N_2: 60 kg N ha^{-1} and N_3: 90 kg N ha^{-1} with ammonium sulphate) and Zn rates (Zn_0: 0%, Zn_1: 0.15%, Zn_2: 0.30% and Zn_3: 0.45% as foliar zinc sulphate-$ZnSO_4 \cdot 7H_2O$). In both seasons, the previous crop was faba beans (*Vicia faba* L.) In autumn, the field was prepared for faba bean cultivation (winter ploughing). The faba beans were harvested in June and the soil was prepared for sesame seeding again. Immediately after preparing the soil, sesame seeds were sown in the field and cultivation began.

The distance between the rows was 70 cm and the distance in the rows was 3 cm, and 6 rows were planted with a planting machine in each plot. The plot size was 3.0 m × 3.0 m (48 plots, 9 m^2 each). Basal fertilization and N fertilizer application (N_0: 0 kg N ha^{-1}, N_1: 30 kg N ha^{-1}, N_2: 60 kg N ha^{-1}, N_3: 90 kg N ha^{-1} as ammonium sulphate) was carried out on the plots prior to seeding. Basal fertilizations were applied with 31 kg ha^{-1} P and 50 kg ha^{-1} K. The recommended doses of triple super phosphate (TSP) and potassium sulphate (PS) were applied full dose to the experimental field during land preparation. Four weeks after sowing, $ZnSO_4$ was applied in the morning with a knapsack sprayer. The plants were sprayed twice with $ZnSO_4$ at different stages of development (30 and 60 d after sowing, DAS). Plants similarly sprayed with water were used as controls. Zinc is preferred as $ZnSO_4 \cdot 7H_2O$, especially in foliar applications, as it increases the microelement content of edible parts. All necessary cultural and plant protection treatments were followed uniformly for all the treatments during the entire period of experimentation. Harvesting was carried out plot-wise when 90% of the pods were mature (at 95 DAS). The plants were then sun-dried in the greenhouse by spreading the bundles on the threshing floor, and the seeds were separated from the stover by beating the bundles.

Criteria examined in research

The plant height (PH), number of capsules (NoC), seed yield (SY), 1000 seed weight (1000SW), capsule length (CL), first branch height (FBH), number of sub-branches (NoSB), number of grain in capsule (NoGC), seed N and Zn levels, seed oil (OC) and protein content (PC) values were also determined in selected plants. The PH and CL were determined by metal ruler while SY and 1000SW by precision weighing. The concentrations of N and Zn were also analyzed in sesame seeds. For the Zn analysis of the leaf and seed samples, each dried plant and seed sample (0.5 g) was digested with an acid mixture of 10 mL $HNO_3/HClO_4$ (4:1) on a hot plate. The samples were then heated until a clear solution was obtained. This procedure was repeated several times. The Zn concentrations in the digests were determined using inductively coupled plasma (Optima DV7000 ICP-OES, PerkinElmer, USA) (Kacar, 2014). The total N was determined using the modified Kjeldahl method. Total protein percentage was calculated by multiplying the sesame seed N content by 6.25. The hot extraction method, based on the principles of determination of oil content in sesame seeds specified in AOAC (1990), was used using a Soxhlet (series bottle heater KI 26, Gerhardt Analytical Systems, Königswinter, Germany) system (James, 1995).

Statistical analysis

Statistical analyses were performed using the SAS (SAS Institute, Cary, North Carolina, USA) software package. The analysis compared data obtained from various treatments and performed an ANOVA. To compare means, the least significant difference test (Duncan) was used at a significance level of $p \leq 0.05$. Additionally, correlation coefficient-based analyses were performed using Minitab 21 (Minitab Inc., State College, Pennsylvania, USA) software. The JMP Pro 17 package (JPM Statistical Discovery, Cary, North Carolina, USA) was applied to calculate and visualize the PCA-Biplot analysis.

RESULTS

Some growth parameters, yield and quality traits in sesame

The effects of different N and Zn doses on plant height were found to be nonsignificant in 2022, and the highest values were obtained from all N treatments except control in 2023 (Table 1).

Table 1. Effect of different doses of N and Zn treatments on plant height, number of capsules, seed yield and number of seeds per capsule in 2022-2023. N rates (kg N ha^{-1}): N_0: 0, N_1: 30, N_2: 60 and N_3: 90 with ammonium sulphate; Zn rates (%): Zn_0: 0, Zn_1: 0.15, Zn_2: 0.30 and Zn_3: 0.45 as foliar zinc sulphate-$ZnSO_4 \cdot 7H_2O$. Means followed by the same letter in each treatment group are not significantly different at 5% level of probability using Duncan multiple range test. ^{ns}Nonsignificant at 5% level of probability; *Significant at 5% level of probability; ***Significant at 0.1% level of probability.

Treatments		Plant height		Capsules per plant		Seed yield		Seeds per capsule	
		2022	2023	2022	2023	2022	22023	2022	2023
		cm		nr $plant^{-1}$		g $plant^{-1}$		nr $plant^{-1}$	
N fertilizer	N_0	136.9	102.2^{b}	37.5	28.0^{c}	8.1^{c}	9.2^{d}	60.5^{b}	73.5^{c}
	N_1	137.1	128.7^{a}	39.9	75.7^{a}	11.6^{b}	12.9^{c}	65.3^{a}	84.7^{a}
	N_2	135.9	131.2^{a}	35.6	57.2^{b}	12.3^{b}	15.1^{b}	61.0^{b}	76.3^{c}
	N_3	136.8	133.7^{a}	45.0	54.9^{b}	14.5^{a}	18.4^{a}	65.7^{a}	80.8^{b}
Zn fertilizer	Zn_0	136.0	122.9	40.6	58.1^{ab}	11.0^{bc}	14.5	62.8	78.1
	Zn_1	140.0	127.6	41.1	47.7^{b}	12.10^{ab}	14.3	62.8	79.2
	Zn_2	135.3	121.6	36.2	46.9^{b}	10.9^{c}	13.0	62.3	78.3
	Zn_3	135.4	123.8	40.1	63.1^{a}	12.5^{a}	13.7	64.7	79.7
Significance	N	0.03^{ns}	26.5^{***}	1.6^{ns}	21.2^{***}	42.5^{***}	76.0^{***}	3.8^{*}	22.2^{***}
	Zn	0.45^{ns}	0.8^{ns}	0.5^{ns}	3.5^{*}	4.1^{*}	2.3^{ns}	0.6^{ns}	0.5^{ns}
	N×Zn	0.97^{ns}	1.4^{ns}	0.9^{ns}	2.2^{*}	1.0^{ns}	1.2^{ns}	0.5^{ns}	2.9^{*}

Nitrogen treatment doses had significant effects on the increase in plant height, but Zn application doses did not affect plant height values. The effect of treatments on number of capsules was found to be nonsignificant in 2022, with N_1 (75.7 $plant^{-1}$) in N application dose, Zn_3 (63.1 $plant^{-1}$) in Zn treatment dose and N_1×Zn_3 (112.1 $plant^{-1}$) in N × Zn interaction provided the maximum number of capsules formation in 2023. There was a significant increase in the number of capsules compared to the control with increasing N doses, while no linear relationship was observed with increasing Zn treatment doses (Table 1). While the N_1 dose contributed significantly to the number of capsules per plant (170% compared to the control), the Zn_3 dose had the greatest effect (8.6% compared to the control). A significant increase was achieved with the N_1 × Zn_3 interaction compared to the control (224% compared to the control) as the number of capsules per plant. Co-application of N and Zn caused a significant increase in the number of capsules. In the effects of different N and Zn doses on seed yield, it was determined that the N and Zn treatment doses in 2022 and only the N treatment doses in 2023 were significant (Table 1).

The effects of different N and Zn doses on seed yield were significant in 2022, and only N doses in 2023 (Table 1). The highest seed yield values in 2022 were obtained from N doses of N_3 (14.5 g $plant^{-1}$), Zn doses of Zn_3 (12.5 g $plant^{-1}$), and N doses of N_3 (18.4 g $plant^{-1}$) in 2023. While increasing N doses resulted in a significant increase in seed yield compared to the control, only the maximum Zn treatment made a significant contribution in 2022. It was revealed that increasing N doses resulted in an increase in sesame yield. The effects of different N and Zn doses on seed number in capsules were significant in 2022 for N and Zn treatments, and in 2023 for N and the N × Zn interaction. In 2022, the maximum values for the number of seeds in the capsule were obtained from the N doses N_1 (65.3 capsules^{-1}) and N_3 (65.7 capsules^{-1}), while in 2023, the maximum values were obtained from the N doses N_2 (84.7 capsules^{-1}). In 2023, the $N_1 \times Zn_1$ (86.2 capsules^{-1}) and $N_1 \times Zn_2$ (84.4 capsules^{-1}) interactions stood out at the optimum treatment dose (Table 1). From this, it can be concluded that the number of seeds in the capsule may be related to the number of capsules.

The effects of different N and Zn doses on 1000 seed weight were nonsignificant in 2022 and 2023 and the importance of the number of capsules and number of plants in the plot on yield emerged (Table 2). While N and Zn doses had nonsignificant effect on capsule length in 2022, among the N treatments in 2023, only the N_1 dose (3.55 cm) provided an 8.9% increase compared to the control. As in capsule length, N and Zn treatments had nonsignificant effect on the first branch height and the number of lower branches in 2022, while only the N_3 dose (26.4 cm) provided a 55% increase in the first branch height compared to the control in 2023. All N doses had a significant effect on the number of side branches compared to the control. Foliar Zn treatments did not a significant effect on 1000 seed weight, capsule length, first branch height and number of sub-branches. In 2023, N doses have significant effects on all parameters except 1000 seed weight.

Table 2. Effect of different doses of N and Zn treatments on 1000 seed weight, capsule length, first branch height and number of sub-branches values in 2022-2023. N rates (kg N ha^{-1}): N_0: 0, N_1: 30, N_2: 60 and N_3: 90 with ammonium sulphate; Zn rates (%): Zn_0: 0, Zn_1: 0.15, Zn_2: 0.30 and Zn_3: 0.45 as foliar zinc sulphate-$ZnSO_4 \cdot 7H_2O$. Means followed by the same letter in each treatment group are not significantly different at 5% level of probability using Duncan multiple range test. ^{ns}Nonsignificant at 5% level of probability; **Significant at 1% level of probability; ***Significant at 0.1% level of probability.

Treatments		1000 Seed weight		Capsule length		First branch height		Number of sub-branches	
		2022	2023	2022	2023	2022	22023	2022	2023
		g		cm		cm		nr plant^{-1}	
N fertilizer	N_0	3.57	3.62	3.60	3.26^c	21.3	17.0^b	2.22	1.60^b
	N_1	3.55	3.70	3.68	3.55^a	19.6	17.6^b	2.35	3.67^a
	N_2	3.55	3.55	3.53	3.36^{bc}	23.7	21.0^b	2.02	3.35^a
	N_3	3.53	3.53	3.68	3.44^b	21.9	26.4^a	2.10	3.07^a
Zn fertilizer	Zn_0	3.65	3.75	3.62	3.42	20.4	20.9	2.20	3.17
	Zn_1	3.43	3.58	3.56	3.35	21.0	22.51	2.17	2.43
	Zn_2	3.57	3.55	3.62	3.43	22.9	20.75	2.10	2.78
	Zn_3	3.55	3.52	3.68	3.41	22.2	17.82	2.22	3.30
Significance	N	0.01^{ns}	0.47^{ns}	2.61^{ns}	13.6***	0.97^{ns}	5.63**	0.46^{ns}	13.2***
	Zn	0.50^{ns}	0.87^{ns}	1.35^{ns}	0.9^{ns}	0.43^{ns}	1.15^{ns}	0.06^{ns}	2.4^{ns}
	N×Zn	1.21^{ns}	0.46^{ns}	0.82^{ns}	0.5^{ns}	1.34^{ns}	1.32^{ns}	0.50^{ns}	2.1^{ns}

The effects of different N doses on seed N levels (%) were significant in 2022 and 2023; in both periods, the N_3 (90 kg ha^{-1}) dose maximized seed N content (4.54% and 4.30%, respectively). Increasing N doses resulted in a significant increase in seed N levels compared to the control in both periods (40% and 59%, respectively) (Table 3). The effects of different Zn doses on seed Zn levels were found to be significant in both years; Zn_2 and Zn_3 doses provided maximum values in both years. Increasing Zn doses led to a significant increase in seed Zn levels compared to the control group in both periods (61% and 67%) (Table 3). Significant increases in seed oil content were found between the treatments in both years. In 2022, the highest values were obtained from N treatments at the N_0 dose (56.3%), and from Zn treatments at the Zn_1 (53.4%), Zn_2 (52.3%), and Zn_3 (47.1%) doses; in 2023, the highest seed oil contents were obtained from N_3 (53.8%) and Zn_2 (51.9%) treatments. For the N × Zn interaction, the highest values were obtained in 2022 from the $N_0 \times Zn_2$ (59.4%) and $N_1 \times Zn_2$ (58.6%) treatments, and in 2023 from the N_3Zn_1 (59.2%) treatment. While N doses had a limited contribution to seed oil content, Zn treatments had a greater effect. The effects of different N doses on seed protein content were significant in both years, with the highest values obtained from N_3 treatment (28.4% and 25.9%). Increasing N doses resulted in a significant increase in seed protein levels compared to the control (40% and 58%) (Table 3).

Table 3. Effect of different doses of nitrogen and zinc on seed N content, Zn content, oil and protein content in 2022-2023. N rates (kg N ha^{-1}): N_0: 0, N_1: 30, N_2: 60 and N_3: 90 with ammonium sulphate; Zn rates (%): Zn_0: 0, Zn_1: 0.15, Zn_2: 0.30 and Zn_3: 0.45 as foliar zinc sulphate-$ZnSO_4 \cdot 7H_2O$. Means followed by the same letter in each treatment group are not significantly different at 5% level of probability using Duncan multiple range test. ^{ns}Nonsignificant at 5% level of probability; ***Significant at 0.1% level of probability.

Treatment		N concentration		Zn concentration		Oil content		Protein content	
		2022	2023	2022	2023	2022	22023	2022	2023
		%		mg kg^{-1}		%		%	
N fertilizer	N_0	3.25^{c}	2.71^{c}	64.2	68.4	56.3^{a}	46.2^{c}	20.3^{c}	17.0^{c}
	N_1	3.93^{b}	3.57^{b}	62.5	62.7	53.0^{b}	49.2^{c}	24.6^{b}	22.3^{b}
	N_2	4.13^{b}	3.71^{b}	66.1	64.4	45.3^{d}	51.9^{b}	25.8^{b}	23.2^{b}
	N_3	4.54^{a}	4.30^{a}	67.4	62.1	47.1^{c}	47.1^{a}	28.4^{a}	26.9^{a}
Zn fertilizer	Zn_0	3.81	3.50	48.0^{c}	46.1^{c}	48.1^{b}	44.4^{c}	23.8	21.8
	Zn_1	3.90	3.37	62.3^{b}	63.3^{b}	53.4^{a}	44.8^{b}	24.4	21.1
	Zn_2	4.08	3.77	72.6^{a}	71.3^{a}	52.3^{a}	51.4^{a}	25.5	23.6
	Zn_3	4.07	3.66	77.4^{a}	76.8^{a}	48.0^{a}	53.8^{c}	25.4	22.9
Significance	N	17.2***	11.5***	0.6^{ns}	2.1^{ns}	135.4***	114.8***	17.2***	11.5***
	Zn	1.0^{ns}	0.8^{ns}	23.1***	45.3***	42.3***	33.6***	1.0^{ns}	0.8^{ns}
	N×Zn	1.1^{ns}	0.7^{ns}	0.4^{ns}	0.6^{ns}	15.5***	44.3***	1.1^{ns}	0.7^{ns}

Pearson correlation analyses

The positive or negative proportional effects of different levels of N and Zn treatments on the parameters examined in sesame were evaluated using Pearson correlation analysis ($p < 0.05$). The mean values of the criteria examined across treatments were used in the correlation analysis and the correlation analysis and its coefficients are shown in Figure 2. In the first year of the study (2022), scatter plots according to the correlation coefficient (r^2) showed a strong positive relationship between seed yield (SY) and N content and protein content (PC) (r^2 = 0.79 and 0.79, respectively), between N content and PC (r^2 = 1.0), and between the number of seeds in the capsule (NoSC) and capsule length (CL) (r^2 = 0.72); while a negative relationship was shown between oil content (OC) and seed N content (r^2 = -0.70) and between PC and OC (r^2 = -0.70).

In the second year of the study (2023), the distribution plots according to the correlation coefficient showed a strong positive relationship between SY and N content, PC, and plant height (PH) (r^2 = 0.80, 0.80, and 0.79, respectively); between number of capsules (NoC) and number of subbranch (NoSB) values (r^2 = 0.93); between N content and PC (r^2 = 1.0); between NoSC and CL (r^2 = 0.77); and between PH and seed N content (r^2 = 0.74).

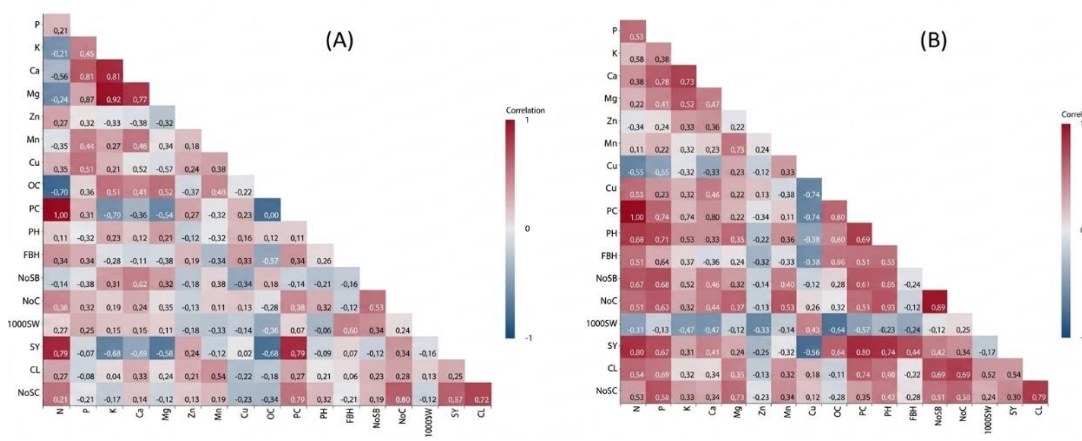

Figure 2. Results of the correlation analysis of the criteria examined in the study for the year 2022 (A) and the year 2023 (B). N, P, K, Ca; Mg, Zn, Mn, and Cu seed concentration; OC: oil content; PC: protein content; PH: plant height; FBH: first branch height; NoSB: number of sub-branches; NoC: number of capsules; 1000SW: 1000 seeds weight; SY: seed yield; CL: capsule length.

Principle component analysis (PCA)

The results of the study were analyzed to determine whether there were significant differences in the means of the various parameters studied in the effects of N and Zn treatments on sesame cultivation and Zn biofortification. Principal component analyses (PCA) were conducted on the parameters studied over a 2 yr period (Figure 3). In the PCA analysis performed in the first year (Figure 3A), the first principal component accounts for 35.1%, the second principal component for 17.2%, and the total variation for 52.3%. In the PCA analysis performed in the second year (Figure 3B), the first component accounts for 46.4%, the second component for 23.1%, and the total variation for 69.5%.

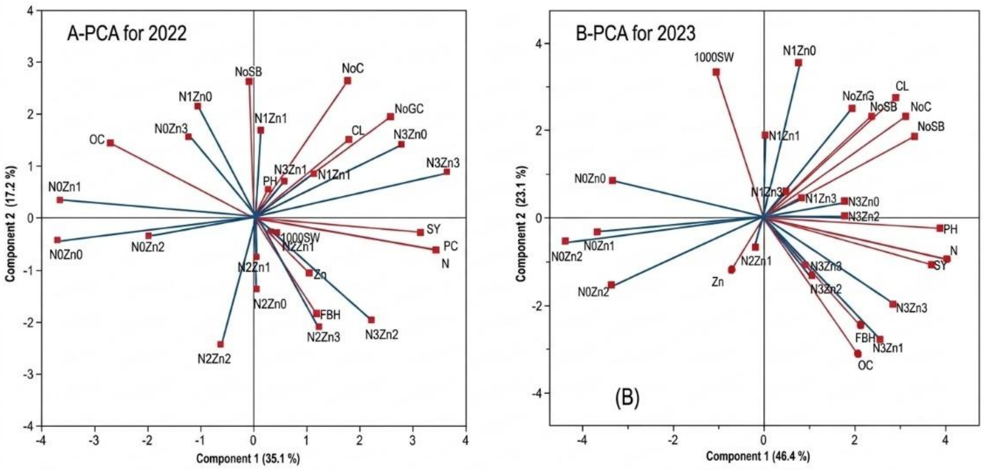

Figure 3. Principal component analyses of the criteria examining the effects of different N and Zn treatments in sesame seeds for 2022 (A) and 2023 (B). N rates (kg N ha^{-1}): N_0: 0, N_1: 30, N_2: 60 and N_3: 90 with ammonium sulphate; Zn rates (%): Zn_0: 0, Zn_1: 0.15, Zn_2: 0.30 and Zn_3: 0.45 as foliar zinc sulphate-$ZnSO_4{\cdot}7H_2O$. PH: Plant height; NoC: number of capsules; SY: seed yield; 1000SW: 1000 seeds weight; CL: capsule length; FBH: first branch height; NoSB: number of sub-branches; OC: oil content; PC: protein content; NoGC: number of grains in capsule.

Figure 3 shows two components for 2022 and 2023. Although two components were shown in both experiment years, the third component was determined to have a positive loading of 1000 seed weight (1000SW) in 2022, and Zn content of sesame seeds in 2023. Red indicates the first component, and blue indicates the second. In the study, the first component in 2022 consisted of PC, N content, SY, and NoSC parameters based on factor loadings, while the second component included NoSB. In the 2022 evaluation, OC parameter was the parameter with a strong negative loading. In the PCA analysis conducted for 2023, the first component consisted of the following factors: N content, PC, PH, SY, NoSB and NoC. The second component featured a value of 1000 SW. In the study, OC and first branch height (FBH) parameters in the second component had strong negative loadings in 2023.

DISCUSSION

Increasing the N treatment rate had a significant effect on the number of sesame capsules, with the maximum value obtained at the N_1 dose (30 kg ha^{-1}) in the second year of the experiment. Compared to the control group, N supplementation increased the number of sesame capsules. Increasing the N rate increases sesame yield and capsule number (Eifediyi et al., 2021; Mahadi and Ahmed, 2023). Nitrogen fertilization (N_3: 90 kg ha^{-1}) had a significant effect on sesame seed yield in both experimental years. Zinc treatment Zn_3 (0.45% zinc sulfate, $ZnSO_4$) provided the maximum seed yield in the first year of the study.

Nitrogen and Zn treatments, independently of each other, can significantly increase sesame seed yield. The fact that increased N and Zn doses lead to increased seed yield highlights the relationship between plant nutrition and yield. Both soil and foliar Zn treatments are effective in achieving high seed yield and improving morphological characteristics (Abdoli et al., 2016). Nitrogen treatment contributes to the yield and yield components of sesame (Zenawi and Mizan, 2019). Eifediyi et al. (2021) found that yield and yield components increased significantly when the Zn content in sesame plants increased from 5 to 15 kg ha^{-1}. The N_1 (30 kg N ha^{-1}) treatment significantly affected the number of seeds per capsule in sesame in both years of the study. In 2023, the $N_1 \times Zn_2$ (Zn_2: 0.30% $ZnSO_4$) treatment increased the number of seeds per capsule by 20.7% compared to the control. Increasing N levels can significantly increase the number of seeds per capsule (Kushawaha et al., 2022). Foliar Zn treatment promotes the photosynthesis process and the transport of photosynthetic products to the plant stem and seeds, contributing to increased yield (Ali et al., 2024).

The N content of sesame seeds increased linearly with increasing N levels, and the highest doses maximized the N content. Bellaloui et al. (2018) reported that the mineral content (N, S, B, Cu, Fe, Zn) in the seeds of different sesame varieties increased with increasing N treatment. Nitrogen fertilizer treatment has a significant effect on the quality of sesame seeds. Seed quality in sesame is determined by seed color, seed size, aroma, oil, and protein content. Therefore, the protein and oil content of sesame seeds is mostly composed of N, and seed size is also affected to some extent by oil and protein content (Zenawi and Mizan, 2019). Since N constitutes a significant portion of sesame seed protein, N fertilizers significantly affect sesame yield and seed quality (Gholamhoseini, 2022).

Increased Zn levels in seeds were found to correlate with rising Zn doses, with the Zn_2 dose (0.30% $ZnSO_4$) proving to be the most economical. Foliar treatment of Zn to plants is an effective method for increasing Zn concentration in grain (Nayak and Singh, 2024). Zinc concentrations in cereal grains have increased with increasing Zn treatments (Hui et al., 2025). Han et al. (2024) found that foliar treatment of amino acids and Zn increased the Zn content in soybean grains. Foliar treatment is more effective and economical than soil treatment for nutrients with limited movement in the soil. During the early growth stage when the plant's roots are not yet fully developed, foliar fertilization is more advantageous than soil treatment in terms of absorption (Kachinski et al., 2020; Ishfaq et al., 2022). It has also been reported that N treatments improve and increase Zn uptake (Manzeke et al., 2020).

The effects of N and Zn treatments on oil content in sesame were investigated. Zinc treatments were found to significantly increase seed oil yield, while the effects of N treatments varied. Seed quality, protein and oil content are significantly affected by N, and 31%-66% of the N absorbed by the plant is transported to the capsules and seeds (Couch et al., 2017). Ahmad et al. (2018) found that sesame seed oil content increased with N treatment. Foliar treatment of Zn resulted in a 6%-9% increase in seed yield, a 6% increase in oil content, and a 10%-30% increase in dry mass in sesame (Hasani et al., 2023). Foliar spraying of micronutrients (Zn, Cu, Fe, Mn and Mo) improved oil content of sesame (Ramya et al., 2023).

CONCLUSIONS

This research aimed to determine the effects of different N and Zn doses on some plant growth parameters, yield components, and seed Zn biofortification in sesame. Nitrogen treatments increased number of capsules, N content, oil and protein content of sesame seed, with maximum values obtained from 90 kg N ha^{-1} dose. Zinc treatments resulted in significant increases in number of capsules, seed yield, Zn content, oil content with 0.45% $ZnSO_4$ dose. The 30 kg N ha^{-1} × 0.30% $ZnSO_4$ interaction had significant effects on number of capsules, number of seed capsule, and oil content. While the 0.30% $ZnSO_4$ and 0.45% $ZnSO_4$ matching doses had similar effects on Zn biofortification in seed, the most effective Zn accumulation in seed was achieved with 0.30% $ZnSO_4$ dose in both experimental periods. Increasing nutrient levels in seeds for N and Zn improved sesame seed quality. Foliar Zn treatments, in particular, demonstrated linear effects with increasing doses, demonstrating an important strategy for seed quality and nutrition.

Author contribution

Conceptualization: Ş.H., İ.S. Data curation: Ş.H., İ.S. Formal analysis: Ş.H., İ.S. Investigation: Ş.H., İ.S. Methodology: Ş.H., İ.S. Project administration: Ş.H., İ.S. Resources: Ş.H., İ.S. Writing-original draft preparation: İ.S. Writing-review and editing: İ.S. Visualization: Ş.H., İ.S. Supervision: İ.S. All authors read and approved of the final manuscript.

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References
Abdoli, M., Esfandiari, E., Sadeghzadeh, B., Mousavi, S.B. 2016. Zinc application methods affect agronomy traits and grain micronutrients in bread and durum wheat under zinc-deficient calcareous soil. Yüzüncü Yıl University Journal of Agricultural Sciences 26(2):202-214.

Ahmad, J., Ahmad, F., Iqbal, S., Shah, S.M.A., Ali, M., Abbas, M.W., et al. 2018. Growth and oil yield of sesame as influenced by sulphur and nitrogen. Open Access Journal of Agricultural Research (OAJAR) 3(7):2474-8846. doi:10.23880/oajar-16000187.

Ali, S., Taimoor, M., Ahmed, U., Ali, R. 2024. Synergistic effect of potassium and zinc application on yield and quality of sesame. Natural Resources and Sustainable Development Journal 14(1):51-66. doi:10.31924/nrsd.v14i1.149.

AOAC. 1990. Official methods of analysis. Association of Official Analytical Chemists (AOAC), Washington D.C., USA.

Bellaloui, N., Abbas, H.K., Ebelhar, M.W., Mengistu, A., Mulvaney, M.J., Accinelli, C., et al. 2018. Effect of increased nitrogen application rates and environment on protein, oil, fatty acids, and minerals in sesame (*Sesamum indicum*) seed grown under Mississippi delta conditions. Food and Nutrition Sciences 9:1112-1135. doi:10.4236/fns.2018.99081.

Cakmak, I., Kutman, U.B. 2018. Agronomic biofortification of cereals with zinc: A review. European Journal of Soil Science 69(1):172-80. doi:10.1111/ejss.12437.

Couch, A., Jani, A., Mulvaney, M., Hochmuth, G., Bennett, J., Gloaguen, R., et al. 2017. Nitrogen accumulation, partitioning, and remobilization by diverse sesame cultivars in the humid southeastern USA. Field Crops Research 203:55-64. doi:10.1016/j.fcr.2016.12.012.

Eifediyi, E.K., Ilori, G.A., Ahamefule, H.E., Imam, A.Y. 2021. The effects of zinc biofortification of seeds and NPK fertilizer application on the growth and yield of sesame (*Sesamum Indicum* L.) Acta Agriculturae Slovenica 117(1):1-11. doi:10.14720/aas.2021.117.1.1252.

Gholamhoseini, M. 2022. Optimizing irrigation and nitrogen fertilization of Iranian sesame cultivars for grain yield and oil quality. Journal of Food Composition and Analysis 108:104448. doi:10.1016/j.jfca.2022.104448.

Guwela, V.F., Broadley, M.R., Hawkesford, M.J., Maliro, M.F.A., Bokosi, J., Banda, M., et al. 2024. Unravelling the impact of soil types on zinc, iron, and selenium concentrations in grains and straw of wheat/*Amblyopyrum muticum* and wheat/*Triticum urartu* doubled haploid lines. Frontiers in Agronomy 6:1305034. doi:10.3389/fagro.2024.1305034.

Han, S., Sönmez, I., Qureshi, M., Güden, B., Gangurde, S.S., Yol, E. 2024. The effects of foliar amino acid and Zn applications on agronomic traits and Zn biofortification in soybean (*Glycine max* L.) Frontiers in Plant Science 15:1382397. doi:10.3389/fpls.2024.1382397.

Hasani, M., Faryabi, S., Ehsanzadeh, P., Vaghar, M. 2023. Foliar-applied zinc enhances sesame physiological and yield attributes under different irrigation regimes. South African Journal of Botany 162:451-460. doi:10.1016/j.sajb.2023.09.008.

Hui, X., Luo, L., Chen, Y., Palta, J.A., Wang, Z. 2025. Zinc agronomic biofortification in wheat and its drivers: A global meta-analysis. Nature Communications 16:3913. doi:10.1038/s41467-025-58397-y.

Ishfaq, M., Kiran, A., Rehman, H., Farooq, M., Ijaz, N.H., Nadeem, F., et al. 2022. Foliar nutrition: Potential and challenges under multifaceted agriculture. Environmental and Experimental Botany 200:104909. doi:10.1016/j.envexpbot.2022.104909.

James, C.S. 1995. Analytical chemistry of foods. Chapman and Hall, London, UK.

Kacar, B. 2014. Bitki, Toprak Analizleri 2: Kolay Uygulanabilir Bitki Analizleri (Plant analysis). Nobel Publications, Ankara, Türkiye.

Kachinski, W.D., Avila, F.W., Muller, M.M.L., dos Reis, A.R., Rampim, L., Vidigal, J.C.B. 2020. Nutrition, yield and nutrient export in common bean under zinc fertilization in no-till system. Ciência e Agrotecnologia 44:e029019. doi:10.1590/1413-7054202044029019.

Kurt, C., Arioglu, H., Kızıldag, N. 2018. Determination of content of micronutrients in some sesame (*Sesamum indicum* L.) accession. Fresenius Environmental Bulletin 27(12):8456-8462.

Kushawaha, S., Singh, A.K., Singh, A., Singh, B.K., Minz, S.D. 2022. Effect of different levels of sulphur and nitrogen on growth yield and quality of sesame (*Sesamum indicum* L.) under Bael (*Aegle marmelos* L.) based Agri-horti system. Ecology Environment and Conservation 28(3):1404-1410. doi:10.53550/EEC.2022.v28i03.043.

Kyle, S. 2025. Think zinc. InnovAiT 18(7):384-389. doi:10.1177/17557380251329910.

Mahadi, A.E.R.A.E., Ahmed, F.E. 2023. Interactive effect of plant density and nitrogen level on growth and yield of sesame under irrigation in Northern Sudan. University of Khartoum Journal of Agricultural Sciences 17(3):333-343. doi:10.53332/uofkjas.v17i3.1937.

Manzeke, M.G., Mtambanengwe, F., Watts, M.J., Broadley, M.R., Murray, L.R., Mapfumo, P. 2020. Nitrogen effect on zinc bio-fortification of maize and cowpea in Zimbabwean smallholder farms. Agronomy Journal 112:2256-2274. doi:10.1002/agj2.20175.

Nandal, V., Solanki, M. 2021. Zn as a vital micronutrient in plants. Journal of Microbiology, Biotechnology and Food Science 11(3):e4026. doi:10.15414/jmbfs.4026.
Nayak, S., Singh, G. 2024. Influence of sulphur and zinc on production of sesame: A review. International Journal of Research in Agronomy 7(11):521-525. doi:10.33545/2618060X.2024.v7.i11g.2053.
Ozdemir, I.S., Karaoglu, O., Dag, C., Bekiroglu, S. 2018. Assessment of sesame oil fatty acid and sterol composition with FT-NIR spectroscopy and chemometrics. Turkish Journal of Agriculture and Forestry 42:444-452. doi:10.3906/tar-1802-130.
Prakash, M., Ganesan, J. 2000. Effect of regulators and micronutrient on certain growth analysis parameters in sesame. Sesame Safflower Newsletter 15:48-57.
Qin, Y., Melse-Boonstra, A., Yuan, B., Pan, X., Dai, Y., Zhou, M., et al. 2012. Zinc biofortification of rice in China: A simulation of zinc intake with different dietary patterns. Nutrients 4:517-528. doi:10.3390/nu4060517.
Ramya, A., Babu, M.R., Sirisha, A.B., Kumari, S.R. 2023. Effect of foliar application of micronutrients on yield and yield attributes of sesame (*Sesamum indicum* L.) under drought stress. Biological Forum 15(9):536-41.
Sharma, L., Saini, C.S., Punia, S., Nain, V., Sandhu, K.S. 2021. Sesame (*Sesamum indicum*) seed. In Tanwar, B., Goyal, A. (eds.) Oilseeds: Health attributes and food applications. Springer, Singapore. doi:10.1007/978-981-15-4194-0_12.
Shehu, H.E. 2014. Effects of manganese and zinc fertilizers on shoot content and uptake of N, P, K in sesame (*Sesamum indicum* L.) on lithosols. International Research Journal of Agricultural Science and Soil Science (IRJAS) 4(8):159-166. doi:10.14303/irjas.2014.065.
Suresh, G., Murthy, I.Y.L.N., Babu, S.N.S., Varaprasad, K.S. 2013. An overview of Zn use and its management in oilseed crops. Journal of SAT Agricultural Research 11:1-11.
Taiz, L., Zeiger, E., Moller, I.M., Murphy, A. 2017. Physiology and plant development. 6th ed. Artmed, Porto Alegre, Brazil.
Thompson, M.W. 2022. Regulation of zinc-dependent enzymes by metal carrier proteins. Biometals 35:187-213. doi:10.1007/s10534-022-00373-w.
Waqeel, J., Khan, S.T. 2022. Microbial biofertilizers and micronutrients bioavailability: Approaches to deal with zinc deficiencies. p. 239-297. In Khan, S.T., Malik, A. (eds.) Microbial biofertilizers and micronutrient availability. Springer, Cham, Switzerland. doi:10.1007/978-3-030-76609-2_12.
Zaman, Q.U., Aslam, Z., Yaseen, M., Ihsan, M.Z., Khaliq, A., Fahad, S., et al. 2018. Zinc biofortification in rice: Leveraging agriculture to moderate hidden hunger in developing. Archives of Agronomy and Soil Science 64(2):147-161. doi:10.1080/03650340.2017.1338343.
Zeb, A., Muhammad, B., Ullah, F. 2017. Characterization of sesame (*Sesamum indicum* L.) seed oil from Pakistan for phenolic composition, quality characteristics and potential beneficial properties. Food Measure 11:1362-1369. doi:10.1007/s11694-017-9514-5.
Zenawi, G., Mizan, A. 2019. Effect of nitrogen fertilization on the growth and seed yield of sesame (*Sesamum indicum* L.) International Journal of Agronomy 2019:5027254. doi:10.1155/2019/5027254.
Zou, C.Q., Zhang, Y.Q., Rashid, A., Ram, H., Savasli, E., Arisoy, R.Z., et al. 2012. Biofortification of wheat with zinc through zinc fertilization in seven countries. Plant and Soil 361:119-130. doi:10.1007/s11104-012-1369-2.