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Response of Flax (*Linum usitatissimum* L.) Cultivars to Nitrogen Rates and Foliar Fertilization: Impacts on Seed Yield and its Component

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Flax is an important dual-purpose crop cultivated for fiber and seed production, but its productivity depends strongly on cultivar selection and nutrient-management practices. This study evaluated the response of two flax cultivars to nitrogen rates and foliar applications of silicon, sulphur and iron under field conditions. The experiment was conducted during the 2022–2023 and 2023–2024 winter seasons at Etay El-Baroud Agricultural Research Station, Egypt, using a split-split plot design. The main plots included two cultivars, Giza 11 and Giza 12, while nitrogen fertilisation at 75% and 100% of the recommended dose was assigned to sub-plots. Foliar treatments containing Fe-EDTA, potassium silicate and potassium thiosulphate were applied individually and in combinations at 50, 60 and 85 days after sowing. The results showed that capsule number, seed yield, straw yield, technical length and mineral content were influenced by interactions among cultivar,

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nitrogen rate and foliar treatment. Giza 12 generally showed higher seed productivity, with seed yield ranging from 0.43 to 0.66 Mg fed⁻¹, whereas Giza 11 ranged from 0.43 to 0.57 Mg fed⁻¹. Combined foliar treatments, especially Si × S, Si × Fe and S × Fe, often produced better yield related responses than individual applications. The findings indicate that cultivar-specific integration of nitrogen and foliar nutrient management can improve flax productivity under the tested conditions.

Keywords: Linum usitatissimum; nitrogen fertilisation; foliar fertiliser; silicon; sulphur; iron; seed yield; straw yield; harvest index; nutrient content.

1. Introduction

Flax (*Linum usitatissimum* L.) is one of the oldest cultivated crops, with evidence of cultivation in the Middle East as early as 7000 B.C. It was widely grown by the ancient Egyptians as a fiber crop for linen production. Flaxseed meal, the by-product remaining after oil extraction, is also a source of protein used in animal feed (Newkirk, 2015). Overall, flaxseed protein contributes to the crop's nutritional value and supports its use in food products and health-promoting diets. Improving flax productivity per unit area requires the selection of high-yielding cultivars and the refinement of appropriate agronomic practices.

Nitrogen is a critical macronutrient that strongly influences flax growth, yield, and quality; however, the crop response depends not only on the applied rate but also on cultivar and nutrient-management conditions. El-Bohramy et al., (2017) reported that applying 45 kg N fed⁻¹ to Giza 11 produced the highest seed index (10.76 g) and seed yield per plant (1.83 g), highlighting the importance of cultivar-specific nitrogen management. Silicon (Si) enhances plant resilience against biotic and abiotic stresses, including drought and salinity (Hellal et al., 2012; Ma, 2004; Bauer et al., 2011), and may contribute to improved crop productivity and sustainability (Ma, 2004). Sulphur (S) is required for the synthesis of amino acids, including cysteine and methionine, as well as proteins, coenzymes, and chlorophyll, thereby influencing plant development, photosynthesis, and oil biosynthesis. Abdelmasieh et al., (2022) showed that 50.0 kg sulphur ha⁻¹ significantly improved several flax traits, including technical length, straw yield, fruiting zone length, capsules per plant, seed yield, fiber length, and fiber yield.

Iron (Fe) is essential for chlorophyll synthesis and several metabolic processes. In Sakha 3 flax, foliar spraying with 200 ppm Fe-EDTA as part of an Fe + Zn + Mn mixture, together with 35 kg N fad⁻¹ and 2% urea, improved seed yield, capsules per plant, 1000-seed weight, and harvest index. Compared with low-nitrogen controls, this combination increased seed yield by more than 22% and performed better than higher nitrogen rates alone. In addition, foliar iron at 3.5%, supplied as iron sulphate, improved seed-yield attributes such as capsule number when applied at bud initiation and capsule filling (Gondal et al., 2023). Tayyiba et al., (2021) reported that high soil pH can restrict micronutrient availability in arable soils, and reduced Fe availability under alkaline conditions is a common constraint in crop production.

Although previous studies have examined the individual effects of nitrogen and selected foliar nutrients on flax performance, information remains limited on the combined response of recently cultivated flax genotypes to nitrogen rate and foliar Si, S, and Fe applications under the soil and climatic conditions represented in the present field experiment. This gap is particularly relevant because cultivar-specific nutrient responses may influence seed yield, straw yield, fiber related traits, and nutrient accumulation.

Therefore, the present investigation was designed to assess the effects of nitrogen rate and foliar fertilisation with Fe, Si, S, and their combinations on two flax cultivars. Specifically, the study evaluated growth, yield, yield components, oil percentage, fiber yield, nutrient content, and related soil-health responses under the tested field conditions.

2. Materials and Methods

Field experiments were conducted at Etay El-Baroud Agricultural Research Station, Agricultural Research Center (ARC), El-Beheira Governorate, Egypt (30°53′ E, 30°39′ N), during two successive winter seasons (2022-2023 and 2023-2024) to evaluate the performance of dual-purpose flax under different fertilisation regimes.

2.1 Experimental Treatments

The study included three factors:

I. Flax cultivars (Cul): Giza 11 (CulG11), Giza 12 (CulG12)

II. Nitrogen fertilisation rates (NR): 75% and 100% of the recommended dose. Nitrogen was applied as ammonium nitrate (33.5% N) at rates of 37.5 kg N fed⁻¹ (75%) and 50 kg N fed⁻¹ (100%). Nitrogen fertiliser was split into three equal doses and applied at 20, 40, and 60 days after planting.

III. Foliar fertilisation treatments (FF): Foliar fertilisation was applied using conventional nutrient sources at three growth stages: 50, 60, and 85 days after sowing.

The treatments included eight combinations:

a. Iron (Fe) as Fe-EDTA (13% Fe) at 1.0 g L^{-1}
b. Silicon (Si) as potassium silicate (K_2SiO_3, 10% K_2O and 25% SiO_3) at 2.0 ml L^{-1}
c. Sulfur (S) as potassium thiosulfate (25% K_2O, 17% S) at 2.0 ml L^{-1}
d. Fe + Si
e. Fe + S
f. Si + S
g. Fe + Si + S
h. Control (sprayed with distilled water)

Application rate per feddan: spray volume, 200 L fed⁻¹; uniform spraying using a knapsack sprayer; and addition of a wetting agent (0.1%) to improve absorption.

2.2 Experimental Design

A split-split plot design with three replicates was used:

A. Main plots: cultivars (Cul)
B. Sub-plots: nitrogen rates (NR)
C. Sub-sub plots: foliar treatments (FF)

2.3 Soil Analysis

Soil samples were collected before sowing and analysed according to standard methods. Physical properties were determined following Klute (1986), and chemical properties were determined following Page et al., (1982) and Cottenie et al., (1982). The initial soil properties are presented in Table 1.

Table 1. Some physical and chemical properties of the experimental site soil before planting

Soil characteristics	Value	Soil characteristics	Value
Particle size distribution, %:		Soluble cations (mmole l^{-1})	
Sand	17.08	Ca^{2+}	3.00
Silt	22.92	Mg^{2+}	2.00
Clay	60.00	Na^{+}	5.10
Textural class*		K^{+}	0.90
Clay			
Soil chemical properties:		*Soluble anions (mmole l^{-1})	
pH (1:2.5)	8.11	CO_3^{2-}	-
$CaCO_3$ %	5.71	HCO_3^{-}	3.00
Organic carbon %	1.37	Cl^{-}	5.00
*EC (dS m^{-1})	1.20	SO_4^{2-}	2.00
Available Macro-nutrients (mg kg^{-1})			

N	P	K
89.50	15.90	360.50

**Saturated soil paste*

2.4 Fertilization Practices before Sowing

Fertilisers were applied during land preparation as recommended by MALR.

Phosphorus: 15.5 kg P_2O_5 fed^{-1}, Source: Single Calcium superphosphate (15.5%)
Potassium: 24 kg K_2O fed^{-1}, Source: Potassium sulfate (48%)

2.5 Plant Sampling and Analysis

At harvest, 150 days after planting, random plant samples were taken from each plot. Samples were oven-dried at 70 °C until a constant weight was reached, and dry weight was recorded. The plant material was ground into a fine powder. Total nitrogen content was determined using the micro-Kjeldahl method (Bremner & Mulvaney, 1982). Phosphorus was determined colorimetrically using the vanadomolybdate yellow-colour method according to AOAC International (2010) with a Jenway 6405 UV/Vis spectrophotometer, while potassium was determined using a Jenway PFP7 flame photometer according to Jackson (1973).

2.6 Statistical Analysis

Data were analysed using ANOVA according to Snedecor & Cochran (1980). Mean comparisons were performed using the L.S.D. test at $P \leq 0.05$.

3. Results and Discussion

Statistical analysis revealed non-significant differences between the two growing seasons. Bartlett's test (1937) was performed to assess the homogeneity of error variances. Therefore, data from both seasons were pooled.

3.1 Total Plant Length (cm)

The total plant length of flax (Table 2) was influenced by nitrogen rate (NR) and foliar application (FF) of different Si, S, and Fe fertiliser sources, with notable interactions between these factors and the flax cultivar. Although the main effects of cultivar, namely Giza 11 (CulG11) and Giza 12 (CulG12), NR, and FF were not individually significant (Table 2), significant differences were observed in the interaction terms. Total plant length was most strongly affected by the interaction among cultivar, NR, and the specific fertiliser sources used in foliar applications. In particular, applying the full recommended nitrogen rate together with the control, S × Fe, or Si × S × Fe treatments produced the tallest plants in both CulG11 and CulG12. Synergistic effects were particularly evident in combined FF treatments, which consistently increased plant height.

Table 2. Total plant length, No. of capsules per plant, no. fruits per plant, length fruiting branches and technical length as affected by different Flax cultivars, nitrogen rate (NR), and foliar fertilizers (FF) (combined analysis of two successive growing seasons)

Treatment		Total plant length, cm		No. of capsules plant -^{1}		No. fruiting plant -^{1}		length fruiting Branches, cm		Technical length, cm	
Cul	CulG11	118.80	a	11.30	b	6.79	a	20.48	a	98.33	a
	CulG12	117.18	a	11.77	a	6.91	a	18.80	a	98.65	a
NR	75	116.11	a	10.90	b	6.68	a	19.70	a	96.67	a
	100	119.88	a	12.17	a	6.91	a	19.58	a	100.30	a
FF	Cont.	121.03	a	10.78	c	6.39	a	26.23	a	94.80	b
	Si	115.15	a	10.93	c	6.68	a	17.54	bc	97.60	b
	S	114.65	a	11.37	bc	6.98	a	18.87	bc	96.81	b
	Fe	113.42	a	11.36	bc	6.66	a	18.63	bc	94.79	b
	Si × S	117.98	a	11.85	ab	6.73	a	21.40	b	96.58	b
	Si × Fe	118.33	a	11.85	ab	6.97	a	19.00	bc	99.33	b
	S × Fe	121.65	a	11.76	ab	6.80	a	20.53	b	101.13	b
	Si×S×Fe	121.74	a	12.39	a	7.13	a	14.91	c	106.83	a

Treatment		Total plant length, cm	No. of capsules plant -^{1}	No. fruiting plant -^{1}	length fruiting Branches, cm	Technical length, cm
LSD 0.05	Cul×NR	3.86	0.43	0.15	2.43	3.48
	Cul×FF	7.72	0.85	0.30	4.87	6.96
	NR×FF	7.72	0.85	0.30	4.87	6.96
	Cul×NR×FF	10.91	1.20	0.42	6.89	9.85

Values followed by the same letter(s) within each column did not differ significantly according to the L.S.D. test at the 0.05 probability level

These findings highlight the importance of integrated nutrient management, in which the interaction between cultivar selection, optimised nitrogen application, and combined foliar Si, S, and Fe fertiliser treatments can improve flax growth and potentially enhance yield.

These results are in agreement with El-Gedwy et al., (2020), who demonstrated that nitrogen fertilisation improves anatomical traits, such as stem diameter and technical length, thereby contributing to increased plant height and yield potential.

3.2 Number of Capsules Plant^{-1}

The number of capsules per plant was significantly affected by cultivar, nitrogen rate, foliar fertiliser application, and their interactions (Table 2). Both cultivars showed increased capsule numbers with higher NR. Foliar application of different fertilisers further enhanced capsule formation. For CulG11, capsule number ranged from 8.20 to 14.50, with the maximum value recorded at 50 kg N fed^{-1} combined with the Si × S treatment. For CulG12, capsule number ranged from 9.70 to 12.97, with the highest value obtained under 100% NR combined with the S × Fe treatment. Across treatments, combined Si, S, and Fe fertiliser applications (Si × S, Si × Fe, and S × Fe) generally outperformed both the control and single-fertiliser treatments. The overall mean capsule number was slightly higher in CulG12 (11.98) than in CulG11 (11.73), although both cultivars showed similar response patterns.

These results indicate that applying the full recommended nitrogen rate in combination with specific foliar fertiliser mixtures, particularly Si × S and S × Fe, can significantly increase capsule number per plant. This is consistent with findings reported by El-Gedwy et al., (2020) and Kakabouki et al., (2021).

3.3 Number of Fruiting Branches Plant^{-1}

The number of fruiting branches per plant was significantly influenced by the interaction among cultivar, nitrogen rate (NR), and foliar Si, S, and Fe fertiliser (FF) applications, whereas the main effects of cultivar and nitrogen rate alone were not significant. Both cultivars showed increased fruiting branch numbers with higher nitrogen rates and combined foliar fertiliser applications. CulG12 recorded a slightly higher mean (6.91) than CulG11 (6.79). Combined foliar treatments (Si × S, Si × Fe, S × Fe, and Si × S × Fe) consistently produced higher values, with the maximum observed under the triple combination (Si × S × Fe) across both nitrogen levels (Fig. 1).

This improvement reflects the role of balanced nutrient supply in promoting vegetative and reproductive branching. Nitrogen is known to influence vegetative growth, particularly branch initiation and elongation. Such growth directly affects the potential number of flowering sites and ultimately influences yield (El-Gedwy et al., 2020; Kakabouki et al., 2021).

3.4 Length of Fruiting Branches, cm

Fruiting branch length was significantly affected by the interaction among cultivar, nitrogen rate, and foliar fertilisation, whereas the individual effects of cultivar and nitrogen rate were not significant (Table 2). CulG11 produced longer fruiting branches (mean: 20.82 cm) than CulG12 (18.40 cm). The highest values for CulG11 were obtained at 100% NR with the control (29.34 cm) and Si × S treatment (23.83 cm). In contrast, CulG12 recorded its maximum values under 75% NR with Fe treatment (26.33 cm) and combined treatments (S × Fe and Si × S). The triple foliar fertiliser combination (Si × S × Fe) tended to reduce branch length in both cultivars.

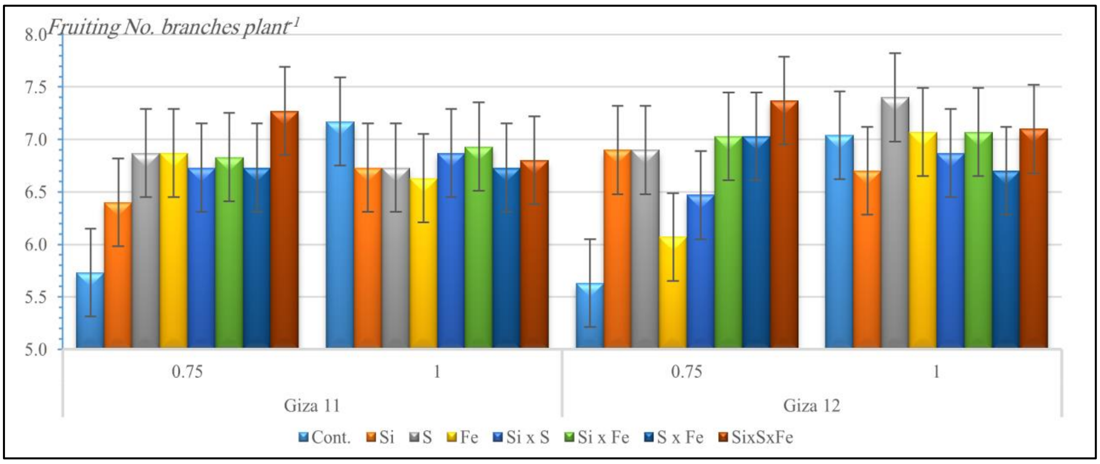


Fig. 1. Number of fruiting branches plant^{-1}as affected by the interaction among the different treatments. (Error bar L.S.D. 0.05)

These results align with the established role of nitrogen in promoting shoot elongation and cell expansion through enhanced photosynthesis and nutrient assimilation (El-Gedwy et al., 2020; Kakabouki et al., 2021). Differences between cultivars reflect genetic variation in growth response and shoot architecture.

3.5 Technical Length, cm

Technical length, a key parameter for fiber quality, was significantly influenced by the interaction among cultivar, nitrogen rate, and foliar Si, S, and Fe fertiliser applications. Although the main effects of cultivar and nitrogen rate alone were not significant, their interactions with foliar treatments were significant (Table 2). The highest technical length (119.00 cm) was recorded for CulG12 under reduced nitrogen (75% of the recommended dose) combined with the triple FF treatment (Si × S × Fe; Fig. 2). CulG11 showed relatively stable performance, with maximum values of 104.33 cm under 100% NR + Fe and 101.83 cm under 75% NR + S × Fe. CulG12 exhibited wider variation, ranging from 84.17 cm (75% NR + Fe) to 119.00 cm (75% NR + Si × S × Fe; Fig. 2).

Technical length is critical for flax fiber yield and quality because longer stems facilitate efficient fiber extraction. The significant interaction effects observed indicate complex relationships between genotype and nutrient management. Although nitrogen alone did not show a significant effect, its combination with foliar fertilisers produced clear synergistic effects that enhanced stem elongation, consistent with previous findings (El-Gedwy et al., 2020; Kakabouki et al., 2021).

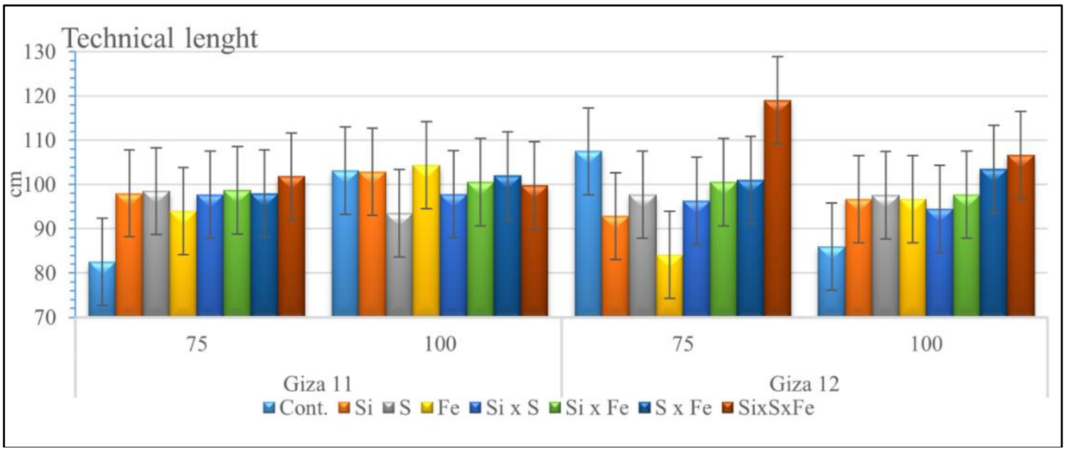


Fig. 2. Technical length as affected by the interaction among the different treatments. (Error bar L.S.D. 0.05)

3.6 Number of Seeds Capsule^{-1}

The results presented in Table 3 demonstrate the effects of flax cultivars, nitrogen fertilisation rates (NR), and foliar application of Si, S, and Fe fertilisers on the number of seeds per capsule. The main effects of cultivar and foliar fertilisation were significant, whereas the effect of nitrogen rate alone was not statistically significant. CulG12 produced a higher number of seeds capsule^{-1} (7.58) than CulG11 (4.96). Foliar iron application and the Si × Fe foliar fertiliser combination produced the highest seed numbers (9.82 and 9.26, respectively). Increasing nitrogen rate generally improved the number of seeds capsule^{-1} by 4.74% over the lower rate. These findings suggest that optimising nitrogen supply together with targeted foliar fertiliser combinations can enhance seed development in flax, particularly in CulG12. Application of N affected yield components, especially the number of seeds per plant, which increased by an average of 56% compared with the control (Dordas, 2010).

The number of seeds capsule^{-1} is an important yield component that reflects successful fertilisation and reproductive development. The substantial increase observed in CulG12 under combined fertiliser treatments supports previous findings that emphasise the importance of micronutrients in reproductive growth. Combined fertiliser formulations containing silicon, sulphur, and iron may exert synergistic effects that improve nutrient uptake, photosynthetic efficiency, and reproductive performance.

Table 3. Yield and yield components as affected by flax cultivars, nitrogen rate (NR), and foliar fertilization (FF) (combined analysis of two successive growing seasons)

Treatment		No. seed capsule		Seed yield, Mg fed^{-1}		Straw yield, Mg fed^{-1}		HI, %	
Cul	CulG11	4.96	a	0.50	b	2.98	a	14.62	a
	CulG12	7.58	a	0.57	a	3.00	a	16.44	a
NR	75	6.12	a	0.50	b	2.91	b	15.05	b
	100	6.41	a	0.56	a	3.07	a	15.69	a
FF	Cont.	4.36	a	0.49	b	2.53	d	15.69	bcd
	Si	5.06	a	0.51	b	2.55	a	17.11	a
	S	5.70	a	0.52	b	2.56	a	16.49	ab
	Fe	9.82	a	0.49	b	2.90	c	15.24	cde
	Si × S	5.39	a	0.56	a	2.96	c	16.05	bc
	Si × Fe	9.26	a	0.57	a	3.32	b	14.88	de
	S × Fe	5.05	a	0.55	a	3.35	b	14.43	e
	Si×S×Fe	5.50	a	0.57	a	3.76	a	13.09	f
LSD 0.05	Cul×NR	ns		0.02		0.16		0.72	
	Cul×FF	ns		0.03		0.31		1.43	
	NR×FF	ns		0.03		0.31		1.43	
	Cul×NR×FF	ns		0.04		0.44		2.02	

Values followed by the same letter(s) within each column did not differ significantly according to the L.S.D. test at the 0.05 probability level

3.7 Seed Yield, Mg fed^{-1}

Flax seed yield was significantly influenced by the interaction among cultivar, nitrogen rate, and foliar fertiliser application (Fig. 3). CulG12 consistently outperformed CulG11, recording a mean seed yield of 0.58 Mg fed^{-1}, with values ranging from 0.43 to 0.66 Mg fed^{-1}, compared with 0.43-0.57 Mg fed^{-1} for CulG11. Increasing nitrogen from 75% to the recommended rate generally enhanced seed yield across treatments in both cultivars. Combined foliar fertiliser applications, particularly Si × S, Si × Fe, and S × Fe, produced higher seed yields than single-nutrient applications or the control treatment. The highest seed yield (0.66 Mg fed^{-1}) was obtained from CulG12 under 100% NR combined with Si × Fe foliar application.

Recent studies have demonstrated that increasing nitrogen fertilisation together with foliar fertiliser application can enhance flax seed productivity. Nitrogen plays a critical role in protein synthesis and plant metabolism and therefore directly affects seed formation and seed size (El-Gedwy et al., 2020; Kakabouki et al., 2021). El-Gazzar and Kineber (2002) reported a considerable increase in flax seed yield fed^{-1} when nitrogen fertiliser was increased from 30 to 60 kg N fed^{-1}. Similarly, El-Nagdy et al. (2010) reported the highest flax seed yield when

45 kg N fed⁻¹ was applied. Likewise, N fertilisation increased seed yield by an average of 37% over the control rate (Dordas, 2010).

Foliar fertiliser applications containing silicon, sulphur, and iron improve nutrient use efficiency and nutrient uptake, leading to enhanced vegetative growth and seed development. These micronutrients contribute to improved photosynthesis, enzymatic activity, and stress tolerance, all of which are essential for seed formation (Gondal et al., 2023; Pavlovic et al., 2021). Bakry et al. (2012) also reported that foliar application of micronutrients improved flax seed yield.

The differential response observed between cultivars indicates the importance of cultivar-specific nutrient management strategies. CulG12 showed greater responsiveness to combined foliar Si, S, and Fe fertiliser applications. Overall, integrating optimised nitrogen rates with targeted foliar fertiliser treatments offers potential for improving seed yield and supporting sustainable flax production.

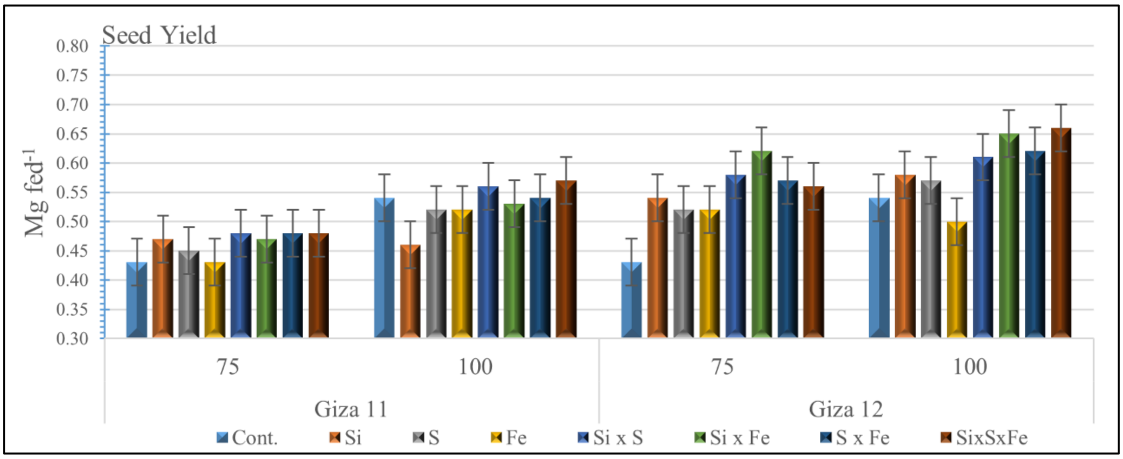


Fig. 3. Seed yield, Mg fed^{-1} as affected by the interaction among the different treatments (Error bar L.S.D. 0.05)

3.8 Straw Yield, Mg fed^{-1}

Straw yield was significantly influenced by cultivar, nitrogen rate, and foliar fertiliser application, with highly significant interaction effects among these factors. The highest straw yield for CulG11 (3.60 Mg fed⁻¹) was obtained under combined foliar fertiliser treatments, particularly Si × S × Fe, at both nitrogen rates. Similarly, CulG12 achieved its maximum straw yield (3.97 Mg fed⁻¹) under 100% NR combined with Si × S × Fe application (Fig. 4).

Combined treatments such as Si × S, S × Fe, and especially Si × S × Fe consistently increased straw yield compared with single-nutrient applications or the control treatment, indicating synergistic effects of multiple micronutrients on biomass accumulation.

These findings agree with those reported by El-Gedwy et al., (2020), who demonstrated that increasing nitrogen fertilisation significantly enhances straw yield and related growth characteristics through improved stem elongation, stem diameter, and biomass accumulation. The cultivar-specific response observed in CulG12 further confirms that nitrogen efficiency and biomass partitioning are strongly influenced by genotype.

3.9 Harvest Index (HI, %)

Harvest index (HI) was significantly influenced by the three-way interaction among cultivar, nitrogen rate, and foliar treatments, although the main effect of cultivar alone was not significant. CulG12 generally produced higher HI values (16.44%) than CulG11 (14.62%). The highest HI (19.49%) was recorded in CulG12 under the recommended nitrogen rate combined with Si × S foliar application (Fig. 5). Individual applications of Si and S also improved HI, particularly at higher nitrogen rates. In contrast, combined treatments such as S × Fe and Si ×

S × Fe generally reduced HI values. These findings indicate that higher nitrogen rates can improve harvest index when paired with appropriate foliar formulations, highlighting the need to optimise both nitrogen and foliar fertilisation strategies according to specific cultivar requirements to enhance yield efficiency and resource utilisation in flax production.

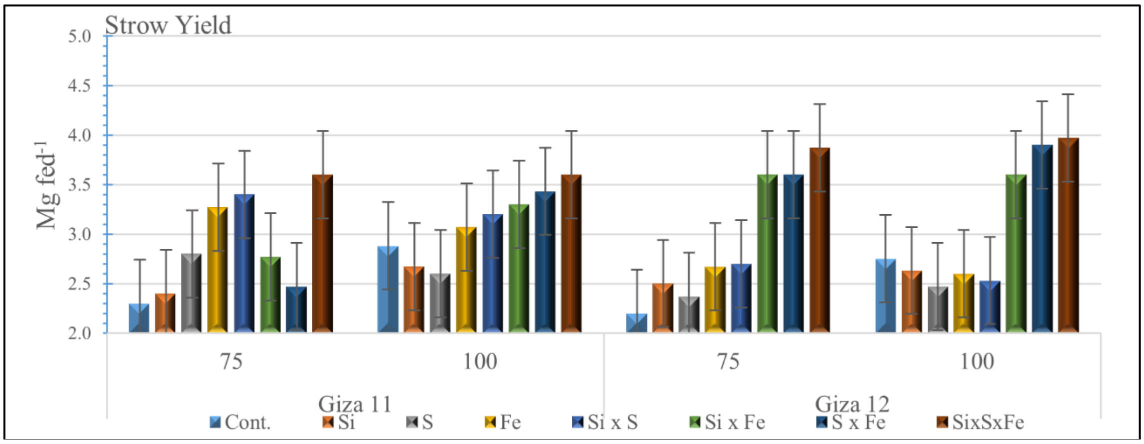


Fig. 4. Straw Yield, Mg fed^{-1} as affected by the interaction among the different treatments. (Error bar L.S.D. 0.05)

The present findings support previous reports showing that foliar fertiliser applications can enhance harvest index by improving nutrient use efficiency and plant physiological performance (Malimbayeva et al., 2026). Foliar fertilisers containing silicon or iron may improve HI through their roles in stress mitigation, nutrient transport, and photosynthetic regulation (Mohamed et al., 2014). Conversely, some combined treatments, particularly those involving sulphur and iron, may induce nutrient antagonism or imbalance, leading to lower HI values.

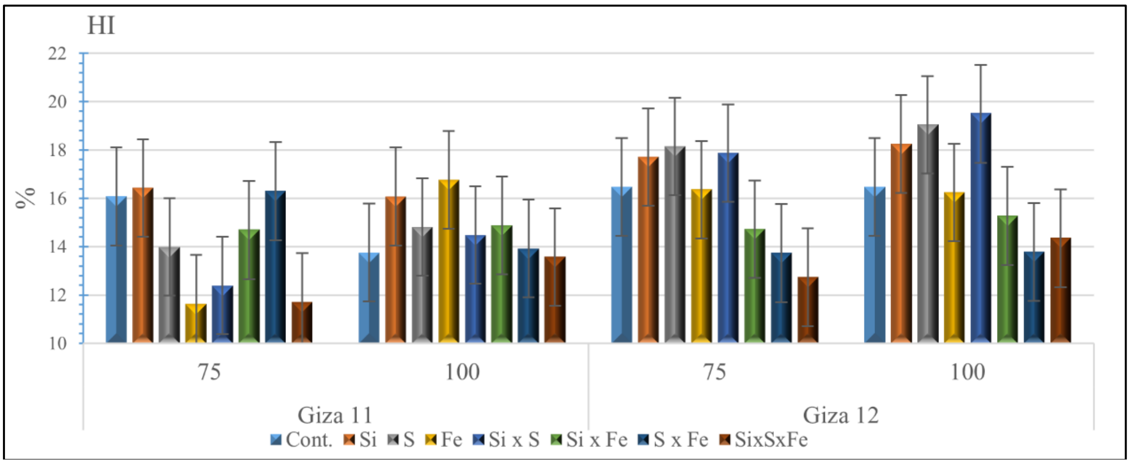


Fig. 5. Harvest Index, % as affected by the interaction among the different treatments. Error bar L.S.D. 0.05

3.10 Seed and Straw Mineral Contents

Giza 11 (CulG11) recorded higher seed total nitrogen (3.08%), seed potassium (0.55%), seed iron (4.69 mg kg⁻¹), straw nitrogen (0.98%), straw phosphorus (372.36 mg kg⁻¹), and straw potassium (0.75%) than Giza 12 (Table 4). However, Giza 12 showed higher seed phosphorus (0.46%) than Giza 11 (0.43%). Regarding nitrogen rate (NR), 100% NR significantly increased seed TN (3.04%), seed TK (0.54%), straw N (0.97%), and straw P (266.46 mg kg⁻¹) compared with 75% NR, while 75% NR resulted in higher seed TP (0.51%), seed Fe (4.28 mg kg⁻¹), and straw K (0.70%). Foliar fertilisation (FF) had pronounced effects; the control treatment (Cont.)

produced the highest seed TN (3.34%), while the S × Fe treatment recorded the highest seed Fe (5.31 mg kg^{-1}). The highest seed TP (0.55%) was observed with the S treatment, and the highest straw N (1.17%) and straw P (372.36 mg kg^{-1}) were recorded with Si × Fe and CulG11, respectively. The Si treatment produced the highest straw K (0.85%). The lowest seed TN (2.51%) was found with S × Fe, while the lowest seed TP (0.36%) was observed under both Cont. and Si treatments. All two-way and three-way interactions among cultivar, nitrogen rate, and foliar fertilisation were significant for all traits, indicating complex interrelationships affecting seed and straw quality in flax.

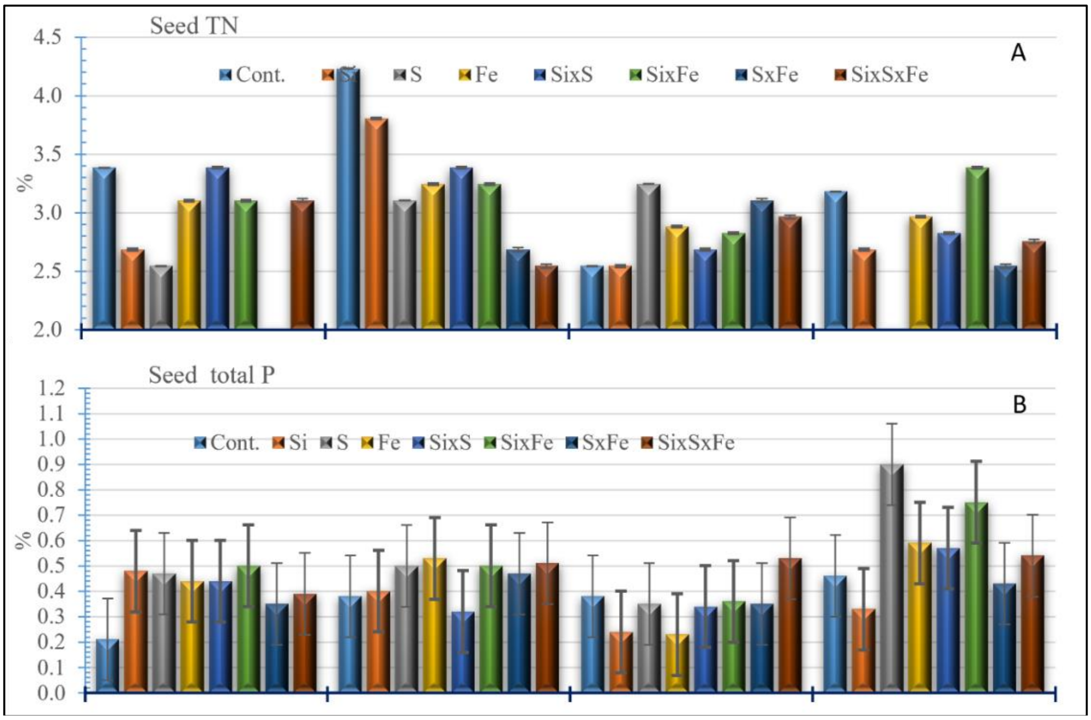
Table 4. Some Seed, Straw Quality as affected by different Flax cultivars, nitrogen rate, and foliar fertilization of different Si, S, Fe-fertilizers (combined analysis of two successive seasons)

Treatment		Seed								Straw					
		TN %		TP		TK		Fe, mg kg^{-1}		TN %		TP mg kg^{-1}		TK %	
Cul	CulG11	3.08	a	0.43	a	0.55	a	4.69	a	0.98	a	372.36	a	0.75	a
	CulG12	2.82	b	0.46	a	0.5	b	3.85	b	0.85	b	206.35	b	0.66	b
NR	75	2.87	b	0.51	a	0.51	b	4.28	a	0.86	b	312.25	a	0.70	a
	100	3.04	a	0.38	b	0.54	a	4.25	a	0.97	a	266.46	b	0.71	a
FF	Cont.	3.34	a	0.36	d	0.70	a	4.34	b	0.88	d	593.18	a	0.76	b
	Si	2.93	e	0.36	d	0.59	b	3.75	c	0.91	c	243.62	c	0.85	a
	S	2.72	g	0.55	a	0.52	c	4.01	c	1.1	b	161.36	c	0.65	e
	Fe	3.05	d	0.45	bd	0.52	c	3.99	c	0.8	g	228.79	c	0.67	de
	Si × S	3.07	c	0.42	cd	0.50	c	4.36	b	0.77	h	374.24	b	0.59	f
	Si × Fe	3.14	b	0.53	ab	0.52	c	3.98	c	1.17	a	212.01	c	0.69	d
	S × Fe	2.51	h	0.40	cd	0.40	e	5.31	a	0.86	e	156.21	c	0.73	c
	Si×S×Fe	2.84	f	0.49	ac	0.44	d	4.36	b	0.82	f	345.45	b	0.71	c
LSD 0.05	Cul×NR	0.001		0.06		0.01		0.2		0.002		30.52		0.02	
	Cul×FF	0.002		0.11		0.03		0.4		0.004		102.13		0.03	
	NR×FF	0.002		0.11		0.03		0.4		0.004		102.13		0.03	
	Cul×NR×FF	0.003		0.161		0.036		0.56		0.006		144.43		0.05	

Values followed by the same letter(s) within each column did not differ significantly according to the L.S.D. test at the 0.05 probability level

Seed total nitrogen percentage (TN%) was maximised in Giza 11 under full nitrogen (100% NR) with the control treatment (4.23%) and minimised in Giza 12 under full nitrogen with sulphur alone (1.99%), confirming cultivar-specific responses (Fig. 6A). For seed phosphorus (TP), the maximum value was achieved by Giza 12 under sulphur application at 75% NR, indicating a positive sulphur-phosphorus interaction (Fig. 6B). For seed potassium (TK), Giza 11 under the control treatment at 100% NR produced the highest values, while combined sulphur and iron applications reduced TK, possibly because of antagonistic or dilution effects (Fig. 6C). For seed iron (Fe), Giza 11 at 75% NR with combined foliar treatments produced the highest concentrations, indicating that iron enrichment can be achieved even under reduced nitrogen input (Fig. 6D). Straw nitrogen, phosphorus, and potassium were each significantly influenced by three-way interactions (Fig. 7). For straw N, Giza 11 showed superior uptake (0.99 vs. 0.89 g kg^{-1}), with combined Si × S and Si × Fe treatments producing the highest values (up to 1.69 g kg^{-1}). For straw P, Giza 11 consistently outperformed Giza 12, with full nitrogen enhancing P accumulation (up to 1113.64 mg kg^{-1}), and the Si × S combination significantly increasing straw P (918.18 mg kg^{-1} in Giza 11 at 75% N). For straw K, Giza 11 again showed higher accumulation (0.75 vs. 0.66 g kg^{-1}), with increased nitrogen enhancing K content, particularly in Giza 11 under full N supply, highlighting a synergistic nitrogen-potassium relationship.

The superior performance of Giza 11 under full nitrogen (100% NR) with the control treatment, which produced the maximum seed TN% (4.23%), suggests that this cultivar has greater nitrogen uptake efficiency and translocation capacity to developing seeds than Giza 12. Genotypic variation in nitrogen-use efficiency (NUE) has previously been documented in flax, where cultivar differences in nitrogen assimilation, remobilisation, and partitioning to seeds play a decisive role in determining final seed protein content (El-Gedwy et al., 2020; Mohamed et al., 2014). Phosphorus is an essential macronutrient involved in ATP formation, nucleic acid synthesis, membrane structure, and energy transfer (Marschner, 2012). The increase in seed phosphorus content with sulphur-containing treatments may be related to the role of sulphur in nutrient uptake and metabolic processes (Pavlovic et al., 2021). Silicon and iron foliar fertilisers may improve phosphorus acquisition indirectly through enhanced physiological performance and root functionality (Kakabouki et al., 2021), while foliar macro- and micronutrient applications can increase nutrient uptake and use efficiency in flax (Malimbayeva et al., 2026). Potassium, which is involved in enzyme activation, osmotic regulation, carbohydrate transport, and photosynthate translocation (Marschner, 2012), showed higher values in Giza 11, reflecting genotypic differences in uptake efficiency (El-Gedwy et al., 2020). Silicon improves membrane stability, nutrient absorption, and stress tolerance through increased root activity and improved translocation (Prado et al., 2026), while combined sulphur and iron treatments may induce competitive interactions that reduce potassium accumulation. Iron, which is involved in chlorophyll biosynthesis, photosynthesis, respiration, and enzymatic activity (Marschner, 2012), accumulated more in Giza 11, reflecting genetic differences (Mohamed et al., 2014). Fe-containing fertiliser combinations may improve absorption because particle-scale characteristics enhance penetration through leaf tissues and translocation to reproductive organs (Mahil & Kumar, 2019). The non-significant effect of nitrogen rate alone suggests that iron accumulation depends more on micronutrient management and genotype than on nitrogen supply. The significant three-way interaction (Cul × NR × FF) confirms that straw nutrient partitioning is governed by closely linked genetic and nutritional factors. Foliar fertilisers likely enhanced leaf absorption and translocation efficiency because of high surface reactivity, improving N assimilation into structural biomass (Abo-Marzoka & El-Borhamy, 2018). For phosphorus, several treatments resulted in P dilution because of biomass-driven dilution effects under enhanced growth conditions, consistent with the classical growth-dilution hypothesis. Nitrogen-mediated stimulation of plant growth plays a central role in enhancing P uptake efficiency (El-Gedwy et al., 2020; Kakabouki et al., 2021). Sulphur has a complementary role in the electron-transport chain and protein synthesis through its participation in the formation of sulphur-containing amino acids, including methionine and cysteine, and Fe-S clusters (Pavlovic et al., 2021). Silicon can alleviate iron deficiency through mechanisms including transcriptional upregulation of iron-transporter genes, increased accumulation of iron-mobilising compounds such as citrate and catechin, and the formation of iron-silicon complexes that promote root-to-shoot iron translocation (Pavlovic et al., 2021; Romera et al., 2021). Foliar silicon application emerged as the most effective treatment for potassium, producing the highest straw K concentrations (1.09 g kg^{-1}), which may be attributed to silicon-induced improvements in membrane integrity, reduced transpiration loss, and enhanced ion selectivity (Bakry et al., 2012). However, significant three-way interactions revealed that some combined foliar treatments caused moderate reductions in K concentration, probably because of nutrient antagonism or dilution effects associated with enhanced biomass accumulation, emphasising the importance of nutrient synchronisation strategies.



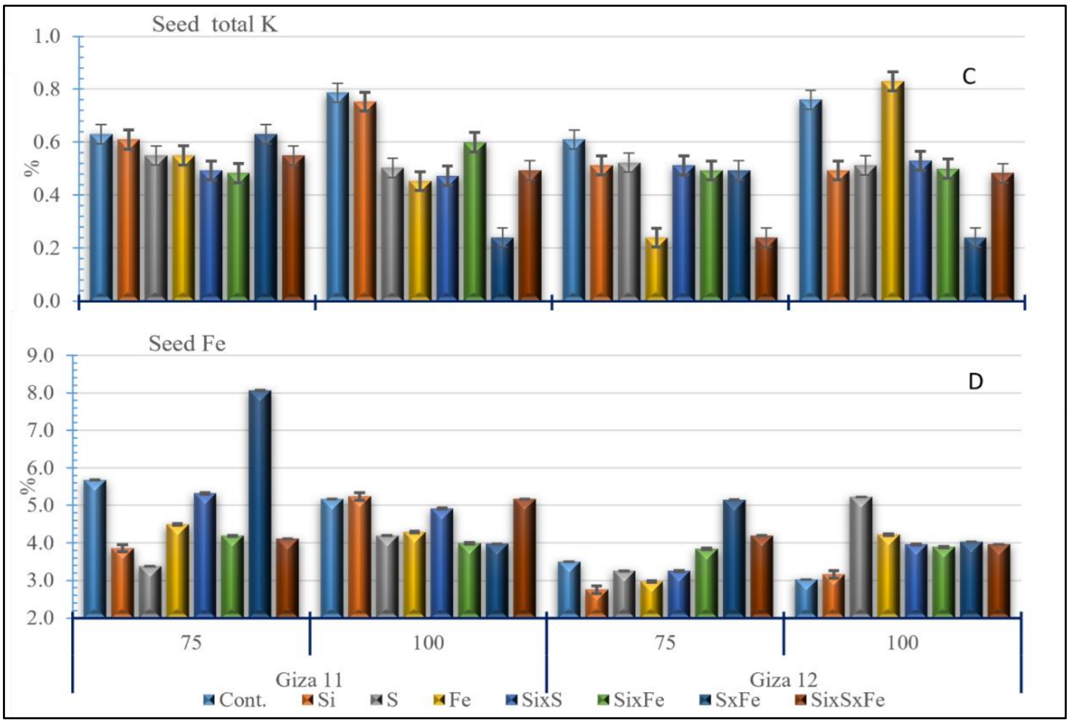


Fig. 6. Seed TN, P, K (%) and Fe mg kg^{-1} as affected by the interaction among cultivar, nitrogen rate, and foliar fertilizer treatments. Error bar L.S.D. 0.05

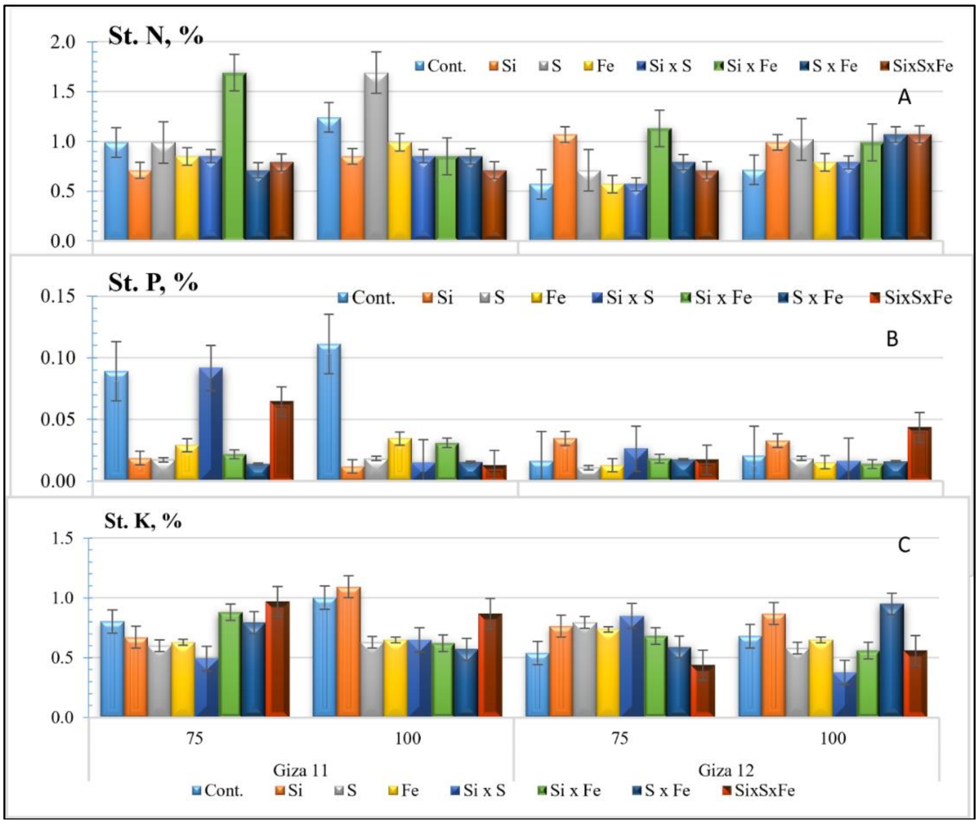


Fig. 7. Straw TN, P, K (%) as affected by the interaction among cultivar, nitrogen rate, and foliar fertilizer treatments. Error bar L.S.D. 0.05

4. Conclusion

This study concludes that flax productivity and nutrient dynamics are strongly governed by the integrated interaction among cultivar, nitrogen rate, and foliar Si, S, and Fe applications. The significant interaction effects across most parameters confirm that optimising flax performance depends more on synchronising these factors than on any single treatment. Applying the full recommended nitrogen rate (50 kg N fed^{-1}) with selected foliar formulations, particularly Si × S, Si × Fe, and S × Fe, improved vegetative growth, yield components, nutrient accumulation, plant height, technical length, fruiting-zone characteristics, capsule formation, straw yield, seed yield, and nutrient uptake efficiency. These results indicate synergistic effects between macro- and micronutrient inputs.

Among the evaluated cultivars, CulG12 generally showed higher productivity and greater responsiveness to integrated nutrient management, particularly under combined foliar fertiliser applications. In contrast, CulG11 showed comparatively greater nutrient accumulation in some vegetative tissues. These genotype-dependent responses emphasise the importance of cultivar-specific fertilisation strategies for maximising productivity and nutrient-use efficiency in flax production systems.

Overall, the findings highlight the agronomic and environmental value of integrating optimised nitrogen fertilisation with foliar Si, S, and Fe fertiliser applications and appropriate cultivar selection. Such strategies can improve flax productivity, enhance nutrient-use efficiency, and reduce potential environmental risks associated with excessive residual nutrients. Therefore, integrated Si, S, and Fe-enabled nutrient management represents a useful approach for sustainable flax production under comparable agroecological conditions.

5. Limitations

This study was conducted at one experimental location over two winter seasons using two flax cultivars and specific foliar nutrient sources. Therefore, the findings may not fully represent responses under other soil types, climatic conditions, cultivars or fertiliser formulations. Further multi-location and multi-season studies are needed to confirm the consistency of the observed cultivar-specific responses and to refine nutrient recommendations for wider flax-growing environments.

Ethical Approval

The authors declared that the following study was conducted in accordance with the ethical standards. The research protocol was reviewed and approved by the research committee (Soil Fertility and Plant Nutrition Dept.) prior to data collection.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of deepseek and quillbot to assist with language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Abdelmasieh, W. K. L., El-Borhamy, A. M. A., & Abd El-Sadek, M. S. (2022). Impact of sulphur fertilization on yield and its components of three flax (*Linum usitatissimum* L.) genotypes. *Moroccan Journal of Agricultural Sciences, 3*(4), 212–217. https://doi.org/10.5281/zenodo.8025156

Abo-Marzoka, E. A., & El-Borhamy, A. M. A. (2018). Response of flax plant to foliar spray by urea and some of micronutrients mixture under different nitrogen levels. *Alexandria Journal of Agricultural Sciences, 63*(4), 251–261. https://doi.org/10.21608/alexja.2018.26150

AOAC International. (2010). *Official methods of analysis of AOAC International* (18th ed., rev. 3). AOAC International. https://www.aoac.org/

Bakry, B. A., Tawfik, M. M., Mekki, B. B., & Zeidan, M. S. (2012). Yield and yield components of three flax cultivars (*Linum usitatissimum* L.) in response to foliar application with Zn, Mn and Fe under newly reclaimed sandy soil conditions. *American-Eurasian Journal of Agricultural & Environmental Sciences, 12*(8), 1075–1080.

Bartlett, M. S. (1937). Properties of sufficiency and statistical tests. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 160*(901), 268–282. https://doi.org/10.1098/rspa.1937.0109

Bauer, P., Elbaum, R., & Weiss, I. M. (2011). Calcium and silicon mineralization in land plants: Transport, structure and function. *Plant Science, 180*(6), 746–756. https://doi.org/10.1016/j.plantsci.2011.01.019

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen—total. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed., pp. 595–624). American Society of Agronomy; Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed

Cottenie, A., Verloo, M., Kiekens, L., Velghe, G., & Camerlynck, R. (1982). *Chemical analysis of plants and soils*. Laboratory of Analytical Agrochemistry, State University of Ghent.

Dordas, C. (2010). Variation of physiological determinants of yield in linseed in response to nitrogen fertilization. *Industrial Crops and Products, 31*(3), 455–465. https://doi.org/10.1016/j.indcrop.2010.01.008

El-Borhamy, A. M. A., Mohamed, E. N. M., & Abd Al-Sadek, M. S. (2017). Comparison of yield, its components and chemical composition of some flax genotypes. *Journal of Plant Production, 8*(1), 13–17. https://doi.org/10.21608/jpp.2017.37462

El-Gazzar, A. A. M., & Kineber, M. E. A. (2002). Response of flax yield and quality to nitrogen fertilizer and its sources. *Journal of Agricultural Research, 28*(1), 93–104.

El-Gedwy, E. M. M. (2020). Effect of nitrogen fertilizer rates and plant density on straw, fiber yield and anatomical manifestations of some flax cultivars. *Annals of Agricultural Science, Moshtohor, 58*(4), 855–870. https://doi.org/10.21608/assjm.2020.134990

El-Nagdy, G. A., Nassar, D. M. A., El-Kady, E. A., & El-Yamanee, G. S. A. (2010). Response of flax plant (*Linum usitatissimum* L.) to treatments with mineral and bio-fertilizers from nitrogen and phosphorus. *Journal of American Science, 6*(10), 207–217. https://jofamericanscience.org/journals/am-sci/am0610/23_3042am0610_207_217.pdf

Gondal, A. H., Areche, F. O., Sumarriva-Bustinza, L. A., Chávez-Sumarriva, N. L., Zela-Payi, N. O., More López, J. M., Saldarriaga, J. Y., García-Díaz, B. L., Porras-Roque, M. S., Ayuque-Rojas, J. C., Vivanco Aguilar, S., Ruiz Vilchez, D., Yaulilahua-Huacho, R., Malpartida Yapias, R. J., & Jabbar, A. (2023). Usage of iron foliar spray in enhancing the growth and yield of the flax plant (*Linum usitatissimum* L.). *Journal of Experimental Biology and Agricultural Sciences, 11*(2), 316–324. https://doi.org/10.18006/2023.11(2).316.324

Hellal, F. A., Abdelhamid, M. T., Abo-Basha, D. M., & Zewainy, R. M. (2012). Alleviation of the adverse effects of soil salinity stress by foliar application of silicon on faba bean (*Vicia faba* L.). *Journal of Applied Sciences Research, 8*(8), 4428–4433.

Jackson, M. L. (1973). *Soil chemical analysis*. Prentice Hall.

Kakabouki, I., Mavroeidis, A., Tataridas, A., Roussis, I., Katsenios, N., Efthimiadou, A., Tigka, E. L., Karydogianni, S., Zisi, C., Folina, A., & Bilalis, D. (2021). Reintroducing flax (*Linum usitatissimum* L.) to the Mediterranean Basin: The importance of nitrogen fertilization. *Plants, 10*(9), Article 1758. https://doi.org/10.3390/plants10091758

Klute, A. (Ed.). (1986). *Methods of soil analysis: Part 1. Physical and mineralogical methods* (2nd ed.). American Society of Agronomy; Soil Science Society of America. https://doi.org/10.2136/sssabookser5.1.2ed

Ma, J. F. (2004). Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. *Soil Science and Plant Nutrition, 50*(1), 11–18. https://doi.org/10.1080/00380768.2004.10408447

Mahil, E. I. T., & Kumar, B. N. A. (2019). Foliar application of nanofertilizers in agricultural crops: A review. *Journal of Farm Sciences, 32*(3), 239–249.

Malimbayeva, A., Amangaliev, B., Zhusupbekov, E., Soltanayeva, A., Sagimbayeva, A., Oshakbayeva, Z., Rustemova, K., & Batyrbek, M. (2026). Effects of different mineral, foliar macro- and micronutrient, and biofertilizer fertilization strategies on oil flax (*Linum usitatissimum* L.) yield and seed quality under semi-arid rainfed conditions. *International Journal of Plant Biology, 17*(3), Article 19. https://doi.org/10.3390/ijpb17030019

Marschner, P. (Ed.). (2012). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Mohamed, M. F., Khalifa, R. K. M., Ahmed, A. G., & Eleiwa, M. E. (2014). Effect of micronutrients combinations as foliar application on flax grown under newly reclaimed sandy soil. *Middle East Journal of Agriculture Research, 3*(2), 378–382. https://www.curresweb.com/mejar/mejar/2014/378-382.pdf

Newkirk, R. (2015). *Flax feed industry guide*. Flax Canada. https://www.flaxcouncil.ca/quadrant/media/files/pdfs/Flax-Feed-Industry-Guide-Final.pdf

Page, A. L., Miller, R. H., & Keeney, D. R. (Eds.). (1982). *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed.). American Society of Agronomy; Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed

Pavlovic, J., Kostic, L., Bosnic, P., Kirkby, E. A., & Nikolic, M. (2021). Interactions of silicon with essential and beneficial elements in plants. *Frontiers in Plant Science, 12*, Article 697592. https://doi.org/10.3389/fpls.2021.697592

Prado, E. da R., Oliveira, R. de, Prado, R. de M., & Gratão, P. L. (2026). Silicon alleviates potassium deficiency in plants by improving photosynthesis, antioxidant defenses, water use efficiency, and potassium use efficiency: A meta-analysis. *Journal of Soil Science and Plant Nutrition, 26*, 5164–5177. https://doi.org/10.1007/s42729-026-03180-1

Romera, F. J., Lan, P., Rodríguez-Celma, J., & Pérez-Vicente, R. (2021). Editorial: Nutrient interactions in plants. *Frontiers in Plant Science, 12*, Article 782505. https://doi.org/10.3389/fpls.2021.782505

Snedecor, G. W., & Cochran, W. G. (1980). *Statistical methods* (7th ed.). Iowa State University Press.

Tayyiba, L., Zafar, H., Gondal, A. H., Farooq, Q., Mukhtar, M. M., Hussain, R., Aslam, N., Muzaffar, A., & Sattar, I. (2021). Efficiency of zinc in plants, its deficiency and sensitivity for different crops. *Current Research in Agricultural Sciences, 8*(2), 128–134. https://doi.org/10.18488/journal.68.2021.82.128.134

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