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Response of Flax (*Linum usitatissimum* L.) Cultivars to Nitrogen Rates and Foliar Fertilization: B- Impacts on Oil, Fiber Yield, and Soil Fertility

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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 (*Linum usitatissimum L.*) is a dual-purpose crop cultivated for seed oil and fibre, and its productivity depends on cultivar performance and balanced nutrient management. A field experiment was conducted during two winter seasons (2022/2023 and 2023/2024) at Etay El-Baroud Agricultural Research Station, Egypt, using a split-split plot design with three replications. Two flax cultivars (Giza 11 and Giza 12) were assigned to the main plots, two nitrogen rates (75% and 100% of the recommended dose; 37.5 and 50 kg N fed^{-1}) to the sub-plots, and eight foliar fertiliser treatments to the sub-sub-plots: control, Fe, Si, S, Si×S, Si×Fe, S×Fe, and Si×S×Fe. Foliar sprays were applied at 50, 60 and 85 days after sowing. The combined analysis showed that Giza 11 recorded higher seed protein content (16.86%), whereas Giza 12 produced

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higher oil yield (105.85 kg fed^{-1}) and fibre yield (69.71 kg fed^{-1}). Increasing nitrogen to 100% of the recommended dose improved protein, oil and fibre yields. Among foliar treatments, Si×Fe recorded the highest mean protein yield (102.94 kg fed^{-1}), Fe produced the highest oil percentage (24.41%) and oil yield (119.61 kg fed^{-1}), and Si×S×Fe gave the highest fibre percentage (12.40%) and fibre yield (70.68 kg fed^{-1}). The results indicate that cultivar-specific nutrient management can improve flax yield, quality and post-harvest soil fertility.

Keywords: Linum usitatissimum; flax cultivars; nitrogen rate; foliar fertilisation; silicon; sulphur; iron; oil yield; fibre yield; soil fertility; nutrient management.

1. Introduction

Flax (*Linum usitatissimum L.*) is cultivated in Egypt as a dual-purpose crop, with its seed used for oil and its stem used for fibre (Omer & Mahmood, 2024). Flaxseed oil is edible and has a favourable fatty acid profile, with low saturated fat content (around 9%) and high proportions of polyunsaturated fatty acids (73%) and monounsaturated fat (18%). Flaxseed protein also contributes to its nutritional value and supports its use in food products and health-promoting diets. Increasing flax productivity per unit area requires the selection of high-yielding cultivars and the improvement of crop management practices. Recent analysis of linseed yield traits also indicates that yield-related characters should be considered when selecting genotypes with improved productivity potential (Shankar *et al.*, 2024).

Nitrogen can enhance fibre characteristics, including strength and uniformity, while also supporting seed oil content (Dordas, 2010). Although nitrogen application can increase flax yield, crop response is often influenced by other management and environmental factors in addition to nitrogen rate. Evidence suggests that optimised nitrogen application can improve productivity while reducing the risk of adverse environmental effects. Recent field evidence in oil flax further indicates that nitrogen supplied with complementary potassium nutrition can influence grain yield and stem-strength-related traits, highlighting the need for balanced nutrient scheduling rather than reliance on nitrogen alone (Li *et al.*, 2026).

In addition, silicon-based fertilisers may improve root development and nutrient uptake, thereby supporting plant vigour (Amalya *et al.*, 2020). Hellal *et al.* (2012) reported that silicate application can alleviate nutritional imbalance and reduce metal toxicity. Sulphur is essential for the synthesis of proteins and amino acids, while foliar applications of potassium silicate and magnesium silicate improved the nutrient status of flax varieties compared with untreated plants (Shedeed *et al.*, 2016). Recent field studies in flax have further shown that integrated foliar macro- and micronutrient fertilisation can support nutrient uptake, seed yield and seed quality under semi-arid conditions, although crop response remains dependent on the nutrient formulation and application strategy (Malimbayeva *et al.*, 2026; Xie *et al.*, 2025).

Sulphur fertilisation is important for flax seed, fibre and oil yield because sulphur is a component of sulphur-containing amino acids, including cysteine and methionine, as well as proteins, coenzymes and chlorophyll, all of which influence plant development, photosynthesis and oil biosynthesis. Abdelmasieh *et al.* (2022) reported that the application of 50.0 kg sulphur ha^{-1} significantly improved most of the studied traits, including fibre yield ha^{-1}.

Foliar Fe-EDTA can improve flax seed, oil and fibre yields, particularly at 200 ppm when applied with urea and nitrogen fertilisation (Abo-Marzoka & El-Borhamy, 2018). Iron deficiency is often more pronounced in alkaline or calcareous soils with low organic carbon content, as well as in strongly limed, salt-affected and wet soils (Gondal *et al.*, 2021a, 2021b). The cultivation of high-yielding crop cultivars therefore requires balanced levels of macronutrients (N and P) and micronutrients (Fe, Zn, Mg and Mn) to optimise seed and straw yield and quality (Abo-Marzoka & El-Borhamy, 2018).

Soils with low organic matter concentrations are particularly vulnerable to sulphur deficiency because sulphur is mainly absorbed by plants as sulphate, and its availability in soil depends strongly on microbial mineralisation and organic matter content. Adequate sulphur nutrition can support root-zone pH stability, cation-anion balance in the rhizosphere and nitrogen-use efficiency through its role in protein synthesis, chlorophyll formation and enzyme activity (Heckman, 2021). Because nutrient availability is mediated by interactions among roots, soil and microorganisms, foliar and soil fertilisation responses should be interpreted together with post-harvest soil fertility indicators (Adal, 2023). However, limited information is available on the combined responses of Giza 11 and Giza 12 flax cultivars to reduced and recommended nitrogen rates with foliar-applied silicon, sulphur and iron, particularly when yield-quality traits and post-harvest soil fertility are assessed together under the conditions of the present study.

This study was conducted to address the limited information on fertiliser use in flax cultivation and post-harvest soil fertility under the conditions of the experiment. It evaluated the effects of nitrogen rate and foliar-applied silicon, sulphur and iron, individually and in combination, on two flax cultivars. The objective was to determine their effects on yield, yield components, oil percentage, fibre yield and selected soil fertility parameters compared with the untreated control, thereby identifying nutrient combinations that may improve cultivar performance under the studied conditions.

2. Materials and Methods

Field experiments were conducted at the Etay El-Baroud Agricultural Research Station in El-Beheira Governorate, Egypt (30°89′ E, 30°65′ N), during two successive winter seasons (2022/2023 and 2023/2024) using a split-split plot design with three replications. The main plots were assigned to two flax cultivars (Giza 11 and Giza 12), which are dual-purpose cultivars grown for both fibre and seed production. The sub-plots received two nitrogen rates (75% and 100% of the recommended dose, equivalent to 37.5 and 50 kg N fed^{-1}), applied as ammonium nitrate in three equal splits at 20, 40 and 60 days after planting. The sub-sub-plots received eight foliar fertilisation treatments (Fe, Si, S, Fe+Si, Fe+S, Si+S, Fe+Si+S and a distilled-water control), applied at 50, 60 and 85 days after sowing using a knapsack sprayer at 200 L fed^{-1} with 0.1% wetting agent.

2.1 Protein Yield

- Protein concentration was calculated

$$\text{Protein concentration \%} = \text{TN (\%) x 5.30.}$$

where, TN: Total nitrogen (Mariotti *et al.,* 2008)

- Protein Yield (Mg fed^{-1}) was calculated by

$$\text{Protein Yield (Kg per fed)} = \text{Grain Yield (kg fed}^{-1}\text{) x Protein (\%)/ 100}$$

2.2 Oil Yield

- Oil content % was determined by soxlet apparatus using petroleum ether (4ºC – 60 ºC) according to the official method (A.O.A.C. 2000)
- Oil Yield (kg fed^{-1}) = Seed yield (kg fed^{-1}) x Seed Oil %/ 100

2.3 Fiber Yield

- Fiber %
- Fiber yield (kg fed^{-1}) = straw yield (kg fed^{-1}) after retting multiplied fiber percentage.

2.4 Soil Analysis

- Mineral nitrogen (N) was determined using the Kjeldahl method.
- Available phosphorus (P) was extracted with 0.5 N $NaHCO_3$ (pH 8.5) and quantified via the ascorbic acid method (Olsen *et al*., 1954; Watanabe & Olsen, 1965).
- Exchangeable potassium (K) was extracted using neutral 1 N NH_4OAc and measured with a flame photometer (Black *et al*., 1965; Cottenie *et al*., 1982).
- Organic matter (OM) was determined by the Walkley-Black method (Black *et al*., 1965).

2.5 Statistical Analysis

Statistical analysis of the data was conducted using ANOVA as described by Snedecor and Cochran (1980). Means were compared using the least significant difference (LSD) test at a significance level of $p \leq 0.05$.

3. Results and Discussion

3.1 Protein Content, g Kg^{-1}

Seed protein content was significantly influenced by the interaction among flax cultivar, nitrogen rate (NR) and foliar fertiliser application. According to the combined analysis presented in Table 1 and Fig. 1, Giza 11 recorded a higher average seed protein content (16.86%) than Giza 12 (14.87%). Increasing the nitrogen rate from 75% to 100% of the recommended dose increased seed protein percentage from 15.18% to 16.09%, indicating the positive role of nitrogen in protein biosynthesis and amino acid formation.

Table 1. Protein, oil and fiber content and yield as affected by different flax cultivars, nitrogen rate, foliar application of different Si, S, Fe-fertilizers (combined analysis of two successive growing seasons)

Treatment		**Protin content**		**Protein yield**		**Oil**		**Oil yield**		**Fiber Content**		**Fiber yield**	
		%		**Kg fed^{-1}**		**%**		**Kg fed^{-1}**		**%**		**Kg fed^{-1}**	
Cul	Giza 11	16.86	a	88.55	a	18.13	a	90.65	b	12.06	a	60.30	a
	Giza 12	14.87	b	92.45	a	18.57	a	105.85	a	12.23	a	69.71	a
NR	75	15.18	b	82.35	b	18.45	a	92.25	b	11.9	b	59.50	b
	100	16.09	a	97.78	a	18.24	a	102.14	a	12.39	a	69.38	a
FF	Cont.	17.68	a	93.98	de	15.45	e	75.71	d	12.02	ab	58.90	c
	Si	15.53	e	85.94	d	18.56	c	94.66	c	11.72	b	59.77	bc
	S	14.42	g	81.33	e	21.55	b	112.06	ab	12.32	a	64.06	bc
	Fe	16.16	d	85.90	d	24.41	a	119.61	a	12.09	ab	59.24	c
	Si × S	16.27	c	98.84	b	13.66	f	76.50	d	12.13	ab	67.93	bc
	Si × Fe	16.64	b	102.94	a	17.1	d	97.47	c	12.20	ab	69.54	bc
	S × Fe	13.30	h	79.37	e	18.81	c	103.46	b	12.28	a	67.54	b
	Si×S×Fe	15.06	f	93.20	c	17.24	d	98.27	c	12.40	a	70.68	a
LSD 0.05	Cul×NR	*0.01*		*2.65*		0.82		5.58		0.25		1.1	
	Cul×FF	*0.01*		*5.31*		1.65		11.17		0.49		2.2	
	NR×FF	*0.01*		*5.31*		1.65		11.17		0.49		2.2	
	Cul×NR×FF	*0.016*		*7.51*		2.33		15.79		0.7		3.1	

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

Among foliar fertiliser treatments, the control treatment recorded the highest mean protein content (17.68%), followed by Si×Fe (16.64%) and Si×S (16.27%). In contrast, the S×Fe combination resulted in the lowest protein content (13.30%). The interaction data showed that Giza 11 under 100% NR combined with the control treatment produced the maximum seed protein percentage, whereas lower values were generally associated with combined sulphur and iron treatments.

These findings suggest that cultivar genotype and nitrogen availability strongly influence protein accumulation in flaxseed, while foliar fertiliser combinations may either enhance or reduce protein synthesis depending on nutrient interactions and plant physiological responses.

Flaxseed is an important plant-based protein source, with protein content commonly ranging from 18% to 30%, depending on cultivar, environmental conditions and nutrient management practices. Nitrogen fertilisation plays a central role in enhancing protein synthesis through its involvement in chlorophyll formation, amino acid metabolism and enzymatic activity (Grant *et al.*, 2016). Previous studies have also shown that foliar micronutrient application can improve nutrient assimilation and protein accumulation in oilseed crops (Basit *et al.*, 2019).

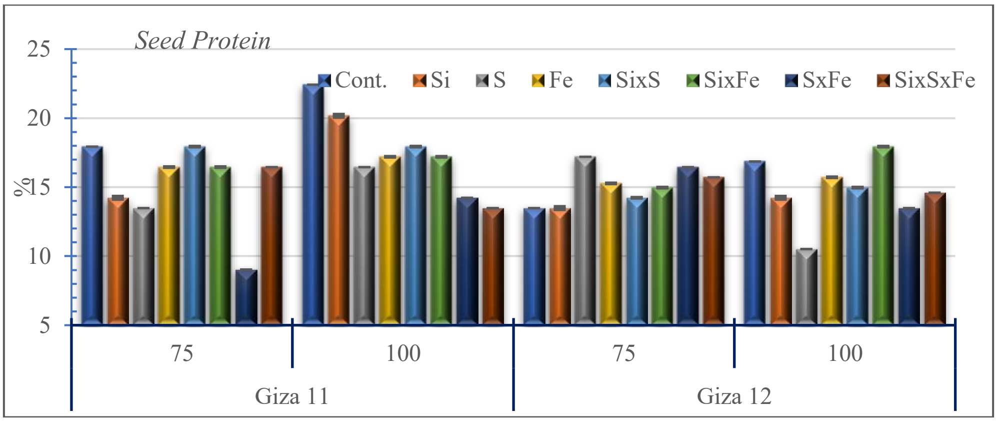

Fig. 1. Seed protein content (%) as affected by the interaction among cultivar, nitrogen rate, and foliar fertilizer treatments

Error bar LSD 0.05

The positive response observed under adequate nitrogen fertilisation agrees with the findings of El-Shimy *et al.* (2020), who reported that increasing nitrogen rates improved protein accumulation and overall seed quality in flax. Moreover, foliar fertiliser formulations can improve nutrient-use efficiency because of their small particle size and high surface reactivity, which enhance foliar absorption and nutrient translocation within plant tissues (Balachandra *et al.*, 2025). However, excessive or imbalanced combinations of micronutrients may induce antagonistic interactions that negatively affect protein synthesis, which may explain the reduced protein percentage observed under the S×Fe treatment.

Overall, the results indicate that optimising nitrogen supply together with appropriate foliar fertiliser combinations can improve seed protein quality in flax, particularly in the Giza 11 cultivar.

3.2 Protein Yield, Kg fed^{-1}

Protein yield of flaxseed was significantly affected by the interaction among cultivar, nitrogen rate and foliar fertiliser treatments (Table 1 and Fig. 2). Although cultivar differences alone were not statistically significant, Giza 12 recorded a slightly higher average protein yield (92.45 kg fed^{-1}) than Giza 11 (88.55 kg fed^{-1}). Increasing the nitrogen rate from 75% to 100% significantly enhanced protein yield from 82.35 to 97.78 kg fed^{-1}, reflecting the positive role of nitrogen in improving seed productivity and protein accumulation.

Among foliar treatments, the Si×Fe combination produced the highest mean protein yield (102.94 kg fed^{-1}), followed by Si×S (98.84 kg fed^{-1}). In contrast, sulphur alone and S×Fe recorded the lowest protein yields. The interaction analysis showed that Giza 12 under 100% NR combined with Si×Fe achieved the maximum protein yield, indicating a positive interaction between adequate nitrogen supply and foliar fertiliser application.

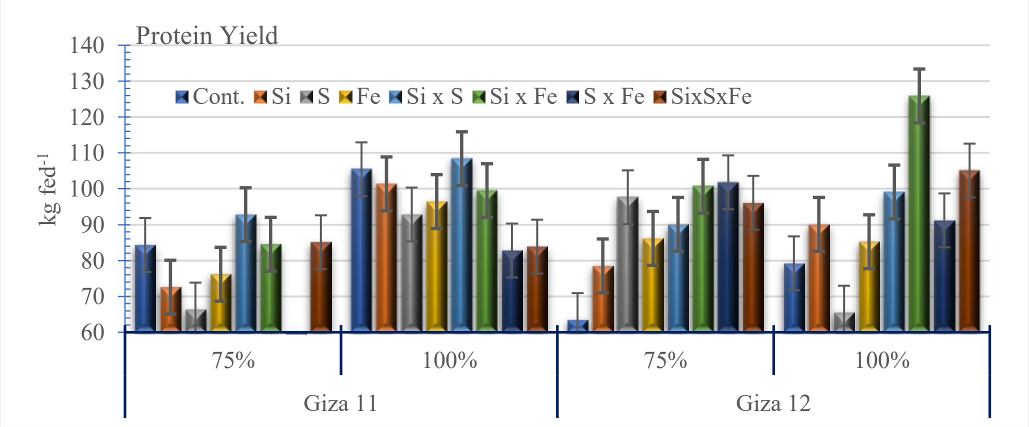

Fig. 2. Protein yield (kg fed^{-1}) as affected by the interaction among cultivar, nitrogen rate, and foliar fertilizer treatments

Error bar LSD 0.05

These findings indicate that integrated nutrient management involving optimised nitrogen fertilisation and combined foliar fertiliser treatments can improve flaxseed protein productivity.

Flaxseed is an important plant-based protein source, containing approximately 18% to 30% protein, depending on genotype, environmental conditions and agronomic practices. Nitrogen nutrition plays a fundamental role in protein synthesis through its involvement in amino acid formation, chlorophyll production and overall metabolic activity (Grant *et al.*, 2016).

The enhanced protein yield obtained with combined foliar fertiliser applications may be attributed to improved nutrient uptake efficiency and physiological performance. Foliar fertilisers provide nutrients in reactive forms with increased surface area, which can improve foliar absorption, nutrient mobility and metabolic utilisation within plant tissues (Balachandra *et al.*, 2025). Silicon and iron applications may also improve photosynthetic efficiency and stress tolerance, thereby increasing assimilate production and protein accumulation in developing seeds.

The superior performance of Giza 12 under the Si×Fe treatment agrees with previous findings showing that cultivar-specific responses to foliar fertiliser application can influence yield and seed quality traits (Basit *et al.*, 2019). Furthermore, balanced micronutrient supplementation combined with adequate nitrogen availability has been shown to enhance protein accumulation and overall nutritional quality in oilseed crops.

Overall, the results indicate that protein yield in flax can be improved through optimised nitrogen management combined with suitable foliar fertiliser formulations, particularly those containing silicon and iron.

3.3 Oil Percentage

Oil percentage in flaxseed was significantly influenced by the interaction among cultivar, nitrogen rate (NR) and foliar fertiliser application (Table 1 and Fig. 3). Although cultivar and nitrogen rate alone did not significantly affect oil percentage, their interaction with foliar fertiliser treatments resulted in considerable variation in seed oil content.

Giza 12 recorded a slightly higher average oil percentage (18.57%) than Giza 11 (18.13%), while the 75% NR treatment produced marginally higher oil content (18.45%) than the recommended nitrogen rate (18.24%). Among the foliar Si, S and Fe fertiliser treatments, iron application resulted in the highest mean oil percentage (24.41%), followed by sulphur application (21.55%) and S×Fe (18.81%). Conversely, Si×S recorded the lowest oil percentage (13.66%).

The interaction analysis showed that Giza 11 at 75% NR combined with iron foliar application produced the highest oil percentage (38.14%), indicating a positive effect of iron foliar fertilisation on oil biosynthesis under moderate nitrogen supply. In contrast, Giza 12 achieved its maximum oil percentage under sulphur application at the recommended nitrogen rate. Combined foliar fertiliser treatments produced variable responses depending on cultivar and nitrogen level.

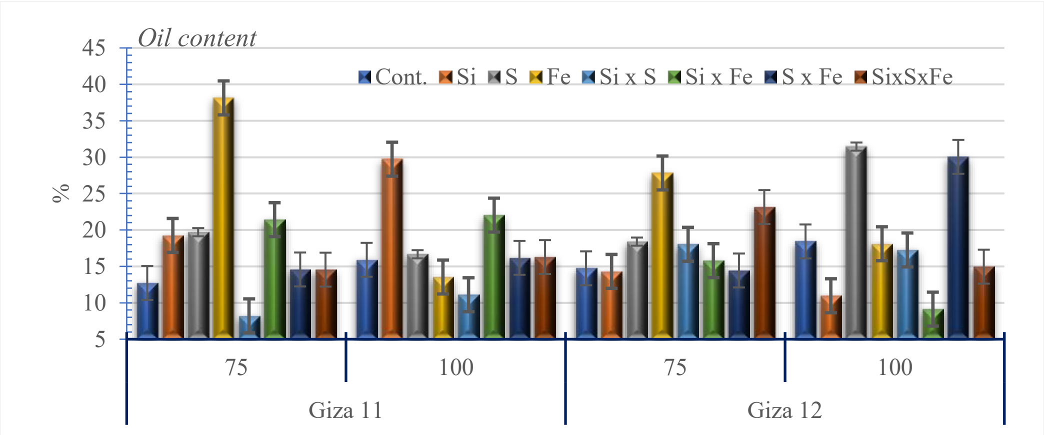

Fig. 3. Oil content (%) as affected by the interaction among cultivar, nitrogen rate, and foliar fertilizer treatments

Error bar LSD 0.05

These findings indicate that optimising the interaction among cultivar, nitrogen fertilisation and foliar fertiliser application is important for improving oil accumulation in flaxseed.

Oil biosynthesis in flax is influenced by nutrient availability and plant metabolic activity. Micronutrients such as iron and sulphur play physiological roles in enzymatic activation, chlorophyll synthesis and fatty acid metabolism, all of which contribute to oil production (Basit *et al.*, 2019). Iron is important in electron transport and photosynthetic processes that supply energy for lipid synthesis, whereas sulphur contributes to the formation of sulphur-containing amino acids and coenzymes involved in metabolic pathways related to oil accumulation.

The higher oil percentage observed under iron and sulphur foliar fertiliser treatments agrees with previous reports indicating that foliar micronutrient application improves oil biosynthesis pathways and enhances seed quality in flax and related oilseed crops (Saleem *et al.*, 2020). Foliar fertilisers can also improve nutrient-use efficiency because of their small particle size and enhanced penetration through leaf tissues, leading to greater nutrient availability and metabolic activity within plant cells.

The reduced oil percentage observed with some combined treatments, such as Si×S, may be attributed to nutrient antagonism or shifts in assimilate partitioning towards vegetative growth rather than oil synthesis. Similar responses have previously been reported under excessive or imbalanced micronutrient combinations in oilseed crops.

Overall, the results demonstrate that targeted foliar Si, S and Fe fertiliser application, particularly iron and sulphur, combined with appropriate nitrogen management can improve flaxseed oil content and nutritional quality.

3.4 Oil Yield, Kg fed^{-1}

Oil yield was significantly affected by the interaction among cultivar, nitrogen rate and foliar fertiliser treatments (Table 1 and Fig. 4). Giza 12 produced a higher average oil yield (105.85 kg fed^{-1}) than Giza 11 (90.65 kg fed^{-1}), reflecting its greater seed productivity and oil accumulation capacity. Increasing the nitrogen rate from 75% to 100% significantly increased oil yield from 92.25 to 102.14 kg fed^{-1}.

Among foliar treatments, iron application produced the highest average oil yield (119.61 kg fed^{-1}), followed by sulphur application (112.06 kg fed^{-1}) and S×Fe (103.46 kg fed^{-1}). In contrast, the control and Si×S treatments resulted in the lowest oil yields. The interaction analysis showed that Giza 12 under the recommended nitrogen rate combined with sulphur and iron application achieved the highest oil yield (187.27 kg fed^{-1}), whereas Giza 11 produced its maximum oil yield under iron application at 75% NR.

Combined foliar fertiliser applications, such as S×Fe and Si×S×Fe, also improved oil yield in several cases, particularly for Giza 12, indicating positive interactions among micronutrients for oil productivity.

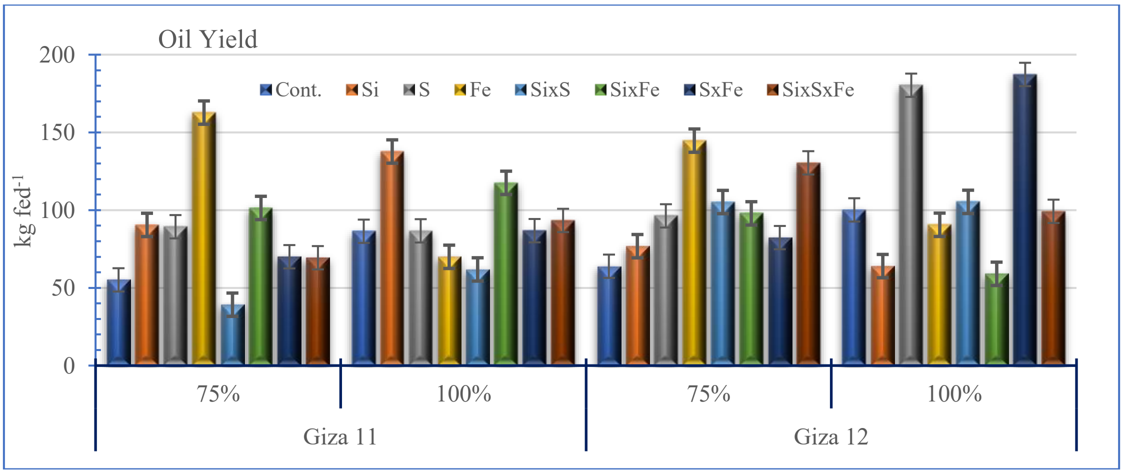

Fig. 4. Oil yield (kg fed^{-1}) as affected by the interaction among cultivar, nitrogen rate, and foliar Si, S, Fe-fertilizer treatments

Error bar LSD 0.05

Oil yield is determined by both seed yield and oil concentration; therefore, improvements in either parameter can contribute to increased oil productivity. Adequate nitrogen supply enhances vegetative growth, photosynthetic activity and assimilate production, which ultimately support seed development and oil accumulation (Kakabouki *et al.*, 2021). However, excessive nitrogen may sometimes favour protein synthesis at the expense of oil accumulation, emphasising the importance of balanced nutrient management.

The positive response of oil yield to sulphur and silicon applications agrees with previous findings indicating that foliar micronutrient treatments improve physiological efficiency and oil biosynthesis in flax (El-Bassiouny *et al.*, 2024; Shedeed *et al.*, 2016). Sulphur-containing compounds are known to enhance antioxidant activity, enzyme function and fatty acid synthesis, thereby improving seed oil productivity. Silicon application may also improve nutrient uptake, stress tolerance and photosynthetic efficiency, resulting in increased assimilate availability for oil formation.

The enhanced performance observed with combined foliar fertiliser applications may be attributed to synergistic interactions among micronutrients that improve nutrient absorption and metabolic activity. These fertilisers may possess high reactivity and improved foliar penetration, thereby increasing nutrient availability and utilisation efficiency within plant tissues.

Overall, the findings indicate that integrated nutrient management involving optimised nitrogen fertilisation and suitable foliar fertiliser combinations can improve oil yield and seed quality in flax production systems, particularly for the Giza 12 cultivar.

3.5 Fibre Yield

3.5.1 Fibre Percentage

Fibre percentage in flax was significantly influenced by the interaction among cultivar, nitrogen rate (NR) and foliar fertiliser application. In both cultivars, increasing nitrogen from 75% to 100% of the recommended dose generally enhanced fibre content. Foliar application of Si, S and Fe fertilisers, particularly the combined treatment of silicon, sulphur and iron (Si×S×Fe), further improved fibre percentage compared with the control and single foliar fertiliser applications.

The highest fibre percentages were recorded under the triple Si, S and Fe fertiliser combination (Si×S×Fe) at the recommended nitrogen rate, where Giza 11 reached 12.93% and Giza 12 reached 12.60%. Treatments involving sulphur, either alone or combined with iron, also enhanced fibre percentage relative to the control treatment. These findings indicate that optimising nitrogen fertilisation together with appropriate foliar fertiliser combinations can improve flax fibre quality.

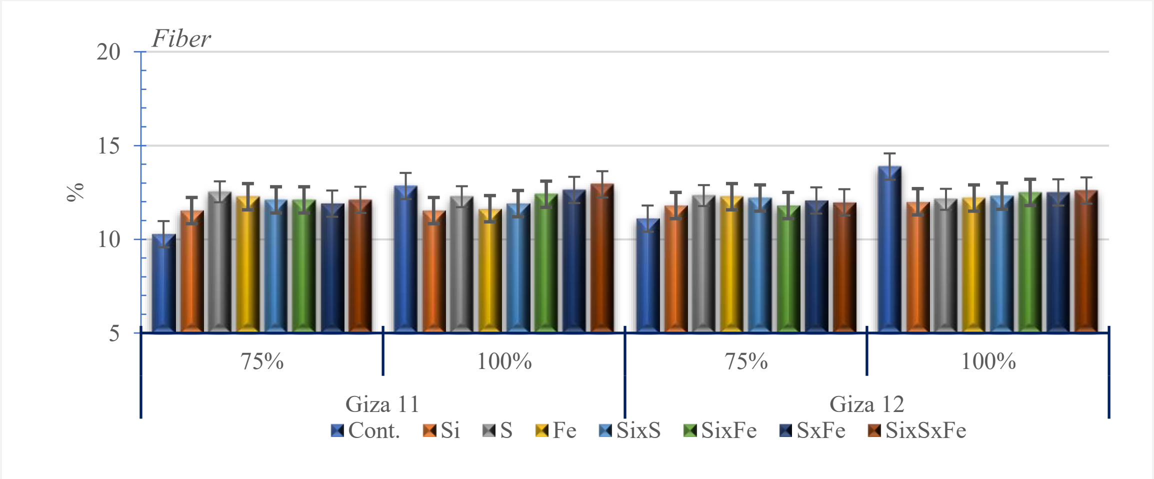

Fig. 5. Fiber percentage (%) as affected by the interaction among the different treatments
Error bar LSD 0.05

The present findings indicate that integrated nutrient management plays an important role in improving flax fibre quality. Similar results were reported by El-Shimy *et al.* (2020), who demonstrated that increasing nitrogen rates enhanced fibre yield and anatomical characteristics of flax cultivars through stimulation of protein synthesis, cell division and stem elongation. The superior performance of combined foliar fertiliser applications, particularly Si×S×Fe, may be attributed to the synergistic effects of these nutrients on physiological and metabolic processes related to fibre formation. Silicon contributes to cell wall strengthening and stress tolerance, sulphur is essential for amino acid and protein synthesis, and iron plays a role in chlorophyll formation and enzymatic activity. Together, these nutrients improve nutrient uptake efficiency and biomass accumulation, thereby enhancing fibre quality (Omer & Mahmood, 2024).

3.6 Fibre Yield, Kg fed^{-1}

Fibre yield of flax was significantly affected by the interaction among cultivar, nitrogen rate and foliar application of Si, S and Fe fertilisers. In general, Giza 12 produced higher fibre yield values than Giza 11 across most treatments. Increasing nitrogen from 75% to 100% of the recommended dose improved fibre yield, particularly when combined with foliar fertiliser applications.

The highest fibre yield was obtained by Giza 12 at the recommended nitrogen rate under silicate plus iron (Si×Fe) and the triple combination (Si×S×Fe), reaching 80.83 and 83.58 kg fed^{-1}, respectively. In Giza 11, fibre yield also increased under combined foliar fertiliser treatments, with the maximum value reaching 74.15 kg fed^{-1} under the Si×S×Fe treatment at the highest nitrogen rate.

According to Dervisevic *et al.* (2014), flax plants that received 30 kg N ha^{-1} had the highest fibre yield. El-Nagdy *et al.* (2010) also reported that the highest values of flax straw yield were obtained when 45 kg N fed^{-1} was applied. Foliar micronutrient application increased flax straw output (Bakry *et al.*, 2012; Liu *et al.*, 2013).

Overall, combined foliar fertiliser applications consistently outperformed the control and single nutrient treatments, demonstrating the beneficial interactions of micronutrient combinations for flax fibre productivity. Statistical analysis confirmed significant interactions among cultivar, nitrogen rate and foliar fertiliser application, highlighting the importance of integrated nutrient management strategies for maximising flax fibre yield.

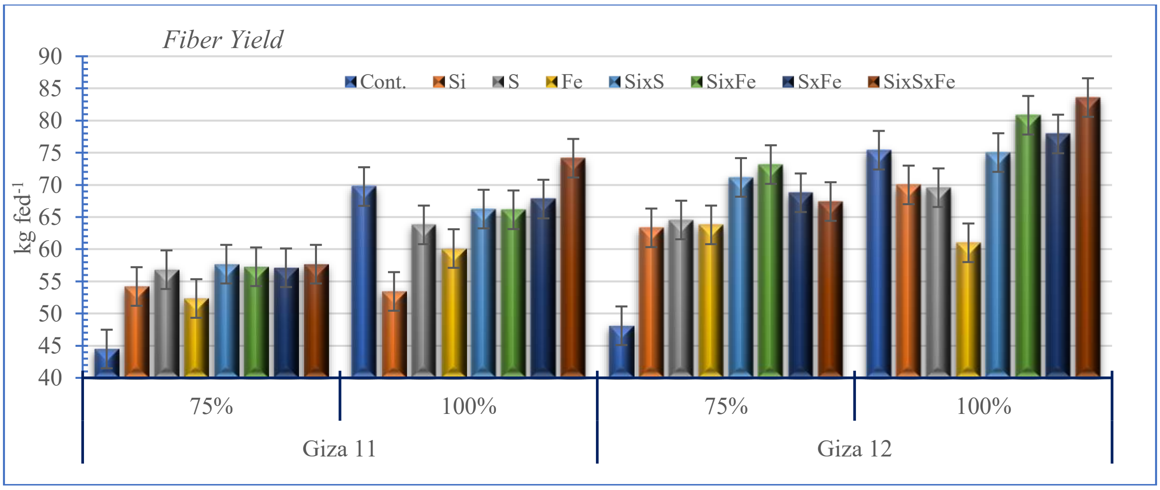

Fig. 6. Fiber yield (kg fed^{-1}) as affected by the interaction among flax cultivars, nitrogen rates, and foliar application of foliar fertilizers

Error bar LSD 0.05

These findings agree with previous studies emphasising the importance of nitrogen fertilisation in improving flax fibre productivity. El-Borhamy (2016) reported that increasing nitrogen rates enhanced stem growth, dry matter accumulation and fibre yield in flax plants.

The synergistic effects observed under combined foliar fertiliser treatments are also consistent with the findings of Shedeed *et al.* (2016), who demonstrated that foliar fertilisers improve nutrient-use efficiency and stimulate physiological processes associated with fibre development. Silicon, sulphur and iron particles likely enhanced fibre yield by improving photosynthetic efficiency, enzymatic activity, nutrient transport and stress tolerance. These results support the potential application of foliar fertiliser technologies as an effective strategy for improving flax fibre yield and quality while promoting sustainable agricultural production systems.

3.7 Soil Fertility

3.7.1 Soil Organic Matter (SOM, g kg⁻¹)

Soil organic matter (SOM) exhibited a statistically significant ($p \leq 0.05$) response to the interaction among flax cultivar, nitrogen rate and foliar Si, S and Fe fertiliser application, confirming the sensitivity of soil C dynamics to integrated nutrient management (Table 2 and Fig. 7). Although cultivar differences were relatively small, Giza 12 maintained slightly higher SOM overall (2.47 g kg^{-1}) compared with Giza 11 (2.37 g kg^{-1}), suggesting a marginally greater contribution of root residues or reduced SOM mineralisation under this genotype.

Nitrogen rate (NR) significantly influenced SOM, with the reduction of nitrogen from 100% to 75% leading to a slight but consistent decline in SOM. This indicates that optimal nitrogen supply supports biomass return to soil and organic matter stabilisation. However, excessive nitrogen inputs may accelerate microbial decomposition, partially offsetting SOM accumulation, consistent with established carbon-nitrogen mineralisation dynamics.

Foliar Si, S and Fe fertiliser treatments significantly modified SOM levels ($p \leq 0.05$), with combined applications, particularly Si×S and Si×S×Fe, generally enhancing SOM compared with single-element treatments or the control. The highest SOM value (3.07 g kg^{-1}) was recorded under Giza 11 combined with Si×Fe at low nitrogen, suggesting improved residue contribution and reduced decomposition intensity under balanced micronutrient supply.

The significant Cul × NR × FF interaction indicates that SOM dynamics were governed by coupled genotype and nutrient interactions. Mechanistically, foliar fertiliser-induced improvements in plant growth likely increased belowground biomass inputs, while balanced nitrogen supply moderated mineralisation rates, thereby stabilising SOM pools (Grant *et al.*, 2016).

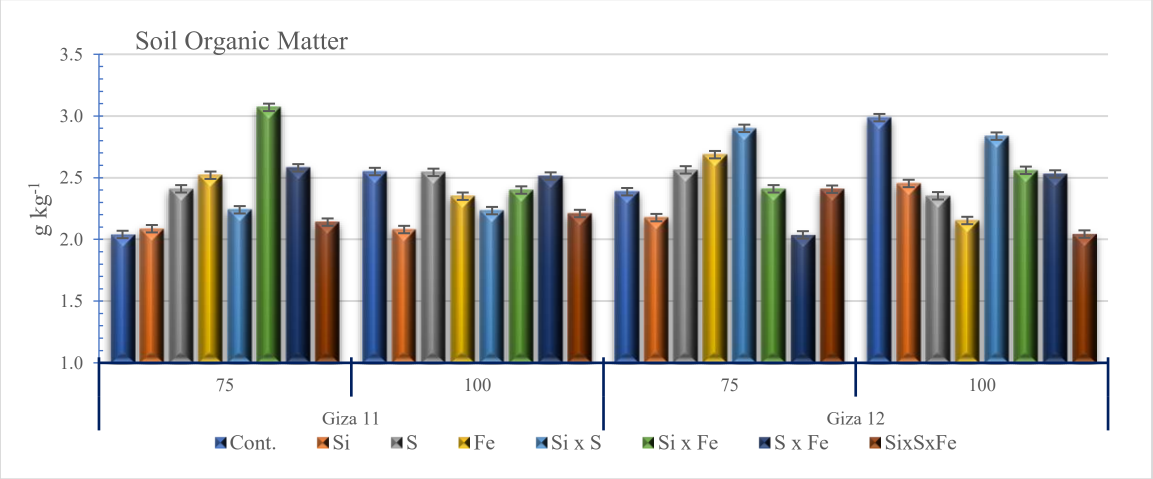

Fig. 7. Soil organic matter g kg^{-1} as affected by the interaction among Cul., NR. and FF
Error bar LSD 0.05

3.8 Soil Mineral Nitrogen (mg kg⁻¹)

Soil mineral nitrogen after harvest showed a significant three-way interaction among cultivar, nitrogen rate and foliar Si, S and Fe fertiliser application, reflecting the dynamic balance between plant uptake and residual soil N

(Table 2 and Fig. 8). Although cultivar effects were not statistically significant, treatment-specific responses were pronounced. Increasing the nitrogen rate to 100% generally elevated residual soil mineral N in some combinations; however, in high-yielding treatments, such as Giza 11 under Si application, soil mineral N decreased to as low as 45 mg kg^{-1}, indicating enhanced nitrogen uptake efficiency and stronger crop demand.

Conversely, the highest residual soil N (105 mg kg^{-1}) was observed in Giza 12 under 100% nitrogen combined with Fe or S foliar application, suggesting reduced uptake efficiency or partial N accumulation in soil due to lower crop demand. The significant interaction ($p \leq 0.05$) indicates that nitrogen fate depended on both genetic and foliar nutrient modulation. Combined Si, S and Fe fertiliser treatments (Si×S and Si×S×Fe) consistently resulted in moderate or reduced residual soil N, suggesting improved nitrogen-use efficiency and reduced post-harvest N losses. This supports the interpretation that Si, S and Fe fertilisers enhanced synchrony between nutrient supply and crop demand.

Table 2. Some soil fertility parameters affected by different Flax cultivars, NR, FF of different Si, S, Fe-fertilizers (combined analysis of two successive seasons)

Treatment		SOM		Min N		Av-P		Exch. K	
Cul.	Giza 11	2.37	b	78.63	a	13.25	a	439.06	b
	Giza 12	2.47	a	73.14	b	13.1	b	441.56	a
NR	75	2.42	a	73.66	b	13.56	a	446.88	a
	100	2.42	a	78.11	a	13.05	b	433.75	b
FF	Cont.	2.49	c	86.63	a	12.11	e	472.5	b
	Si	2.2	f	86.5	a	12.27	e	420	e
	S	2.47	d	76.13	b	13.27	c	450	c
	Fe	2.43	e	75.25	b	12.75	d	435	d
	Si×S	2.55	b	84	a	14.78	b	490	a
	Si×Fe	2.61	a	60.68	c	12.72	d	395	g
	S×Fe	2.42	e	81.38	a	13.25	c	405	f
	Si×S×Fe	2.2	f	56.5	c	15.29	a	455	c
CV	*%*	*0.74*		*7.06*		*4.29*		*1.41*	

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

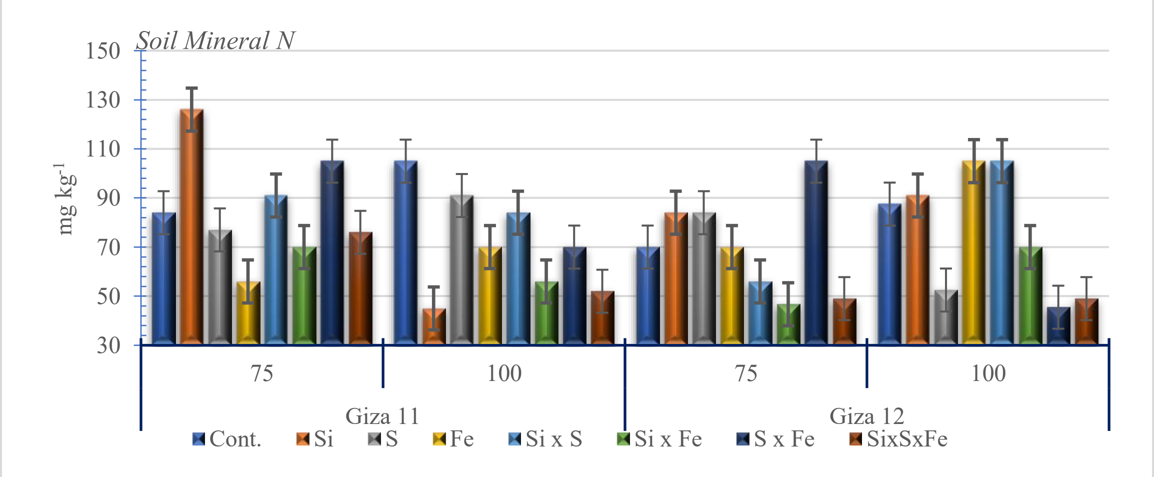

Fig. 8. Soil mineral N (mg kg^{-1}) as affected by the interaction among Cul., NR. and FF
Error bar LSD 0.05

Across treatments, higher residual N under 75% nitrogen reflects reduced plant uptake due to lower biomass production, supporting established findings that excessive soil mineral N accumulation is inversely related to crop N recovery efficiency (Grant *et al.*, 2016).

3.9 Soil Available Phosphorus (mg kg^{-1})

Soil available phosphorus was significantly affected ($p \leq 0.05$) by cultivar, nitrogen rate and foliar Si, S and Fe fertiliser interactions, indicating strong biological control over phosphorus cycling in the soil-plant system (Table 2 and Fig. 9). Giza 11 maintained a slightly higher mean available P (13.25 mg kg^{-1}) than Giza 12 (13.10 mg kg^{-1}), suggesting marginally higher P mobilisation or reduced depletion. Nitrogen rate had a relatively weak direct effect, indicating that P availability was more strongly regulated by biological and microbial interactions than by nitrogen supply alone under the studied conditions. The most pronounced increases in soil available P were associated with combined Si, S and Fe fertiliser treatments, particularly Si×S×Fe, which significantly ($p \leq 0.05$) elevated P availability to 20.31 mg kg^{-1} in Giza 11 at 75% N. This indicates enhanced phosphorus solubilisation and mobilisation processes in the rhizosphere.

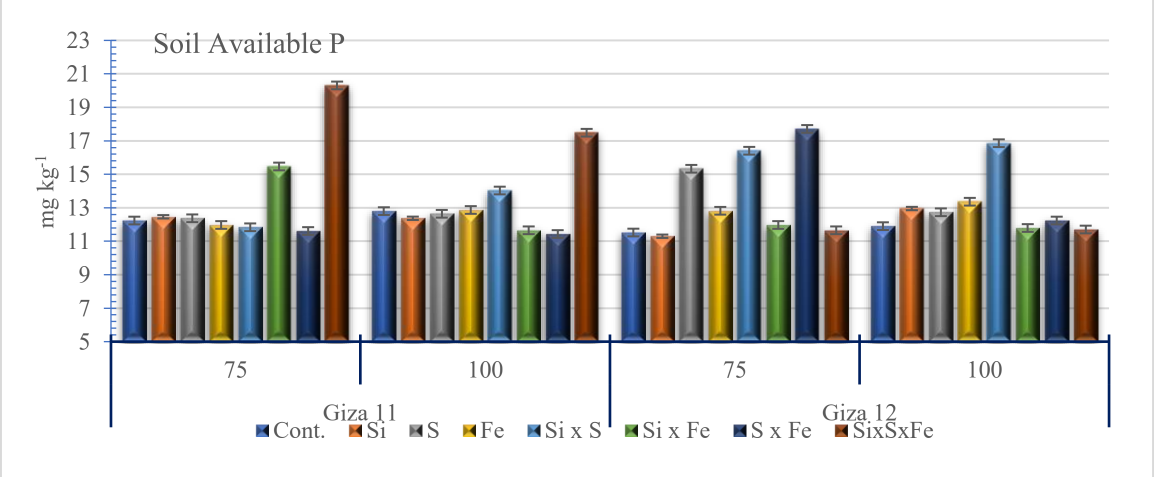

Fig. 9. Soil Available P, (mg kg^{-1}) as affected by the interaction among Cul., NR. and FF
Error bar LSD 0.05

The mechanism is likely linked to silicon- and sulphur-mediated stimulation of microbial activity and organic acid exudation, which enhances the dissolution of insoluble P compounds (Marschner, 2012). The stability of soil P across nitrogen levels suggests that foliar Si, S and Fe fertiliser-driven processes, rather than N supply alone, dominated P dynamics. These findings support integrated nutrient management strategies aimed at improving phosphorus efficiency while minimising dependence on high mineral fertiliser inputs (Kakabouki *et al.*, 2021).

3.10 Soil Exchangeable Potassium (mg kg^{-1})

Soil exchangeable potassium (Table 2 and Fig. 10) was significantly influenced ($p \leq 0.05$) by the interaction among cultivar, nitrogen rate and foliar Si, S and Fe fertiliser application, reflecting complex nutrient redistribution patterns after flax cultivation. Mean values between cultivars were comparable (Giza 11: 436 mg kg^{-1}; Giza 12: 444 mg kg^{-1}), indicating a limited genetic effect on bulk soil K status. At 75% nitrogen, combined Si, S and Fe fertiliser applications markedly increased soil K availability, with Si×S and S×Fe reaching up to 540 mg kg^{-1} in Giza 11, while Si×S achieved the highest value in Giza 12 (600 mg kg^{-1}). These increases suggest enhanced K cycling and reduced fixation under integrated nutrient treatments. In contrast, 100% nitrogen in some treatments was associated with reduced exchangeable K, likely due to enhanced plant uptake under higher biomass production or nutrient antagonism between nitrogen-driven growth and potassium retention in soil exchange complexes.

Mechanistically, silicon and sulphur applications may improve soil cation-exchange dynamics and microbial-mediated mineralisation processes, thereby enhancing K availability (Marschner, 2012). The significant interaction effects confirm that potassium dynamics are not solely governed by fertilisation level but by complex physiological and soil biochemical interactions. Overall, the results emphasise that balanced fertilisation strategies integrating Si, S and Fe nutrients are important for sustaining soil potassium reserves while maintaining crop productivity (Kakabouki *et al.*, 2021).

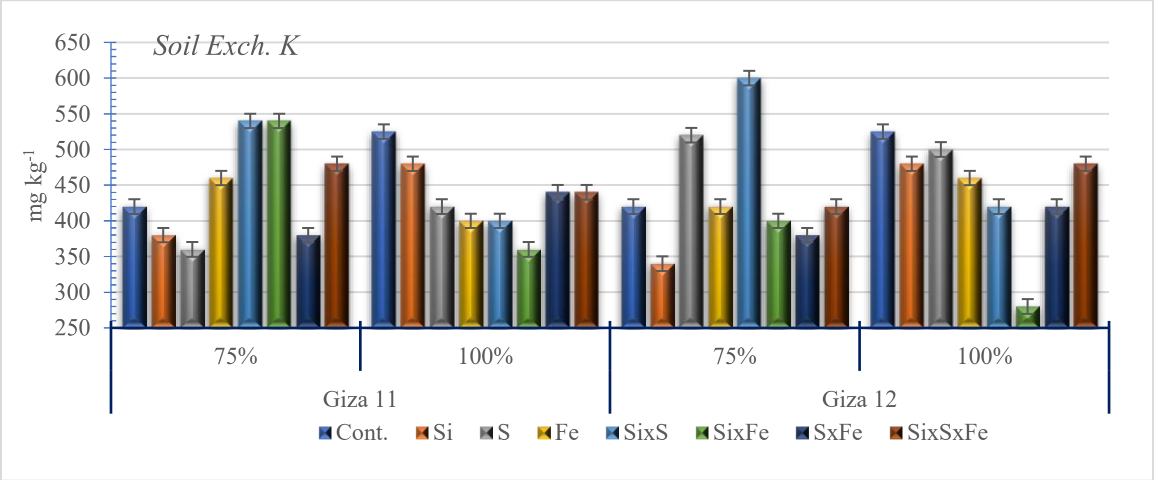

Fig. 10. Soil Exchangeable potassium, mgKg^{-1} as affected by the interaction among Cul., NR. and FF
Error bar LSD 0.05

4. Conclusion

This study showed that the response of flax to fertilisation depended on the interaction among cultivar, nitrogen rate and foliar application of Si, S and Fe. Giza 11 produced the higher mean seed protein content, whereas Giza 12 showed better performance for oil yield and fibre yield. The 100% recommended nitrogen rate improved protein, oil and fibre yields compared with the reduced nitrogen rate, although oil percentage was slightly higher at 75% nitrogen. Among foliar treatments, Si×Fe was most effective for mean protein yield, Fe was most favourable for oil percentage and oil yield, and the Si×S×Fe combination gave the highest mean fibre percentage and fibre yield.

Soil fertility indicators also responded to the integrated treatments, with changes in soil organic matter, mineral nitrogen, available phosphorus and exchangeable potassium after harvest. Lower residual soil mineral nitrogen under highly productive treatments indicated more efficient nitrogen recovery by the crop and reduced risk of environmental N losses. These findings suggest that cultivar-specific combinations of nitrogen and foliar nutrients can improve flax productivity and quality while supporting soil fertility under the conditions of this experiment. However, wider validation under additional soil and climatic conditions is required before broad agronomic recommendations are made.

5. Limitation

This study was limited to two flax cultivars grown at a single experimental location over two winter seasons; therefore, the findings may not fully represent wider agro-ecological conditions. The assessment focused mainly on yield, quality traits, and selected soil fertility parameters, while detailed soil microbial activity, long-term nutrient dynamics, and economic feasibility were not evaluated. Further multi-location and long-term studies involving more cultivars, fertilizer rates, and environmental conditions are recommended to confirm the broader applicability of these nutrient-management strategies.

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 they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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