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Effect of Foliar Application of Organic and Chemical Fertilizers on Yield, Yield Components, Nutrient Uptake, Nutrient Availability, and Anatomical Traits in Three Flax (*Linum usitatissimum* L.) Cultivars Grown under Sandy Soil Conditions

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ABSTRACT

Two field experiments were conducted at Ismailia Agricultural Research Station during the winter seasons of 2022 and 2023 to investigate the effects of various foliar applications on different flax cultivars about yield, nutrient uptake, and anatomical traits in sandy soil. The treatments were arranged in a split-plot design with four replications, with main plots consisting of three cultivars: Giza-12, Sakha-6, and Giza-11. Eight foliar spray treatments were applied as sub-plots: control(T1); K-Silicates(T2), K-humates(T3), gibberellin(T4), gibberellin+K-humates(T5), calcium sulphate(T6), calcium sulphate+K-humates(T7) and Humic(T8). Sprinkler irrigation was utilized throughout the experiments. Significant differences were observed in the means of the flax cultivars under study, with notable increases compared to control group for various growth traits and yield components. Sakha-6 the significantest outperformed cultivars, achieving the highest straw yield and fiber yield with treatment (T3). Giza-12 excelled in seed yield and total fiber under treatments(T5 andT7), while Giza-11 recorded the highest seed oil% and oil yield when treated with (T5), compared to Giza-12, which was treated with water(T1). In terms of nutrient uptake, Giza-11 exhibited the highest (N) and (K) uptake in seeds under treatment(T5), whereas Sakha-6 had the highest (P) uptake under the same treatment. For straw uptake, Sakha-6 also recorded the highest N and P uptake under treatment(T3). Giza-11 and Giza-12 under treatment(T7) recorded the highest available N and P, while available K was significantly affected in the same cultivars under(T3). The best anatomical traits were obtained from Giza-11 with treatment(T7) and Sakha-6 with treatment(T3). Treatments(T7 andT3) significantly increased cell wall thickness.

Keywords: flax, fertilization, yield, nutrients, histological.

INTRODUCTION

Flax (*Linum usitatissimum* L.) is a valuable source of two main products: flaxseed for oil and fiber for textile products. In Egypt, flax is the second-largest fiber crop after cotton, both in terms of cultivated area and economic importance. The seeds are consumed by humans as a source of omega-3 fatty acids and are also used in animal feed. The flax oil industry utilizes the oil to produce paints, varnishes, printing ink, linoleum, and soap. Flax is an ancient economic crop in Egypt, playing a significant role in the national economy due to its exports and contributions to local industries (Bakry *et al*., 2014). The benefits of flax extend beyond traditional uses; it is also employed in several specialized sectorss, particularly in producing electrical insulation and non-textile medical materials (Bakry et al., 2013). Linseeds contain 30–48% fatty acids (linseed oil), primarily composed of α-linolenic acid (40–68%) and linolenic acid (20%), with technical purity reaching 95% for stearic acid (8%) and oleic acid. The quality of oil is often assessed based on its essential fatty acid (EFA) content (Johnson *et al*., 2008). The omega-3, 6, and 9 fatty acids are crucial for good health, and studies have shown that the high intake of omega-3 fatty acids, such as those consumed by Eskimos, can reduce triglycerides, heart rate, blood pressure, and the risk of atherosclerosis (Morris, 2004). Omega-3 and omega-6 fatty acids are vital for the formation of cell membranes and hormones that regulate various bodily functions. Flaxseed is one of the richest sources of omega-3 fatty acids, boasting a high ratio of α-linolenic (omega-3) to linoleic (omega-6) fatty acids (Johnson, 2008; Emam *et al.,;*2011 Minakshi and Bobade, 2018). Increasing flax production can be achieved using high-yielding cultivars and appropriate fertilizer application. Rashwan *et al.* (2017) demonstrated the effects of various chemical fertilization treatments and growth regulators on flax growth traits, yield, and yield components. Additionally, El-Borhamy *et al.* (2017) examined the effects of yield, its components, and the chemical composition (NPK) of different flax genotypes. Adani *et al.* (2006) noted that humic substances are complex, non-biodegradable organic components that are largely hydrophilic and resistant to chemical and biological degradation.

Foliar spraying with potassium and humic substances can improve nutrient uptake and soil quality (El-Boray *et al*., 2013). Mayhew (2004) reported that humic substances could chelate nutrients, improve nutrient

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uptake, detoxify soils, solubilize minerals, and enhance soil structure and water retention. Silicate application has also been shown to significantly increase growth, yield, and chemical content in leaves and seeds (Arkadiusz, 2018). Mukhtar *et al*. (2011) found that foliar application can enhance leaf water potential, growth, and the shoot-to-root ratio. K-humates improves the physical and chemical properties of soil, nutrient movement, and reduces the adverse effects of salt stress (Ibrahim and Ali, 2018). Foliar application of humic substances at 0.3% in sandy loam soil resulted in higher yield, yield components, leaf area index, and chlorophyll content. Such practices are particularly beneficial in soils with low nutrient use efficiency, enhancing fertilizer effectiveness, nutrient availability, root distribution, soil temperature resistance, moisture retention, and mineral uptake (Swetha Reddy *et al*., 2020). Humic substances enhance yield and yield components, nutrient availability, and soil structure while improving the quality of various oilseed crops. They influence plant growth by enhancing soil properties, increasing chlorophyll content, plant respiration, hormonal growth, and membrane penetration (Metre *et al*., 2013). Foliar application of silicates in linseed varieties grown in sandy soil has been shown to increase yield, yield components, shoot growth, fresh root weight, dry weight, photosynthetic pigments, carbohydrates, proline, free amino acids, indole acetic acid, phenol content, and oil yield while decreasing lipid peroxidation (Bakry *et al*., 2012). The application of potassium sources has shown positive effects on fiber flax varieties in sandy soil, enhancing yield, yield components, and oil yields, with silicon improving nutrient availability (Osama *et al*., 2020). Gypsum provides sulfur and calcium, essential nutrients that enhance phosphorus fertilizer efficiency and improve productivity in reclaimed sodic soils (Delgado *et al*., 2002). Calcium plays a crucial role in maintaining the structural integrity of plant membranes, stabilizing cell walls, regulating transport, and controlling ion-exchange behavior (Tuna *et al*., 2007).

The combined application of gibberellic acid and calcium chloride has been shown to increase dry weight per plant, seed yield, oil content, and fiber production across different linseed genotypes (Mohamed *et al*., 2010). GA3 application through seed priming reduces emergence time by enhancing water efficiency and metabolic activity (Archard *et al*., 2009). At low concentrations, GA3 can break seed dormancy, promote growth, and enhance overall productivity (Afroz *et al*., 2005). Gibberellic acid stimulates root and shoot growth and increases leaf number by influencing cell division and elongation (Kashif *et al*., 2021). Its application significantly increases 1000-seed weight, pod count per plant, seed count per pod, dry weight, total carbohydrates, total protein, and total chlorophyll content (Nasir *et al*., 2010). Thus, gibberellic acid is recommended for enhancing plant productivity in sandy soil (Sumera *et al*., 2009). Anatomical studies are essential for assessing fiber yield and quality among different flax genotypes. Hella *et al*. (1989) observed significant differences in the anatomical features of flax stems based on genotype and agronomic practices. Other studies have also investigated the anatomy of flax (El-Shimy *et al*., 1993; Mostafa *et al*., 2003; El-Emary *et al*., 2006). The main objective of this investigation is to study the effects of various fertilizer strategies applied as foliar sprays on yield, yield components, nutrient uptake, soil nutrient availability, and some anatomical traits in three flax cultivars grown in sandy soil.

MATERIALS AND METHODS

Under sprinkler irrigation in sandy soil, two field experiments were conducted during the flax-growing winter seasons of 2021–2022 and 2022–2023 at the Experimental Farm of Ismailia Research Station (Lat. 30° 36' 31" E, elevation 3 m above sea level). The sandy soil (Arenosol AR; Typic Torripsamment; Entisol) properties are presented in Table 1. The experiments aimed to determine the effects of gibberellin, K-silicates, K-humates, and calcium (Ca++) fertilizers on yield, yield components, NPK uptake, soil nutrient availability, and some anatomical traits of three flax cultivars: Sakha-6, Giza-11, and Giza-12.

Treatments Used in This Study

The field experiments utilized a foliar spray solution of gibberellin, K-silicates, K-humates, and calcium salts at 30, 45, and 60 days after sowing. A control treatment was included with no foliar application and/or with K-humates. In total, 24 treatments were arranged in the split-plot design with four replications. The first factor main plots consisted of three flax cultivars: Giza-12 (C_1), Sakha-6 (C_2), and Giza-11 (C_3). The second factor sub-plots included the following treatments: control (T_1), K-silicates spray (T_2), K-silicates spray following K-humates spray at a 24-hour interval (T_3), gibberellin spray (T_4), gibberellin spray following K-humates spray at a 24-hour interval (T_5), calcium salt spray (T_6), calcium salt spray following K-humates at a 24-hour interval (T_7), and K-humate (T_8). The chemical and physical properties of the experimental soil used are shown in Table 1. Some physical and chemical properties of a representative soil sample used in the experimental soil (0-30 cm depth) as average of the two seasons.

Table 1. Some characteristics of the experiment soil cultivation.

	Character	Value		Character	Value
Particle Size distribution (%)	Coarse sand	60.95	Available nutrients (mg/kg)	P	2.25
	Fine sand	30.05		N	18.50
	Silt	6.30		K	75.10
	Clay	2.70			
	Texture class	Sandy		Bulk Density ($Mg\ m^{-3}$)	1.76
	$CaCO_3$ (%)	0.29		pH†	8.01
	EC ($dS\ m^{-1}$)‡	0.45			
	Organic Matter (O.M.) (%)	0.21			

(1:2.5 soil : water suspension) ‡ (1:5 soil : water extract)

Preparation of solution spray application

K-humate was applied at a rate of 3 mL L^{-1} of water, containing 46.2% total organic carbon, 4.33% N, 8% K, and 0.38% P. K-silicates was applied at a rate of 250 mg Si L^{-1} of water, with gibberellin at 150 mg L^{-1} and calcium sulfate (CaSO4, high purity gypsum containing 95% CaSO4 and 4% insoluble CaSO4) at a rate of 3 g L^{-1}. Each solution was applied in a total of 714 L of irrigation water per hectare. K- silicates (K2SiO3) contained 487.1 g K/L and 113.9 g Si/L, imported by Techno Gene

Company, China, and mixed at 1.571 L/K-silicates per hectare. K-humates (5% humic substances) was mixed at 2.142 L/K-humates per hectare with irrigation water, with properties showing 540.60 g/L of organic matter, pH 7.93, EC (dS/m) 7.85, CEC (cmolc/kg) 402.0, total Ca (g L^{-1}) 5.81, N (g/L) 31.0, P (g L^{-1}) 4.6, and K (g L^{-1}) 47.0. Gibberellic acid was mixed at 107.1 cm³/ha with irrigation water, and calcium salt solution was mixed at 2.142 kg/ha. The control treatment included 100% NPK fertilizers without any foliar spray.

Field Experiments

The two field experiments were carried out at the Experimental Farm of Ismailia Agricultural Research Station, Agricultural Research Center (ARC), Giza, Egypt, during the 2021/2022 and 2022/2023 seasons. The objective was to assess the effects of foliar spraying with various organic and mineral compounds, applied individually or in combinations, on growth, yield, yield components, fiber yield, and quality in three flax cultivars grown under sandy soil conditions. The three flax cultivars were obtained from the Fiber Crops Research Section at ARC, Giza, Egypt. The studied factors included:

1- Flax cultivars (C) :

C_1: Giza 12 cultivar
C_2: Sakha 6 cultivar
C_3: Giza 11 cultivar

The pedigree of the three tested flax cultivars were as follows: Giza 12 c.v.: dual purpose type selected from the cross between S.2419/1 × S. 148/6/11.(New variety).Sakha6 c.v.: selected from the cross between Giza 8 c.v. × S.2419/1/4.(New variety). Giza 11 c.v.: selected from the cross between Giza 8 c.v. × S.2419/1.(New variety).

2- Fertilization treatments (T):

T_1: Control (foliar spray with water).
T_2: Foliar spray with K-Silicates (K-Si) at a rate of 250 mg siL^{-1}.
T_3: Foliar spray with K-Silicates + K-humates (H+K-Si).
T_4: Foliar spray with gibberellin (Gb) at a rate of 150 mg L^{-1}.
T_5: Foliar spray with gibberellin + K-humates (H+Gb).
T_6: Added calcium sulfate ($CaSo_4$).
T_7; Added calcium sulfate + K-Humates ($H+CaSO_4$).
T_8: Added K-humates at a rate of 3 ml L^{-1}.

The foliar solution volume was 714.0 L/ha, sprayed three times using a hand sprayer until saturation. The first spray occurred before flowering at 30 days post-sowing, the second at 45 days, and the third at the beginning of flowering at 60 days. Each experiment included 24 treatments, combining the three flax cultivars with the eight fertilization treatments.

The split-plot design with four replications was implemented, with the three flax cultivars arranged in the main plot and the eight fertilization treatments in the sub-plot. The sub-plot area (experimental unit) measured 2× 3 m (6 m² or 0.0006 hectares). The experimental soil was sandy, and its physical and chemical properties were determined according to Jackson (1973). Soil samples were randomly collected from a depth of 0-30 cm before the growing seasons. Seeds of the three tested flax cultivars were hand-drilled into rows 15 cm apart at a sowing rate of 60 kg seeds/feddan, as recommended for dual-purpose types, on November 3rd and 5th for the first and second seasons, respectively.

Flax fertilization during cultivation for both seasons included super mono-phosphate (15.5% P_2O_5) applied at a rate of 16.1 kg P/ha before sowing. Nitrogen was supplied in the form of ammonium nitrate (33.5%) at a rate of 166.6 kg N/ha in four equal doses. Potassium sulfate (48.5% K_2O) was added at 47.5 kg K/ha in two equal doses: the first during sowing and the second during flowering. Weeds were controlled mechanically. Irrigation was carried out using modern sprinkler irrigation methods. All other recommended agronomic practices for flax cultivation were followed. At full maturity, ten randomly selected plants were taken from each sub-plot and air-dried for one week to determine growth, yield, and yield components. Seed, straw, and fiber yields per hectare were calculated from an area of 2.5 m² of each sub-plot, converting yields to Mg/ha.

Character Studied:

Growth yield and yield components:

1. Total plant height (cm).
2. Technical length (cm).
3. Number of capsules/plant
4. Number of seeds/capsules
5. 1000-seed weight (g).*
6. Seed yield /plant (g).*
7- Seed yield (Mg ha^{-1}).*
8. Straw yield (Mg ha^{-1})
9. Fiber yield /fed (ton)
10. Total fiber % : Determined as follows:

$$\text{Total Fiber }\% = \frac{\text{Total Fiber Yield / fad}}{\text{Retted Straw Yield/ fad}} \times 100$$

11. Seed oil %: It was determined by using the Soxhlet apparatus and using pure petroleum ether as solvent according to A.O.A.C.(2000).
12. Oil yield (Mg ha^{-1}): It was calculated by multiplying seed oil% *seed yield /ha.

At full maturity, ten guarded plants were taken at randomly from each sub-plot to determine the yield components of flax. However, yields of straw, fiber and seed per hectares were calculated from a control area of 2.5 m^2 which as estimated in kg m^2 and therefor it was converted to yields of fiber, straw and seed (Mg ha^{-1}).

Nutrient uptake:

N uptake, P uptake, K uptake

Soil content availability:

N available, P available, K available

Histological studies:

Epidermis with cuticle, cortex, bast fiber tissue, phloem tissue and xylem tissue.

Analysis of Soil and Plant Samples

Soil samples were collected from air-dried plots, dry sieved through a 1.5 mm sieve, and analyzed for EC, $CaCO_3$, bulk density, CEC, pH, and organic matter (Black, 1982). Soil extracts were prepared using KCl (1:10 w/v) and 0.5 N $NaHCO_3$, with available N, P, and K determined using 1 N NH_4OAc at pH 7.0. Plant samples were oven-dried at approximately 70°C for 60 hours and digested using a 1:1 acid mixture (H_2SO_4: $HClO_4$) according to Jackson (1973). Nitrogen concentration in plants and soil was determined through distillation, while available P was measured using UV-Vis spectrophotometry. Potassium content in soil and plant samples was determined using a flame photometer with stannous chloride ($SnCl_2$) (Black, 1982; Page *et al.*, 1982). Total fiber percentage was estimated using a measuring tape balance (Dhirhi *et al*., 2015).

Histological Studies

Transverse sections (5 µm thick) of stem internodes were fixed in a solution of glacial acetic acid, formalin, and ethyl alcohol (1:2:17 mL V/V). The samples were dehydrated with an ethanol series, cleared with ethanol-xylene, and embedded in paraffin wax (melting point 55-58ºC) (Willey, 1971). Sections were cut using a rotary microtome and stained with Safranin O-Fast Green double stain before being cleared with xylene and mounted in Canada balsam (Sass, 1961). Photomicrographs were taken using a LEICA DM500 microscope fitted with a digital camera, and measurements were averaged from ten readings taken from three slides for comparative evaluation.

Statistical Analysis

Analysis of variance for the split-plot design was performed for each season according to Gomez and Gomez (1984). Differences among treatment means were assessed using the least significant difference (L.S.D.) at the 5% level of significance. Additionally, combined analysis of variance over the two seasons was conducted for each character according to Leclerg *et al.* (1966).

RESULTS AND DISCUSSION

Yield and yield components:

Effects of cultivar:

Seasonal visual observations on the effects of cultivar on the mean values of yield and its components for three flax cultivars, based on the combined analysis over two seasons, are presented in Tables (2, 3, 4, and 5). The data revealed significant differences among the flax cultivars studied, with notable relative increases compared to the control for several growth traits, yield, and yield components. The Sakha 6 cultivar significantly surpassed both Giza-11 and Giza-12 cultivars in plant height (5.37 cm), technical length (19.95 cm), number of capsules per plant (15.58%), straw yield (28.30 Mg/ha), and fiber yield (34.86 Mg/ha). Conversely, the Giza-11 cultivar exhibited the highest values for number of seeds per capsule (5.80%), seed weight per plant (29.31 g), seed index (1000 seed weight) (17.37%), and seed yield (9.55 Mg/ha) compared to the other two cultivars. Additionally, Giza-12 showed significant differences in total fiber content (11.06%) when compared to all cultivars.

There were no significant differences between Giza-12 and Giza-11 in terms of technical length, number of capsules per plant, number of seeds per capsule, seed weight per plant, and seed yield. The favorable effects of the three flax cultivars on yield and its components can be attributed to their adaptability to soil texture and variability in genetic constituents and potential. Notably, the Giza-11 cultivar ranked first, significantly outyielding Giza-12 by 8.15%. No significant differences were observed between Giza-12 and Sakha-6 regarding seed oil percentage. The data indicated significant differences among the tested flax cultivars, with Giza-11 recording the highest oil yield per hectare, exceeding Giza-12 by 16.21% on average over both seasons. Many researchers have reported higher varietal differences in yield and its components across various flax-growing regions such as Verma and Pathak (1993), (Eman El-Kady and AbdEl-Fatah (2009), Hussein (2012), El- Shimy *et al*., (2015), Rashwan *et al*., (2016), El- Borhamy *et al*., (2017), El- Sorady *et al.*, (2022) and (Ebied and Badawi (2023).

Effects of organic and chemical fertilizers treatments:

The yield and yield parameters of the three flax cultivars significantly increased due to the application of treatments T_2 (K-Si), T_3 (H+K-Si), T_4 (Gb), T_5 (H+Gb), T_6 ($CaSO_4$), T_7 (H+$CaSO_4$), and T_8 (humic substances) compared to the control. The chemical treatments resulted in higher values for yield and yield parameters across all cultivars in this study. The mean values for yield and its components from the combined analysis over two seasons are presented in Tables (2, 3, 4, and 5). The results indicated that the application of chemical treatments, particularly in combination with humic substances, had significant effects on yield and its components.

All treatments demonstrated superiority in all studied traits compared to the control. Treatment T_3 (H+K-Si) achieved highly significant improvements in plant height, straw yield, and fiber yield; however, the increase in technical length was not significant. Relative increases compared to the control included plant height (43.37 cm), straw yield (91.39 Mg/ha), and fiber yield (150.65 Mg/ha), while technical length increased by 33.62 cm, which was not significant. This indicates that T_8 (humic substances) combined with potassium silicate (T_3) as a foliar application is effective for enhancing crop production under sandy soil conditions.

Treatment T_5 (H+Gb) yielded the best results for the number of capsules per plant, number of seeds per capsule, seed weight per plant, and seed yield. In contrast, treatment T_7 (H+$CaSO_4$) produced the best results for seed index and total fiber across all cultivars. The relative increases compared to the control for T_5 included number of capsules per plant (141.38%), number of seeds per capsule (58.42%), seed weight per plant (143.90%), and seed yield (105.08 Mg/ha). Treatment T_7 (H+$CaSO_4$) resulted in significant increases in seed index (1000 seed weight) (84.96%) and total fibers (33.91%) across all cultivars compared to the control. Combined data presented in (Table 5) showed significant differences among the eight fertilization treatments. Treatment T_5 (H+Gb) followed by T_3 (H+K-Si) recorded the highest values for seed oil percentage, with T_5 exceeding the control treatment (foliar spraying with water) by 11.62%. Other treatments provided intermediate values between T_3 and T_1 (control) over the two seasons. The results indicated significant differences for oil yield (Mg/ha), with T_5 (H+Gb) recording the highest values, exceeding T_1 (control) by 129.33%. Other treatments produced intermediate estimates.

Gibberellins (GA_3) have been shown to enhance plant physiology (Yuan and Xu, 2001) and can effectively promote flax growth while regulating physiological and biochemical characteristics (Khalid *et al*., 2022; Khan, 2008; Glick, 1995). Gibberellins are capable of increasing growth-promoting compounds, improving plant cell division and overall growth. The roles of sulfur and calcium in enhancing phosphorus uptake and productivity are well-documented (Delgado *et al*., 2002). Calcium is essential for plant cell structure, improving function, stabilizing cell walls, facilitating nutrient transport, and increasing nutrient absorption (Tuna *et al*., 2007). Humic substances play a crucial role in enhancing transpiration and drought resistance in plants. These findings align with results from various researchers (Ahmed *et al*., 2017; Al-Shaheen and Awany, 2018; Qasim *et al*., 2018; Abou-Khadrah *et al*., 1999; El-Gazzar and El-Kady, 2000; Abd El-D aiem, and Amal El- Manzlawy, 2016)

Table 2. Effect of fertilization treatments on some growth traits of three flax cultivars (average of the two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	Plant height (cm)				Technical length (cm)				Number of capsules /plant			
T_1: Control	72.67	76.97	75.58	75.07	49.76	60.01	46.75	52.17	6.33	9.02	5.90	7.08
T_2: K-Si	92.70	100.06	102.90	98.55	59.20	69.58	62.07	63.62	10.75	9.87	11.77	10.80
T_3: H+K-Si	104.27	110.37	108.25	107.63	67.00	77.58	64.55	69.71	15.88	18.95	13.28	16.04
T_4: Gb	86.92	97.58	95.10	93.20	60.30	73.75	73.85	69.30	10.88	14.43	12.53	12.61
T_5: H+Gb	97.01	109.96	99.92	102.30	67.73	79.26	56.81	67.93	17.73	16.86	16.68	17.09
T_6: $CaSO_4$	84.06	85.48	88.25	85.93	55.78	75.71	56.98	62.82	10.72	14.02	11.40	13.92
T_7: H+$CaSO_4$	91.66	93.08	91.74	92.16	59.70	70.25	57.33	62.43	17.06	19.63	14.73	15.27
T_8: Humic	95.37	90.10	86.92	90.80	62.80	65.57	58.25	62.21	12.73	11.73	12.71	12.39
Mean	90.58	95.45	93.58	93.2	60.28	71.46	59.57	63.7	12.76	14.31	12.38	13.2
LSD 0.05 C		1.46				2.24				0.49		
LSD 0.05 T		2.39				3.66				0.84		
LSD 0.05 CxT		4.14				6.34				1.45		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T : LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Table 3. Effect of fertilization treatments on some yield components of three flax cultivars (average of the two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	Number of Seeds Capsule^{-1}				Seed index (1000 Seeds weight) (g)				Seed weight Plant^{-1} (g)			
T_1: Control	5.14	5.37	5.87	5.46	4.90	4.95	5.52	5.12	0.50	0.33	0.41	0.41
T_2: K-Si	6.27	6.82	6.70	6.59	7.85	6.39	8.63	7.62	0.61	0.45	0.61	0.57
T_3: H+K-Si	8.45	7.62	7.69	7.92	9.17	8.59	9.72	9.16	0.84	1.05	0.82	0.90
T_4: Gb	6.15	6.27	6.44	6.28	8.29	6.35	8.42	7.68	0.66	0.49	0.66	0.62
T_5: H+Gb	8.57	7.94	9.43	8.65	9.57	8.64	9.70	9.30	1.25	0.69	1.25	1.00
T_6: $CaSO_4$	6.92	6.72	6.28	6.64	6.67	6.14	7.85	6.88	0.57	0.43	0.57	0.53
T_7: H+$CaSO_4$	7.84	7.89	8.94	8.22	9.17	9.23	10.02	9.47	0.85	0.65	0.85	0.78
T_8: Humic	6.20	6.50	6.99	6.56	6.40	7.72	8.24	7.45	0.75	0.55	0.65	0.64
Mean	6.94	6.89	7.29	7.0	7.75	7.25	8.51	7.8	0.75	0.58	0.73	0.7
LSD 0.05 C		0.30				0.29				0.03		
LSD 0.05 T		0.49				0.48				0.05		
LSD 0.05 Cx T		0.85				0.83				0.09		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T: LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Table 4. Effect of fertilization treatments on seeds yield, straw yield, and total fiber % of three flax cultivars (average of the two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	Seeds yield (Mg ha^{-1})				Straw yield (Mg ha^{-1})				Total Fibers (%)			
T_1: Control	1.27	1.24	1.03	1.18	5.48	6.30	5.65	5.81	13.77	15.77	13.74	14.42
T_2: K-Si	1.70	1.84	1.97	1.84	7.52	8.52	7.68	7.91	16.97	18.07	16.83	17.29
T_3: H+K-Si	2.54	2.28	1.85	2.22	9.68	13.36	10.33	11.12	17.92	20.08	18.49	18.83
T_4: Gb	1.60	1.57	1.40	1.52	7.10	7.28	6.46	6.95	18.37	16.90	15.05	16.77
T_5: H+Gb	2.80	2.04	2.42	2.42	9.00	12.80	9.52	10.44	20.22	17.99	16.83	18.34
T_6: $CaSO_4$	1.52	1.56	1.80	1.63	7.34	7.82	7.08	7.42	17.90	16.35	14.58	16.28
T_7: H+$CaSO_4$	2.52	1.92	2.21	2.22	8.52	12.50	9.78	10.27	20.49	18.87	18.59	19.31
T_8: Humic	2.04	1.78	1.38	1.73	6.41	9.76	6.98	7.72	17.23	17.09	14.57	16.30
Mean	2.00	1.78	1.76	1.9	7.63	9.79	7.94	8. 5	17.86	17.64	16.08	17.2
LSD0.05 C		0.50				0.31				0.87		
LSD0.05 T		0.05				0.03				0.09		
LSD0.05 C x T		0.59				0.37				1.03		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T: LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Table 5. Effect of fertilization treatments on fiber yield, Seed oil % and Oil yield of three flax cultivars (average of the two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	Fiber yield (Mg ha^{-1})				Seed oil (%)				Oil yield (Mg ha^{-1})			
T_1: Control	0.754	0.993	0.776	0.841	37.74	39.43	41.52	39.56	0.388	0.488	0.527	0.467
T_2: K-Si	1.276	1.539	1.292	1.369	41.03	41.92	43.85	42.26	0.697	0.771	0.863	0.777
T_3: H+K-Si	1.734	2.682	1.910	2.108	42.11	42.78	45.59	43.49	0.779	0.975	1.157	0.970
T_4: Gb	1.304	1.230	0.972	1.168	39.25	40.25	42.70	40.73	0.549	0.631	0.683	0.621
T_5: H+Gb	1.819	2.302	1.602	1.907	42.85	43.38	46.26	44.16	1.036	0.884	1.295	1.071
T_6: $CaSO_4$	1.313	1.278	1.032	1.207	40.34	41.60	43.35	41.76	0.613	0.648	0.780	0.680
T_7: H+$CaSO_4$	1.745	2.358	1.818	1.973	41.63	41.84	44.61	42.69	1.049	0.803	0.985	0.945
T_8: Humic	1.104	1.667	1.016	1.262	39.75	41.58	43.37	41.53	0.810	0.740	0.597	0.715
Mean	1.381	1.756	1.302	1.479	40.58	41.59	43.89		0.740	0.742	0.860	
LSD 0.05 C		0.145				0.780				0.098		
T		0.122				0.670				0.076		
C x T		0.096				0.490				0.065		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T: LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Effects of the interaction between cultivars, organic and chemical fertilizers treatments:

The interactions between three flax cultivars and eight fertilization treatments on yield and yield parameters are summarized in Tables (2 to 5). The highest relative increases compared to the control were observed in plant height (cm), technical height (cm), number of capsules per plant, number of seeds per capsule, seed index (1000 seed weight in g), seed weight per plant (g), seed yield (Mg/ha), straw yield (Mg/ha), total fibers, and fiber yield (Mg/ha). Data from these tables indicated significant effects due to the interaction of the two studied factors for all growth and yield component traits. The Sakha 6 cultivar achieved the highest values in plant height, straw yield, and fiber yield, recording increases of 51.87%, 143.79%, and 255.70%, respectively, when treated with T_3 (H+K-Si).

Treatment T_5 (H+Gb) also resulted in significant increases in these traits, particularly a 69.58% increase in technical length and a 232.71% increase in the number of capsules per plant when applied to the Sakha 6 cultivar. In contrast, the Giza 11 cultivar demonstrated the highest values for the number of seeds per capsule (83.46%) and seed weight per plant (278.78%), significantly influenced by T_7 (H+CaSO4), which increased the seed index (1000 seed weight) by 104.48%. Additionally, the Giza 12 cultivar excelled in seed yield and total fiber, recording increases of 171.84% and 49.12%, respectively, under chemical treatments T_5 (H+Gb) and T_7 (H+$CaSO_4$). These results align with findings from Bakry *et al.* (2013) and Ibrahim *et al.* (2013).

The interaction effects between the three tested flax cultivars and the eight studied fertilizer treatments were significant. As shown in (Table 5), a notable interaction was observed between the flax cultivars and fertilization treatments. The Giza 11 cultivar, when treated with T_5 (H+Gb), recorded the highest values for seed oil percentage and oil yield per hectare, with increases of 22.57% and 2.3376%, respectively, compared to the Giza 12 cultivar treated with the control (water, T_1). The lowest oil yield per hectare was observed in Giza 12 under the control treatment. This trend may be attributed to the physiological processes in flax cultivars, particularly Giza 11 for seed yield production, Sakha 6 for straw yield, and Giza 12 for fiber. The treatments, particularly T_3 (H+K-Si), T_5 (H+Gb), and T_7 (H+CaSO4), enhanced photosynthetic activity. Similar results were reported by Khan *et al.* (2010), Ismail *et al.* (2017), and El-Edfawy *et al.* (2021).

Nutrient Uptake

Effect of Cultivar

Mean values for NPK uptake (kg/ha) by seeds and straw from the three flax cultivars, based on combined analysis over two seasons, are presented in Tables 6 and 7. The data revealed significant differences among the cultivars for nitrogen (N), phosphorus (P), and potassium (K). In seeds, the Sakha 6 cultivar exhibited the highest values for N, P, and K, surpassing both Giza-11 and Giza-12. In straw, the Giza-12 cultivar demonstrated the highest values for N, while Sakha 6 excelled in P, and Giza 11 in K. The relative increases of NPK in seeds compared to the control were as follows: Sakha 6 for N (1.51%), P (3.19%), and K (2.09%). In straw, Giza-12 showed a relative increase for N (5.50%), while Sakha 6 increased for P (1.77%) and Giza 11 for K (2.63%). The favorable effects of the three flax cultivars on N, P, and K uptake (kg/ha) can be attributed to their respective capacities for nutrient absorption. These findings are consistent with reports on flax cultivation (Metre *et al*., 2013; El-Borhamy *et al*., 2017; Osama *et al*., 2020; Swetha Reddy *et al*., 2020).

Effects of Organic and Chemical Fertilizer Treatments

Applications of T_2 (K-Si), T_3(H+K-Si), T_4 (Gb), T_5 (H+Gb), T_6 (CaSO4), T_7 (H+$CaSO_4$), and T_8 (humic substances) positively affected and significantly increased N, P, and K (kg/ha) uptake for seeds and straw compared to the control across the three flax cultivars. The mean values for N, P, and K uptake due to these treatments from the combined analysis over two seasons are presented in Tables (6 and 7). The treatments, whether applied alone or in combination with humic substances, showed superiority in all traits studied compared to the control. For seeds, treatment T_5 (H+Gb) recorded highly significant increases in N, while T_6 ($CaSO_4$) showed significant increases in P and K, with no significant differences between them in the same treatment. For straw, T_5 (H+Gb) was highly significant for N, while T3 (H+K-Si) was significant for P and K, with no significant differences in the same treatment.

Relative increases compared to the control under T_5 (H+Gb) were recorded as follows: N (9.39%), P (281.49%), and K (111.78%). For straw, T_5 (H+Gb) recorded N (196.98%), while T_3 (H+K-Si) recorded P (216.59%) and K (200.17%), with no significant differences in the same treatment. It can be concluded that humic substances, when combined with potassium silicates, calcium sulfate, or gibberellin as foliar applications, are effective practices for increasing crop production under sandy soil conditions. These results agree with reports by Khan *et al.* (2010), Bakry *et al.* (2015), Mohaseb *et al.* (2018), Ismail *et al.* (2017), Arkadiusz (2018), and Swetha Reddy *et al.* (2020).

Effect of the Interaction Between Cultivars and Fertilizer Treatments

The interactions between the three flax cultivars and foliar treatments (T_2 K-Si, T_3 H+K-Si, T_4 Gb, T_5 H+Gb, T_6 $CaSO_4$, T_7 H+$CaSO_4$, and T_8 humic substances) on N, P, and K uptake (kg/ha) by seeds are indicated in Table (6), showing significant effects for all N, P, and K uptake. The Giza 11 cultivar under treatment T_5 (H+Gb) achieved the highest relative increases compared to control for N (108.82%) and K (122.22%), while Sakha 6 under T_5 (H+Gb) had the highest relative increase for P (343.82%). The interaction effects on N, P, and K uptake (kg/ha) by straw, as shown in Table (7), indicated that Sakha 6 gave the highest relative increases for N and P under T_3 (H+K-Si) treatment (211.62% and 244.70%, respectively), while Giza-11 under T_3 (H+K-Si) had the highest relative increase for K (222.86%). These findings are consistent with those reported by Khan *et al.* (2010), Bakry *et al.* (2014), Ismail *et al.* (2017), Arkadiusz (2018), and Swetha Reddy *et al.* (2020).

Combined data in Table 6 showed that Giza-11 and Sakha-6 cultivars under foliar sprays of T_5 (H+Gb) and T_7 (H+$CaSO_4$) yielded the highest values for N, P, and K uptake in seeds compared to T_3 (H+K-Si). Table 7 also indicates that total NPK uptake by straw of the three flax cultivars was significantly affected by foliar spraying of T3 (H+K-Si), which produced the highest mean values in N, P, and K straw uptake, exceeding the values produced by T_5 (H+Gb) and T_7 (H+$CaSO_4$). Regarding the interaction effect between foliar fertilizer treatments and the three flax cultivars on total NPK uptake by both seeds and straw, data in Tables (6 and 7) showed that T_5 (H+Gb) resulted in the highest values for NPK uptake in seeds, arranged as follows: Giza-11 > Sakha-6 > Giza-12. Conversely, T_3 (H+K-Si) provided the highest values of NPK uptake for straw, arranged as Sakha-6 > Giza-11 > Giza-12. These results align with findings from Bakry *et al.* (2013), Mohamed *et al.* (2013), El-Borhamy *et al.*, 2017, Mohaseb *et al.* (2018), and El-Edfawy *et al.* (2021).

Soil Available N, P, and K

Effect of Cultivar

Mean values of soil available N, P, and K (g. kg^{-1}) for the three flax cultivars over two seasons are presented in Table (8). The data revealed significant differences among the three flax cultivars under H+$CaSO_4$ treatment. The Giza-12 cultivar surpassed both Giza-11 and Sakha-6 in soil available P and K, while Giza-11 excelled over Giza-12 and Sakha-6 for soil available N. The Giza-12 cultivar showed the highest relative increase for soil available P (1.47%) and K (1.04%), while Giza-11 demonstrated the highest relative increase for soil available N (0.41%). The favorable effects of the three flax cultivars on soil available N, P, and K (g. kg^{-1}) can be attributed to the physiological effects of the cultivars and root zone distribution, as well as variability in genetic constituents. These results are consistent with reports from Mukhtar *et al.* (2011), Metre *et al.* (2013), Ibrahim and Ali (2018), Arkadiusz (2018), and Swetha Reddy *et al.* (2020).

Effect of Organic and Chemical Fertilizer Treatments

Foliar chemical fertilizer treatments significantly increased soil available N, P, and K (g. kg^{-1}) compared to the control treatment across the three flax cultivars. The mean values of soil available N, P, and K (g. kg^{-1}) resulting from T_7 (H+$CaSO_4$) are presented in Table (8). This treatment had significant effects on soil available N, P, and K, yielding the highest relative increases compared to the control: N (78.09%), P (175.16%), and K (180.04%).

Effects of the Interaction Between Cultivars and Fertilizer Treatments

The interactions between the three flax cultivars and T_2 (K-Si), T_3 (H+K-Si), T_4 (Gb), T_5 (H+Gb), T_6 ($CaSO_4$), T_7 (H+$CaSO_4$), and T_8 (humic substances) on soil available N, P, and K (g. kg^{-1}) are detailed in Table (8). Significant increases in soil available N, P, and K were observed. Giza 11, under treatment T_7 (H+$CaSO_4$), recorded the highest mean soil available N (28.67), while Giza-12 under the same treatment achieved the highest mean soil available P (8.68) and K (27.52), surpassing other cultivars and foliar treatments. The foliar treatment T_3 (H+K-Si) produced the highest mean soil available K across the three flax cultivars. The highest relative increases compared to the control due to T_7 (H+$CaSO_4$) for Sakha-6, Giza-11, and Giza 12 were 88.49%, 194.23%, and 195.25%, respectively. These results are consistent with reports by Tuna *et al.* (2007), Sumera *et al.* (2009), Mukhtar *et al.* (2011), Bakry *et al.* (2014), Metre *et al.* (2013), and Kashif *et al.* (2021).

Regarding the interaction effect between the flax cultivars and foliar fertilizer treatments on soil available NPK, results indicated that available N and P were significantly affected by T_7 (H+$CaSO_4$), T_3 (H+K-Si), and T_5 (H+Gb) treatments compared to other foliar treatments. The treatment T_7 (H+$CaSO_4$) yielded higher mean values for soil available N and P than other treatments, while T_7 (H+$CaSO_4$) and T_3 (H+K-Si) provided better mean values for available K. Concerning the main effects of the three flax cultivars, Giza-11 and Giza-12 exhibited the highest values for soil available N, P, and K across all treatments. The interaction effects showed that Giza-11 and Giza-12 under T_7 (H+$CaSO_4$) recorded the highest mean values for available N and P. Additionally, available K was significantly affected by Giza-11 and Giza-12 under T_7 (H+$CaSO_4$) > T_3 (H+K-Si), resulting in higher mean values than other treatments. These results suggest that humic substances and calcium sulfate contributed to a decrease in soil pH, resulting in increased chelation and availability of nutrients in the rhizosphere. These findings align with those obtained by Ewees and Abd el Hafez (2010), Bakry *et al.* (2013), Mohaseb *et al.* (2018), and El-Edfawy *et al.* (2021).

Table 6. Effect of fertilizer treatments on total NPK uptake by seed (kg. ha^{-1}) of flax cultivars (average of two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	N				P				K			
T_1: Control	15.31	14.48	15.18	14.99	2.64	2.62	2.35	2.54	12.06	12.19	12.13	12.13
T_2: K-Si	27.35	27.42	26.75	27.17	8.20	8.70	8.56	8.49	23.32	23.44	23.76	23.51
T_3: H+K-Si	24.38	25.46	25.33	25.06	8.80	8.81	8.40	8.67	24.39	24.72	24.61	24.58
T_4: Gb	23.42	23.39	23.42	23.41	8.42	8.24	10.42	9.03	20.00	19.64	19.33	19.66
T_5: H+Gb	28.39	29.11	29.92	29.14	8.34	10.42	9.40	9.38	18.94	26.43	26.80	24.06
T_6: $CaSO_4$	25.64	26.30	26.17	26.04	10.41	9.21	9.44	9.69	26.51	25.23	25.34	25.69
T_7: H+$CaSO_4$	28.34	28.71	29.01	28.69	9.28	9.66	8.63	9.19	25.41	24.70	24.66	24.92
T_8: Humic	27.66	27.26	27.75	27.56	9.83	9.51	7.92	9.09	24.72	22.72	22.19	23.21
Mean	25.25	25.27	25.25	25.3	8.24	8.40	8.14	8.3	21.92	22.38	22.35	22.2
LSD0.05 C		0.03				Ns				o.o4		
T		0.16				0.12				0.15		
Cx T		0.27				0.26				0.22		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T : LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Table 7. Effect of fertilizer treatments on total NPK uptake by straw (kg.ha^{-1}) of flax cultivars (average of two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	N				P				K			
T_1: Control	5.22	5.54	5.16	5.30	2.17	2.51	2.21	2.29	6.03	5.61	5.38	5.67
T_2: K-Si	12.31	12.62	13.54	12.82	5.50	5.30	5.78	5.52	15.41	15.11	14.89	15.14
T_3: H+K-Si	15.70	16.08	15.44	15.74	7.25	7.48	7.03	7.25	16.96	16.73	17.37	17.02
T_4: Gb	11.23	8.30	11.93	10.49	4.37	4.66	4.13	4.39	13.73	13.23	13.97	13.64
T_5: H+Gb	13.52	13.08	13.62	13.41	6.33	6.62	6.27	6.41	15.34	15.21	15.75	15.43
T_6: $CaSO_4$	11.47	7.83	11.82	10.37	5.23	5.10	5.40	5.24	14.34	14.74	15.58	14.89
T_7: H+$CaSO_4$	13.89	14.74	11.22	13.28	5.13	5.29	5.12	5.18	14.70	15.27	15.62	15.20
T_8: Humic	13.20	13.33	12.99	13.17	4.61	4.30	4.68	4.53	13.44	13.39	14.05	13.63
Mean	12.07	11.44	11.96	11.8	5.07	5.16	5.08	5.1	13.80	13.66	14.02	13.8
LSD0.05 C		0.05				0.02				0.33		
T		1.51				0.17				1.12		
Cx T		0.83				0.75				2.11		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T : LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Table 8. Effect of fertilizer treatments on Soil content of available NPK (g. Kg^{-1}soil) after harvesting (average of two seasons).

Fertilization treatments (T)	Cultivars (C)											
	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
	N				P				K			
T_1: Control	16.84	15.74	15.21	15.93	2.95	3.06	3.31	3.10	10.21	9.48	9.91	9.87
T_2: K-Si	22.71	22.37	22.75	22.61	6.45	6.60	6.34	6.46	26.21	26.22	26.31	26.24
T_3: H+K-Si	24.44	24.90	24.90	24.74	8.29	8.25	8.61	8.38	27.52	27.31	27.42	27.42
T_4: Gb	23.31	23.58	23.19	23.36	5.81	5.48	5.99	5.76	25.33	25.22	25.53	25.36
T_5: H+Gb	25.49	25.61	25.44	25.52	8.61	8.46	8.36	8.48	24.66	24.90	25.07	24.87
T_6: $CaSO_4$	26.52	26.63	26.22	26.46	7.75	7.51	7.20	7.49	26.44	25.50	25.89	25.94
T_7: H+$CaSO_4$	28.31	28.12	28.67	28.37	8.68	8.61	8.30	8.53	27.99	27.45	27.47	27.64
T_8: Humic	25.21	25.18	25.61	25.33	6.43	6.20	6.53	6.39	24.27	24.59	24.29	24.39
Mean	24.10	24.02	24.00	24.0	6.87	6.77	6.83	6.8	24.08	23.83	23.99	24.0
LSD0.05 C		0.06				0.08				0.04		
T		1.69				0.44				0.53		
CxT		1.23				1.55				1.87		

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T: LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Histological studies:

Effect of cultivar.

The mean values for the thickness of the epidermis with cuticle, cortex thickness, diameter of bast fiber, phloem, and xylem tissue across three flax cultivars over two seasons are presented in Tables 9 and 10. The data revealed significant differences among the three cultivars. The Giza-11 cultivar surpassed Giza 12 and Sakha 6 in thickness of the epidermis with cuticle, diameter of bast fiber tissue, and diameter of phloem tissue. Conversely, Sakha 6 exceeded Giza-12 and Giza-11 in cortex thickness, while Giza-12 outperformed both Sakha-6 and Giza-11 in diameter of xylem tissue. The relative increases for Giza-11 in thickness of the epidermis with cuticle, diameter of bast fiber tissue, and phloem tissue were (23.91%, 119.67%, and 20.30%), respectively. Sakha-6 demonstrated a relative increase of (10.35%) in cortex thickness, and Giza-12 recorded a (7.16%) increase in xylem tissue. The favorable effects observed in the histological studies among the three flax cultivars can be attributed to the physiological characteristics of the cultivars and variations in genetic constituents. These results are consistent with reports by Ibrahim and Ali (2018), Arkadiusz (2018), and Swetha Reddy *et al*. (2020).

Effect of Organic and Chemical Fertilizer Treatments

Foliar fertilizers significantly improved the histological characteristics of the stems of the three flax cultivars. The mean values from control, (H+K-Si), (H+Gb), and (H+$CaSO_4$) treatments, based on combined analysis over the two seasons, are presented in Tables 9 and 10. Treatment T_3 (H+K-Si) outperformed other treatments in thickness of the epidermis with cuticle, diameter of phloem, and xylem tissue, with increases of (51.92%, 367.23%, and 624.29%), respectively, compared to control. Treatment T_7 (H+$CaSO_4$) led to the highest increment in the diameter of bast fiber tissue, with an increase of (446.23%)compared to control. These findings align with those reported by Ibrahim and Ali (2018), Arkadiusz (2018), and Swetha Reddy *et al*. (2020).

Table 9. Effect of some treatments on epidermis and cortex thickness of flax cultivars stems:

Fertilization treatments (T)		Thickness of (µm)							
		Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_2)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
		Epidermis with cuticle				Cortex			
T_1: Control		16.7	15.0	15.0	15.6	32.2	33.1	33.3	32.9
T_3: H+K-Si		18.8	26.3	26.0	23.7	31.3	32.5	33.5	32.3
T_5: H+Gb		17.5	18.6	25.0	20.4	30.0	35.0	32.2	32.4
T_7: H+CaSo4		20.7	19.3	25.0	21.7	33.8	35.7	25.0	31.5
Mean		18.4	19.8	22.8	20.3	31.8	34.1	30.9	32.3
LSD 0.05	C	0.2				0.4			
	T	0.2				0.4			
	C x T	0.3				0.7			

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T: LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Table 10. Effect of some treatments on bast fiber, phloem and xylem tissue of flax cultivars stems:

Fertilization treatments (T)		Diameter of (µm)											
		Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean	Giza 12 (C_1)	Sakha 6 (C_2)	Giza 11 (C_3)	Mean
		Bast Fiber tissue				Phloem tissue				Xylem Tissue			
T_1: Control		1834.0	2623.5	2040.0	2165.8	1947.4	877.1	1868.8	1564.4	3559.3	3000.0	4400.0	3653.1
T_3: H+K-Si		7460.9	9615.8	17648.4	11552.8	5617.3	7936.0	8375.0	7309.4	24565.3	27750.0	27063.0	26459.4
T_5: H+Gb		9100.0	4995.0	15385.0	9826.7	2446.9	1890.0	2219.1	2185.3	11500.0	7426.6	16569.0	11831.9
T_7:H+CaSo4		12000.2	6477.0	17014.0	11830.4	3579.9	3326.5	3889.2	3598.5	23718.6	7658.1	11078.8	14151.8
Mean		7582.1	5927.8	13021.9	8843.9	3397.9	3507.4	4088.0	3664.4	15835.8	11458.7	14777.7	14024.1
LSD 0.05	C	359.9				126.9				977.6			
	T	415.6				146.5				1128.8			
	Cx T	713.0				246.8				1941.4			

Control: without application, K – Si: potassium Silicates at a rate of 250 mg/L, H: potassium humates at a rate of 3 ml/L, Gb: gibberellin at a rate of 150 mg/L, $CaSo_4$: calcium sulphate at a rate of 3 g/L. C: LSD between cultivars at 0.05, T : LSD between fertilizers at 0.05, C* T: the interaction between cultivars and fertilizers. ns: non-Significant at the 5% levels of probability at L.S.D test.

Effect of the Interaction Between Cultivars and Fertilizer Treatments

Interactions between the three flax cultivars and treatments T_1, T_3, T_5, and T_7 on stem histological characteristics are detailed in Tables 9 and 10, and Figure (1). Significant increases were observed in stem histological characteristics, with Giza-11 surpassing Giza-12 and Sakha-6 at T_3 (H+K-Si) for the diameter of bast fiber and phloem tissue, with increments of (862.29% and 330.06%), respectively.

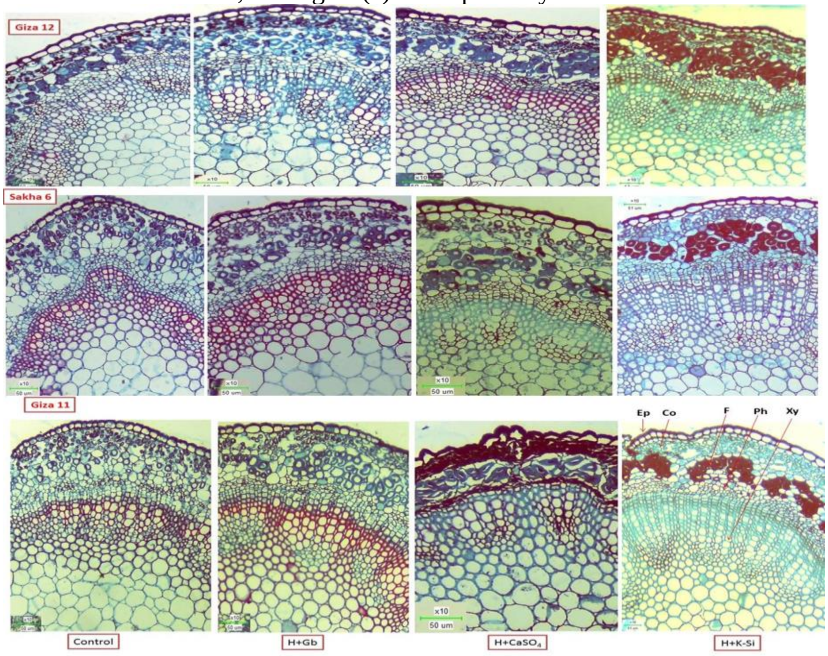

Fig. 1. Cross-sections of the stem three flax cultivars, affected by the (H+K-Si), (H+$CaSo_4$), (H+Gb), and Control treatments.

Meanwhile, Sakha-6 exceeded Giza-11 and Giza-12 at T_3 (H+K-Si) for thickness of the epidermis with cuticle and diameter of xylem tissue, with increases of (75.30% and 825.00%), respectively. Additionally, Sakha-6 outperformed Giza-11 and Giza-12 at T_7 (H+$CaSO_4$) in cortex thickness, with an increment of (42.80%).

The observed stimulation due to the application of (H+K-Si), (H+$CaSO_4$), and (H+Gb) is noteworthy. Mohamed *et al.* (2010) reported that gibberellic acid and $CaCl_2$ enhance fiber production in linseed genotypes. Moreover, gibberellic acid promotes shoot growth, cell division, and elongation (Kashif *et al*., 2021). Calcium is essential for maintaining the structural and functional integrity of plant membranes, stabilizing cell wall structures, regulating transport and selectivity, and controlling ion-exchange behavior and enzyme activities (Tuna *et al*., 2007). Additionally, humic substances enhance chlorophyll content, plant respiration, and hormonal growth, improving membrane permeability (Metre *et al*., 2013). Silicates promote increases in shoot growth, photosynthetic pigments, polysaccharides, carbohydrates, proline, free amino acids, indole acetic acid, and phenolic compounds in linseed varieties (Bakry *et al*., 2012).

Potassium is a crucial mineral for all phases of protein synthesis. Throughout growth, potassium regulates the production of proteins and enzymes, making adequate potassium levels vital for these processes. Findings from Salih *et al*. (2014) indicate that potassium positively impacts fiber yield by increasing nitrogen content in the fiber cell wall. Additionally, Abou-Khadrah *et al*. (1999) emphasized potassium's role in various plant growth processes, enhancing crop yields by increasing protein content, cellulose formation, and sugar translocation. Several investigators have studied the anatomy of flax plants, including Hella *et al*. (1989), El-Shimy *et al*. (1993), Ismail *et al*. (2017), and El-Emary *et al*. (2006).

CONCLUSION

Based on the assessment of results, it can be concluded that using humic substances as a foliar application at a rate of 3m L^{-1}, combined with gibberellic acid at 150 mgL^{-1}, potassium silicates at 250 mgL^{-1} ,and calcium sulfate at 3 g L^{-1} , significantly enhanced the growth, seed yield, fiber yield, total fiber and chemical composition of the Giza-11 and Giza-12 of flax cultivars. These treatments also improved the available NPK in the soil after harvesting. In contrast, the Sakha 6 cultivar produced higher mean straw values, moreover seed oil, oil yield affected by Giza-11 and with Giza-12 cultivars in conjunction with treatment T_5 (H+Gb). All three tested flax cultivars were significantly affected by treatments T_5 (H+Gb), T_7 (H+$CaSO_4$), and T_3 (H+K-Si) with Giza-12 showing the greatest response, followed by Giza-11 and Sakha-6. Furthermore, these treatments increased the diameter of bast fiber, phloem and xylem tissue. While T_7 (H+$CaSO_4$) and T_3(H+K-Si) treatments enhanced cell wall thickness. Thus, the combination of T_5 (H+Gb), T_7 (H+$CaSO_4$), and T_3(H+K-Si) is recommended for use with flax plants under sandy soil conditions to increase yield, yield characteristic, NPK uptake and soil content of available NPK across the three tested cultivars.

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تأثير التسميد الورقي للأسمدة العضوية و الكيمائية على المحصول ومكوناته وامتصاص العناصر وتيسرها بالتربة والصفات التشريحية لثلاثة أصناف من الكتان تحت ظروف الأراضي الرملية

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الملخص

أجريت تجربتان حقليتان في محطة البحوث الزراعية بالإسماعيلية خلال الموسمين الشتويين ٢٠٢٢ و٢٠٢٣ لدراسة تأثير بعض المعاملات المضافة رشا على الصفات المحصولية والعناصر بالنبات والتربة وبعض الصفات التشريحية للكتان في الأراضي الرملية. نفذت التجربة في تصميم قطاعات كاملة العشوائية، حيث احتوت القطع الرئيسية على الأصناف جيزة١٢ وسخا٦ وجيزة١١، بينما اشتملت القطع الشقية على ٨ معاملات تسميد ورقي هي:(١)-كنترول (٢)-سليكات البوتاسيوم (٣)-سليكات بوتاسيوم مع هيومات البوتاسيوم (٤)-جبريلين (٥)-جبريلين مع هيومات البوتاسيوم (٦)-كبريتات الكالسيوم (٧)-كبريتات الكالسيوم مع هيومات البوتاسيوم (٨)-هيومات البوتاسيوم. قد وجد فروق معنويه ببين متوسطات أصناف تحت الدراسة في صفات النمو والمحصول ومكوناته، كما تفوق صنف سخا٦ على باقي الأصناف. أعطى سخا٦ أعلى قيمة إنتاجية في محصول القش ومحصول الألياف مع الرش بمخلوط سليكات البوتاسيوم وهيومات البوتاسيوم، وتفوق صنف جيزة١٢في محصول البذور ونسبة الألياف الكلية وتحت معاملتي الرش رقم(٥) و(٧)بالترتيب. سجل جيزة١١ أعلى نسبة في نسبة الزيت ومحصول الزيت عند رش النباتات بالجبريلين وهيومات البوتاسيوم بالمقارنة بالكنترول جيزة١٢. جيزة١١مع الرش بالجبريلين وهيومات البوتاسيوم أعطى أكبر نسبة نيتروجين وبوتاسيوم ممتص في البذور وسخا٦ مع الرش بالجبريلين وهيومات البوتاسيوم أعلى نسبة فوسفور. سخا٦ مع الرش بسليكات بوتاسيوم مع هيومات البوتاسيوم أعلى نسبة نيتروجين وبوتاسيوم ممتص في القش وأعلى بوتاسيوم جيزة١١مع الرش بسليكات بوتاسيوم مع هيومات البوتاسيوم. جيزة١١و جبزة١٢ مع المعاملة بكبريتات الكالسيوم مع هيومات البوتاسيوم أعلى قيمة للنيتروجين والبوتاسيوم الميسر بالتربة، لكن أعلى بوتاسيوم بواسطة جيزة١١ وجبزة١٢ مع معاملة الرش بسليكات بوتاسيوم مع هيومات البوتاسيوم. أفضل القيم للصفات التشريحية المدروسة كانت للصنف جيزة١١مع (٧) وسخا٦مع (٣). أظهرت معاملات الرش (٣) و(٧) أفضل مقاييس لقطر الليفة و صفات جودة لليفة و كذلك إنتاج الألياف.