Menoufia J. Plant Prod., Volume 10 Issue 10 (2025): 162 – 185

MENOUFIA JOURNAL OF PLANT PRODUCTION

https://mjppf.journals.ekb.eg/

IMPACT OF FOLIAR APPLICATION WITH DROUGHT-TOLERANT SUBSTANCES ON QUANTITATIVE TRAITS OF SOME FLAX CULTIVARS CULTIVATED UNDER DROUGHT CONDITIONS

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Received: Oct. 9, 2025 Accepted: Oct. 22, 2025

ABSTRACT: One of the biggest risks to food security in the context of climate change is drought stress. Flax crop predicted to suffer from drought, which will lower growth metrics, straw, seed, fiber yield, and fiber quality. It is essential to lessen the detrimental effects of drought stress on the productivity of the flax crop. The goal of the study was to determine how four flax cultivars under drought stress, with or without foliar application of drought-tolerant substances, performed in terms of straw, seed, fiber, and water productivity characteristics. The field experiments were conducted at the Agricultural Research Station in Gemmeiza, Gharbia Governorate, Egypt, during the winter seasons of 2020/21 and 2021/22. Irrigation regimes, flax cultivars, and their interaction significantly affected the straw, seed, fiber yields, water productivity, and most evaluated traits in both growing seasons. Drought treatments significantly reduced the yields of straw, seed, and fiber, as well as all assessed attributes, as compared to the 30-day treatment. Irrigation every 45 days, integrated with foliar spray of drought-tolerant substances, significantly increased the yields of straw, seed, and fiber, as well as all evaluated attributes, compared to irrigation every 45 days without foliar application in both growing seasons. The 45-day + KSi treatment often yielded the highest values of straw, seed, and fiber yields as well as all assessed qualities in both growing seasons when compared to other drought stress treatments. These findings demonstrated the beneficial effects and positive role of KSi treatment on the growth and development of flax plants during drought conditions, which saved water about 29.86% and 30.16% in the first and second seasons, respectively. The highest values were observed by the Giza 12 cultivar for straw yield and water productivity, by the Sakha 6 cultivar for seed yield, and by the Sakha 3 cultivar for fiber yield. Based on the results of the irrigation regimes × flax cultivars interaction and PCA, the Giza 12 cultivar for straw yield, the Sakha 6 cultivar for seed yield, and the Sakha 3 cultivar for fiber yield with KSi foliar application under drought conditions were superior compared with the other cultivars under other foliar application treatments in both growing seasons. These results shed insight into the potential of applying KSi as a successful strategy to increase flax's tolerance to the impacts of water stress in regions that are susceptible to drought.

Keywords: Drought stress, drought-tolerant substances, seed, fiber, water productivity, correlation plot, PCA, flax.

INTRODUCTION

One of the world's five main oilseed crops, flax (*Linum usitatissimum* L.), is the third-largest natural source of fiber (Mishra and Awasthi, 2021). It belongs to the Linaceae family, and it is considered a major crop for fiber and oil production around the world (Mahmoud and Noman, 2024). One of the most significant crops cultivated in Egypt is flax, which serves both as a seed and a fiber (dual-purpose plant). Flax is regarded as the second most important fiber crop in Egypt, behind cotton (Sadak and Bakry, 2020). It is self-pollinating, diploid (2n = 30), and grown for its seeds, which are high in fiber and valuable oils. Flax has significant nutritional and economic value (Fawaz and Alnuaimi, 2025). Flax seeds are rich in vital fatty acids, proteins,

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mucilage, and cyanogenic glycosides; they contain 30-40% edible oil with great nutritional value (Sadak and Bakry, 2020). Many industries rely on the production of flax oil and fiber, and its seeds are a rich source of unsaturated fatty acids, including oleic acid (19-20%), linoleic acid (17-19%), and linolenic acid (45-60%). These nutrients make flax seeds extremely nutritious and have health benefits, including the ability to help treat cardiovascular diseases (El-Gedwy *et al.,* 2020). Additionally, the organic and animal feed sectors use flaxseed oil, which is the remnant left over from the seed after oil extraction (Mahmoud and Noman, 2024). Flax fibers can be a viable substitute for synthetic fibers, which produce non-biodegradable waste with limited recycling potential, because of their favorable environmental qualities that make them ideal for textile applications. Clothes made of linen are becoming increasingly popular due to growing environmental consciousness and the need for comfortable clothing. Flax merits consideration as a textile material because of its many benefits. Flax fibers' antibacterial, antioxidant, and phenolic acid content all contribute to their health-promoting qualities (Kwiatkowska *et al.,* 2024). Some of the flax products can be utilized to produce various forms of compact wood (particle board) and animal and poultry feed (Bakry *et al.,* 2013).

Globally, drought stress is a significant barrier to sustainable flax production, where the yield gap is made worse by unfavorable agronomic and environmental practices. Crop development, yield, and quality are all adversely affected by drought, which interferes with physiological, biochemical, and molecular processes (Mutanda *et al.,* 2025). Water shortages have a variety of effects on plants. Slowly developing water deficits slow down growth by causing turgor loss, which slows down cell division and expansion rates. They can also result from the osmotic effect of water stress, which upsets the water balance of stressed flax plants, lowering photosynthetic pigments and slowing down growth (Sadak and Bakry, 2020). Drought can change the content of fatty acids and reduce seed production (Dai *et al.,* 2020). Flax genotypes' yield and yield components were decreased by water stress (Sadak and Bakry, 2020). In comparison to the control, the seed yield of all genotypes decreased by 34%, 39%, and 49% under light, moderate, and severe water-deficit conditions, respectively (Valipour *et al.,* 2025). The yield and biochemistry of the extracted technical flax fibers can be impacted by drought (Melelli *et al.,* 2022). Thus, the stability and profitability of flax agriculture in the future depend on finding flax genotypes with higher phenotypic flexibility and resilience to abiotic challenges (Čeh *et al.,* 2020). The yield and its components of different flax genotypes significantly differed. A lack of water throughout the flax growing season decreased the fiber's density and tenacity (Kwiatkowska *et al.,* 2023). Nonetheless, it is imperative to create flax crop management plans that will improve agricultural sustainability under adverse environmental circumstances (Valipour *et al.,* 2025).

One important tactic for reducing drought stress in plants is the use of exogenous drought tolerance substances (Fan *et al.,* 2022; El-Beltagi *et al.,* 2024; and Sharma *et al.,* 2024). The second most prevalent element in soil after oxygen is silicon, a significant tetravalent metalloid mineral (El-Beltagi *et al.,* 2020 and 2024). In silicon gathering, the function of silicon in plant development has been studied, and it seems to have a major impact (Jinab *et al.,* 2008, and Bassiouni *et al.,* 2020). Silicon is essential for plant growth and affects a number of plant functions, including improving the plants' water status, chlorophyll content, and enzyme activity, especially when they are stressed (El-Beltagi *et al.,* 2020, and Abo-yousef *et al.,* 2025). Over the past 20 years, a great deal of research has been done on silicon supplementation in plants, and its benefits in reducing biotic and abiotic stress have been well-established (Tayade *et al.,* 2022). By increasing the activities of enzymatic antioxidants and osmolyte (proline and soluble protein) concentrations, silicon applied to foliage greatly increased yield and yield characteristics and decreased the buildup of reactive oxygen species (El-Beltagi *et al.,* 2024). A crucial nutrient for plants, potassium is necessary for several metabolic processes in plant tissues, including photosynthesis, enzyme activity, protein synthesis, and water status maintenance (Marschner, 2012). It has also been demonstrated that small doses of potassium enhance yield quality (Tarabih *et al.,* 2014). This may be linked to the effects of potassium mineral on plant processes such as photosynthesis, oxidative stress, chlorophyll synthesis, nucleic acid synthesis, and solution translocation (Bakry *et al.,* 2015b and Shedeed *et al.,* 2016). Additionally, its plant height, straw yield, fruiting branches/plant, seeds/capsule, capsules/plant, 1000-seed weight, seed yield, and oil% all significantly increased as a result of the potassium fertilizer (Noaman *et al.,* 2024). Drought tolerance substances have been demonstrated in numerous studies to be beneficial in promoting drought recovery, such as salicylic acid (Decsi et al., 2025), potassium silicate (Shedeed et al., 2016), ascorbic acid (Sharma et al., 2024), and selenium (Fan *et al.,* 2022). Silicon aids in the recovery from a variety of stressors. When plants are under extreme stress, potassium silicate enhances their growth, nutrition, physiology, and biochemistry (Khan *et al.,* 2025). By improving photosynthesis, potassium silicate applied to plants increases their ability to withstand stress. According to Alharbi *et al.* (2024), potassium is necessary for a number of plant metabolic processes. It is essential for respiration, absorption, enzyme activities, and CO_2 level regulation. By controlling stomatal opening, it also influences photosynthesis and aids in protein synthesis. Potassium also improves a plant's resistance to environmental stressors like drought. To lessen the adverse effects of water scarcity, this is essential (Johnson *et al.,* 2022). By physically fortifying cell walls, enhancing water control, raising chlorophyll content, and bolstering antioxidant defense systems, potassium silicate improves the stress tolerance of flax plants, leading to increased growth and productivity. Additionally, mesophyll cells with a greater potassium ion concentration can use water more efficiently (Hu *et al.,* 2022). In order to help plants withstand environmental stressors, including drought, salt, and cold, salicylic acid functions as an endogenous signal molecule (Wassie *et al.,* 2020). One of the most widely utilized natural plant protection substances, salicylic acid is thought to be among the best at reducing the harm that biotic and abiotic stressors may do to plants (Decsi *et al.,* 2025). Under drought stress, selenium significantly improved both the quantitative and qualitative characteristics of plants (Fan *et al.,* 2022). Following seed treatment with ascorbic acid, which has been shown to improve crop resistance to abiotic stress, there were some variations in the defense responses of plants and mechanisms of minimizing the harm of drought stress (Zhang *et al.,* 2024).

The current study aims to develop a drought management strategy for flax by investigating the effects of foliar application with drought-tolerant substances (salicylic acid, selenium, potassium silicate, and ascorbic acid) on straw, seed, and fiber yields, as well as water productivity in selected flax cultivars.

MATERIALS AND METHODS

Experimental procedures

During the two winter growing seasons of 2020/21 and 2021/22, two field experiments were conducted at the Agricultural Research Station in Gemmeiza, Gharbia Governorate, Egypt. The goal of the study was to determine how four flax cultivars under drought stress, with or without foliar application of drought-tolerant substances, performed in terms of seed, fiber, and water productivity characteristics.

Experimental treatments

A- Irrigation regimes

Six irrigation treatments were tested, including normal irrigation (irrigation every 30 days as a control) and stress drought (irrigation every 45 days), with or without foliar application of drought-tolerant substances, such as salicylic acid (SA), selenium (Se), potassium silicate (KSi), and ascorbic acid (As), as shown in Table 1. The first irrigation was applied 21 days after sowing (DAS) for all experimental treatments, then the other irrigations were applied according to each tested regime. Drought-tolerant substances were sprayed twice at 35 and 55 DAS at a rate of 0.25 g/L for each of SA, Se, and As, and with 5 cm^3/L for KSi, which contains 10% K_2O and 25% SiO_2.

Table 1. Time and number of irrigations of the tested irrigation regimes.

Irrigations No. / Irrigation regimes	1st	2nd	3rd	4th	5th	Total irrigations Number
	Irrigation time (DAS)					
(I_1) 30 D	21	51	81	111	141	5
(I_2) 45 D	21	66	111	-	-	3
(I_3) 45 D + SA	21	66	111	-	-	3
(I_4) 45 D + Se	21	66	111	-	-	3
(I_5) 45 D + KSi	21	66	111	-	-	3
(I_6) 45 D + As	21	66	111	-	-	3

B- Cultivars

Four flax cultivars (two fiber types and two dual types) were evaluated. The Classification and pedigree of the tested cultivars of flax were listed in Table 2.

Table 2. Classification and pedigree of the four tested cultivars of flax.

Cultivars	Pedigree	Origin	Type
Sakha 3	Belinka × I. 2569	Local Variety	Fiber
Giza 10	S. 420 × Bombay	Local Variety	Fiber
Giza 12	S. 2419 × S. 148/6/11	Local Variety	Dual
Sakha 6	Giza 8 × S. 2419/1	Local Variety	Dual

Experimental design

Flax seeds were sown in a strip plot design in a randomized complete block with three replicates. The six irrigation regimes were arranged at random in the vertical plots as irrigation every 30 days (normal), irrigation every 45 days (drought), and irrigation every 45 days with foliar application of drought tolerance substances. However, the four flax cultivars were assigned to the horizontal plots.

Site characteristics

Before planting, soil samples were taken from the experimental site for physical and chemical analysis. The results of soil analysis using standard techniques at the study site for a depth of 0-30 cm in both growing seasons are displayed in Table 3a, according to Jackson (1973) and Page *et al.* (1982). For the two growing seasons, the topsoil at the location where the two experiments were conducted had a clay texture with slightly alkaline pH. Furthermore, the investigated soil was classified as suitable for flax cultivation. Meteorological data of Gemmeiza Agriculture Research Station during the flax growth period of 2020/2021 and 2021/2022 seasons are noted in Table 3b.

Crop management

After harvesting the preceding crop (maize in the first season and rice in the second season), the experimental field was prepared by ploughing twice, leveling, and dividing into plots with a size of 6 m^2 (2 m × 3 m). A buffer area (1 m) was left between all experimental plots to eliminate any interference effect from irrigation water leakage and the spray of drought tolerance substances. Sowing dates were on 4th November in both growing seasons. The sowing was done in 3 m-long rows with 15 cm separating each row. For the flax crop in this region, all agricultural methods were implemented following the guidelines provided by the Egyptian Ministry of Agriculture and Land Reclamation.

Table 3a. Physical and chemical characteristics of soil (0-30 cm depth) during 2020/21 and 2021/22 seasons.

Characteristic	Unit	Season	
		2020/21	2021/22
Particle size distribution			
Sand	(%)	16.18	15.79
Silt		31.69	30.00
Clay		52.13	54.21
Texture class	---	Clay	Clay
Bulk density	(g cm^{-3})	1.27	1.32
Organic matter	(%)	1.76	1.69
pH	---	7.53	8.03
EC_e	(dS m^{-1})	1.21	1.14
Soluble cations			
Ca^{2+}	(meq L^{-1})	5.23	5.11
Mg^{2+}		5.83	5.31
Na^{+}		6.17	7.01
K^{+}		1.58	1.28
Soluble anions			
SO_4^{2-}	(meq L^{-1})	8.82	7.58
Cl^{-}		7.52	8.27
HCO_3^{-}		2.47	2.86
CO_3^{2-}		-	-
Available nutrients			
N	(ppm)	40.27	39.74
P		12.19	11.43
K		269.87	278.38
Soil moisture			
Field capacity	(%)	40.87	40.63
Permanent wilting point		19.84	19.69
Available soil water		21.03	20.94

Table 3b: Meteorological data of Gemmeiza Agriculture Research Station during the flax growth period of 2020/2021 and 2021/2022 seasons.

Season	2020/2021					2021/2022				
Month	Temp °C		Relative humidity (%)	Rain (mm)	ETo	Temp °C		Relative humidity (%)	Rain (mm)	ETo
	Max	Min				Max	Min			
November	24.80	11.10	68.10	0.00	5.15	24.62	13.80	65.32	0.51	5.10
December	20.59	7.80	73.90	14.0	3.94	21.80	8.52	70.38	8.62	4.02
January	19.50	6.50	68.42	16.4	3.48	20.09	7.26	68.91	11.35	3.50
February	21.15	6.61	70.40	18.2	3.70	21.76	7.31	70.35	9.28	3.81
March	24.80	8.90	64.80	1.00	4.10	22.35	8.94	68.13	6.23	4.14
April	26.61	12.10	66.10	10.6	4.18	25.84	10.73	69.04	3.20	4.25

Measurements

- Flax traits

At full maturity, flax plants were manually harvested on 14th April in both growing seasons. Ten plants were randomly collected from each plot to measure plant height (cm), technical length (cm), stem diameter (mm), straw yield/plant (g), number of main apical branches/plant, number of capsules/plant, number of seeds/capsule,1000-seed weight (g), seed yield/plant (g), and total fiber (%). Experimental plots were harvested to determine seed, straw, and fiber yields per unit area, then converted to seed yield/fed (kg), straw yield/fed (ton), and fiber yield/fed (ton).

- Water relations

Total water applied (TWA)

The amount of applied irrigation water was measured by a flow meter and was calculated according to Vermeiren and Jopling (1984) as follows: TWA = ETc/Ea, ETc = ETo × Kc, where, TWA is total water applied in irrigation (m^3/fed), ETc is crop evapotranspiration, ETo is a reference evapotranspiration, Kc is the crop coefficient and Ea is irrigation efficiency (60% for surface irrigation). The total rain fall during the season were taken into account when calculated the total water applied/fed.

Water productivity (WP)

The water productivity was calculated according to Jensen (1983) as follows: WP = Ya/TAW, where Ya is the seed yield of various treatments (kg/fed), and TWA is the seasonal total applied water (m^3/fed).

Statistical analysis

In accordance with Snedecor and Cochran's (1980) methodology, the measured data were put through an ANOVA test to identify any significant variations in the impact of experimental factors and their interactions. Duncan's multiple range test (Duncan, 1955) was used to compare the means of the treatments at 5% probability. The mean values within each column followed by the same letters are not significantly different. Principal component analysis (PCA) and Pearson's correlation plot were used to better understand the relationship between the features under study throughout both growing seasons and experimental conditions. The computer applications CoStat package version 6.45 (Cohort software, USA), PAST version 4.03, and Origin Pro 2021 were used to perform the ANOVA, Pearson's correlation plot, and PCA, respectively.

RESULTS AND DISCUSSIONS

Responses of straw yield and its component traits

The main effects of irrigation regimes and flax cultivars significantly affected straw yield and its related characters in both growing seasons, except for the technical length trait by flax cultivars in the 2020/21 growing season (Table 4). All straw yield and its related characters were significantly increased under the 30-day treatment compared with the other studied irrigation regimes in both growing seasons. Therefore, these characteristics were reduced under the drought conditions compared with the 30-day treatment in both growing seasons. The foliar application of drought-tolerance substances increased these traits compared to 45-day irrigation without foliar application. Generally, the highest values of straw yield and its related characters were obtained with 45-day + KSi treatment in both growing seasons compared with other drought conditions. According to Mirshekari *et al.* (2012), Rashwan *et al.* (2016), Sadak and Bakry (2020), and El-Borhamy *et al.* (2022), the control irrigation treatment (every 30 days) produced the largest straw yield and its constituent flax components, whereas limited irrigation stress (every 45 days) produced the lowest of these characteristics. Compared with the 30-day treatment, the highest decrease in straw yield/fed (ton) was observed under the 45-day treatment, with values of 19.46%, followed by the 45-day + Se treatment with values of 14.27%, and the 45-day + As treatment with values of 9.80% as an average of the 2020/21 and 2021/22 growing seasons. The lowest decrease in straw yield/fed (ton) was observed under the 45-day + KSi treatment, with an average value of 7.12%, followed by the 45-day + SA treatment, which averaged 8.32%, across both the 2020/21 and 2021/22 growing seasons. According to Bakry *et al.* (2015b), the potassium silicate considerably increased the yield of flax straw/fed by 17.5% compared with the control treatment. Kariuki *et al.* (2016) and Sallam *et al.* (2023) mentioned that irrigation rates showed a significant difference for straw yield, but an insignificant difference for plant height and technical stem length in both seasons. While highly significant differences were found among irrigation treatments and flax cultivars on technical length, main stem diameter, and straw yield in both seasons, according to Rashwan *et al.* (2016) and El-Borhamy *et al.* (2022). Also, there were significant differences among genotypes and irrigation regimes in plant height (Valipour *et al.,* 2025). Also, Bakry *et al.* (2015b) mentioned that potassium silicate had a substantial impact on the straw yield and morphological characters of flax.

The application of silicon led to a significant increase in total phenolic, flavonoid, and α-tocopherol levels in the shoots of flax genotypes when compared to control plants (Shivappa *et al.,* 2024). Additionally, it improved plant growth, nucleic acid content, and chlorophyll concentrations (Saleem *et al.,* 2020). Applying the silicon to plants reduced the detrimental effects of unfavorable weather, improved flax plants' reactivity to mineral fertilizers, and helped them utilize fertilizer nutrients more thoroughly (Konova *et al.,* 2023). In order to increase crop productivity, potassium silicate (K_2SiO_3) acts as a stimulant for plants, giving them soluble silicon and potassium. In agricultural production systems, potassium silicate is mostly utilized as a source of silicon alteration. The application of silicon fertilizer improves lodging, mineral nutrient balance, and plant development. Flax productivity and nutritional content were enhanced by foliar application of potassium silicate fertilizers (Shedeed *et al.,* 2016). Improved root properties, including total root length, root surface area, and lateral root length, were also noted in plants fed with silicon, resulting in increased drought tolerance (Ma, 2004).

The Giza 12 cultivar recorded the highest significant values for straw yield and its related characters in both seasons, with the exception of the technical length trait, which was the most significant value for the Sakha 3 cultivar in the 2021/22 growing season (Table 4). Sakha 3 gave the lowest straw yield and its related characters in both seasons, except Sakha 6 and Giza 12 cultivars gave the lowest technical length in the first and second seasons, respectively.

Table 4. Effects of irrigation regimes and flax cultivars on straw yield and its related characters during 2020/21 (S1) and 2021/22 (S2) seasons.

Treatments	Plant height (cm)		Technical stem length (cm)		Stem diameter (mm)		Straw yield/plant (g)		Straw yield/fed (ton)	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
A- Irrigation regimes										
(I_1) 30 D	105.38 a	83.00 a	93.94 a	71.33 a	2.41 a	1.72 a	1.91 a	1.33 a	3.52 a	3.21 a
(I_2) 45 D	90.15 d	74.00 e	77.29 d	61.58 d	2.01 d	1.38 c	1.39 c	0.97 c	2.83 d	2.59 d
(I_3) 45 D + SA	98.35 bc	78.67 c	84.15 bc	67.83 b	2.27 ab	1.58 ab	1.76 ab	1.24 ab	3.23 b	2.94 b
(I_4) 45 D + Se	94.47 c	75.85 d	81.01 cd	64.17 c	2.05 cd	1.45 bc	1.53 bc	1.03 c	3.02 c	2.75 c
(I_5) 45 D + KSi	99.52 b	80.08 b	87.40 b	68.04 b	2.26 abc	1.63 ab	1.83 a	1.27 ab	3.26 b	2.99 b
(I_6) 45 D + As	96.10 bc	76.76 d	82.58 c	66.30 b	2.13 bcd	1.49 bc	1.67 ab	1.19 b	3.17 bc	2.90 bc
B- Cultivar										
Sakha 3	93.21 c	75.19 c	84.46 a	68.54 a	1.99 c	1.42 b	1.39 c	1.01 c	2.99 b	2.72 c
Giza 12	102.08 a	80.64 a	84.99 a	64.07 b	2.35 a	1.66 a	1.92 a	1.43 a	3.36 a	3.09 a
Sakha 6	98.64 ab	79.29 ab	83.46 a	65.56 ab	2.24 ab	1.57 ab	1.76 ab	1.17 b	3.25 a	2.97 b
Giza 10	95.38 bc	77.12 bc	84.68 a	68.00 a	2.16 bc	1.51 ab	1.64 b	1.07 c	3.08 b	2.81 c
C- (A×B)	*	*	*	*	NS	NS	*	*	*	*

All these characters by all evaluated flax cultivars were increased in the 2020/21 growing season compared to the 2021/22 growing season. The genetic constitution of the many flax cultivars may be the cause of these variations. Generally, Giza 12 cultivar increased straw yield/fed (ton) by 12.99, 9.53, and 3.71% compared to Sakha 3, Giza 10, and Sakha 6 cultivars, respectively, as an average of both seasons. El-Borhamy *et al.* (2022) reported that the Giza 12 cultivar was superior in straw yield/plant and straw yield/fed, while Sallam *et al.* (2023) stated that Sakha 6 gave the highest values for plant height, technical stem length, and straw yield traits in both seasons.

The results in Table 5 indicate that the interaction between irrigation regimes and flax cultivars significantly affected straw yield and its associated characteristics in both growing seasons, with the exception of the stem diameter trait, which was not significant. Flax cultivars exhibit significant variability in their response to irrigation treatments, with a notable interaction observed between these treatments and the cultivars concerning straw yields in both the plant and the feed. El-Borhamy et al. (2022). The relationship between flax cultivars and potassium silicate levels had a substantial effect on straw yield and its constituents (Bakry *et al.,* 2015b). In both growing seasons, the four flax cultivars were superior in straw yield and its related characters under the 30-day irrigation treatment, while they decreased under the 45-day irrigation treatment. The foliar application with drought-tolerance substances increased these traits in the four flax cultivars compared with 45-day irrigation without foliar application in both growing seasons. The four flax cultivars were superior in straw yield and their related characters under 45-day + KSi treatment than under the other foliar application treatments in both growing seasons. Among all treatments with flax cultivars, potassium silicate with a high rate showed superiority for straw yield and its constituents (Bakry *et al.,* 2015b). The highest values were observed for straw yield and most of its related characters by the Giza 12 cultivar under each or all irrigation regimes in both growing seasons, opposite to what was noticed for the Sakha 3 cultivar. Similarly, four irrigations using the Giza 12 cultivar produced the highest values for straw yield and its component traits in both seasons (El-Borhamy *et al.,* 2022). Generally, Giza 12 recorded the highest straw yield and most of its related characters with KSi foliar application under drought conditions compared with the other foliar applications in both growing seasons. The KSi foliar application on flax plants that grown under water stress (45-day) reduce the decline in the straw yield in Giza 12 cultivar compared to normal irrigation with 7.28%, while represented increases about 3.10, 3.90, 7.82 and 9.78%, as an average of both seasons, compared to 45-day + SA, 45-day + As, 45-day + Se, and 45-day treatments, respectively. Due to genetic characteristics, different flax genotypes respond differently to water stress; some were sensitive to drought, while others were tolerant (Sallam *et al.,* 2023).

Responses of seed yield and its component traits

Results in Table 6 show the effects of irrigation regimes and flax cultivars on seed yield and its component traits. The two factors of irrigation regimes and flax cultivars significantly influenced the seed yield and its component traits across the 2020/21 and 2021/22 seasons. Normal irrigation (irrigation every 30 days) gave the highest values of flax-seed yield/plant and /fed as well as yield component traits. Irrigation every 45 days as drought treatment significantly decreased all these traits compared with the 30-day treatment in both growing seasons. Water stress reduces flax-seed yield by negatively changing the plant's metabolic activity, growth parameters, and yield components, as demonstrated by Sadak and Bakry (2020). In both growing seasons, seed yield and other yield component traits were significantly enhanced by foliar application of drought-tolerant substances as opposed to 45 days of irrigation without foliar application.

Table 5. Effects of the interaction between irrigation regimes and flax cultivars on straw yield and its related characters during 2020/21 (S1) and 2021/22 (S2) seasons.

Interaction treatments		Plant height (cm)		Technical stem length (cm)		Straw yield/plant (g)		Straw yield/fed (ton)	
		S1	S2	S1	S2	S1	S2	S1	S2
(I_1) 30 D	Sakha 3	100.98 bcd	81.83 abc	93.76 ab	73.00 a	1.51 b-h	1.22 d-g	3.22 bc	2.92 b-e
	Giza 12	113.50 a	84.17 a	98.50 a	68.83 a-d	2.12 a	1.57 a	3.72 a	3.42 a
	Sakha 6	106.04 ab	83.67 ab	91.17 a-d	70.67 ab	2.03 ab	1.28 cde	3.71 a	3.38 a
	Giza 10	101.00 bcd	82.33 abc	92.33 abc	72.83 a	1.98 a-d	1.26 de	3.44 ab	3.14 abc
(I_2) 45 D	Sakha 3	86.63 g	71.17 g	78.38 ef	63.17 bcd	1.19 h	0.84 j	2.62 f	2.38 i
	Giza 12	95.43 b-g	77.33 a-g	78.50 ef	60.33 d	1.51 b-h	1.14 d-h	3.14 bcd	2.89 b-f
	Sakha 6	89.63 fg	76.00 b-g	73.87 ef	61.00 cd	1.49 c-h	1.00 f-j	2.84 def	2.59 f-i
	Giza 10	88.91 fg	71.50 fg	78.42 ef	61.83 bcd	1.35 fgh	0.88 ij	2.73 ef	2.49 hi
(I_3) 45 D + SA	Sakha 3	95.33 c-g	75.33 c-g	85.16 b-e	69.83 abc	1.44 e-h	1.03 e-j	3.12 bcd	2.82 c-g
	Giza 12	101.33 bcd	81.50 abc	84.33 b-e	66.83 a-d	2.04 ab	1.51 abc	3.34 b	3.08 bcd
	Sakha 6	99.39 b-f	79.67 a-d	82.00 def	65.67 a-d	1.85 a-f	1.25 def	3.33 b	3.00 bcd
	Giza 10	97.34 b-f	78.17 a-g	85.09 b-e	69.00 a-d	1.70 a-h	1.15 d-g	3.15 bcd	2.88 b-f
(I_4) 45 D + Se	Sakha 3	90.11 efg	71.83 efg	79.95 ef	67.07 a-d	1.30 gh	0.85 j	2.82 def	2.56 ghi
	Giza 12	97.96 b-f	79.00 a-f	80.88 def	60.93 cd	1.77 a-g	1.32 bcd	3.20 bcd	2.94 b-e
	Sakha 6	96.96 b-g	77.00 a-g	81.50 def	62.33 bcd	1.62 a-h	1.04 e-j	3.16 bcd	2.88 b-f
	Giza 10	92.83 d-g	75.56 c-g	81.72 def	66.33 a-d	1.43 e-h	0.90 hij	2.89 c-f	2.63 e-i
(I_5) 45 D + KSi	Sakha 3	95.56 b-g	77.83 a-g	87.67 b-e	69.83 abc	1.46 d-h	1.12 d-i	3.11 bcd	2.83 c-g
	Giza 12	103.91 bc	82.33 abc	86.69 b-e	64.33 a-d	2.10 a	1.55 ab	3.45 ab	3.17 ab
	Sakha 6	100.82 bcd	81.33 abc	87.37 b-e	67.83 a-d	1.94 a-e	1.26 def	3.29 b	3.04 bcd
	Giza 10	97.80 b-f	78.83 a-g	87.87 b-e	70.17 abc	1.82 a-g	1.16 d-g	3.18 bcd	2.90 b-f
(I_6) 45 D + As	Sakha 3	90.67 d-g	73.17 d-g	81.83 def	68.33 a-d	1.42 e-h	0.97 g-j	3.07 b-e	2.79 d-h
	Giza 12	100.33 b-e	79.50 a-e	81.02 def	63.17 bcd	2.00 abc	1.50 abc	3.32 b	3.05 bcd
	Sakha 6	99.00 b-f	78.06 a-g	84.83 b-e	65.83 a-d	1.66 a-h	1.20 d-g	3.20 bcd	2.91 b-e
	Giza 10	94.40 c-g	76.33 b-g	82.65 c-f	67.85 a-d	1.60 a-h	1.09 d-j	3.10 bcd	2.83 c-g

Table 6. Effects of irrigation regimes and flax cultivars on seed yield and its attributes during 2020/21 (S1) and 2021/22 (S2) seasons.

Treatments	No. of apical branches/ plant		No. of capsules/plant		No. of seeds/capsule		1000-seed weight (g)		Seed yield/plant (g)		Seed yield/fed (kg)	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
A- Irrigation regimes												
(I_1) 30 D	5.11 a	4.02 a	9.55 a	7.87 a	7.83 a	7.02 a	7.86 a	7.74 a	0.285 a	0.230 a	433.23 a	326.62 a
(I_2) 45 D	4.04 b	3.48 c	7.09 c	3.80 d	6.02 d	4.82 b	7.35 e	7.20 d	0.208 d	0.150 e	341.53 d	255.74 e
(I_3) 45 D + SA	4.74 a	3.80 b	8.33 abc	5.18 bc	7.31 b	6.59 a	7.68 bc	7.53 b	0.241 bc	0.200 bc	391.29 b	292.98 c
(I_4) 45 D + Se	4.15 b	3.59 c	7.65 bc	4.67 c	6.55 c	5.38 b	7.49 d	7.37 c	0.225 cd	0.175 d	363.58 c	272.02 d
(I_5) 45 D +KSi	4.87 a	3.80 b	9.10 ab	5.80 b	7.47 ab	6.84 a	7.74 b	7.62 b	0.257 ab	0.213 ab	419.85 a	314.37 b
(I_6) 45 D + As	4.25 b	3.66 bc	7.88 bc	4.92 c	7.22 b	6.38 a	7.59 cd	7.42 c	0.240 bc	0.188 cd	381.79 bc	285.78 c
B- Cultivar												
Sakha 3	3.87 c	3.54 c	5.86 d	4.90 c	6.36 c	5.32 c	5.36 d	5.24 d	0.173 d	0.160 d	337.99 d	252.61 d
Giza 12	4.82 b	3.82 a	8.79 b	5.56 ab	7.28 b	6.63 a	9.31 b	9.19 b	0.278 b	0.200 b	411.41 b	302.69 b
Sakha 6	5.35 a	3.91 a	11.60 a	5.79 a	8.06 a	6.71 a	9.62 a	9.47 a	0.317 a	0.230 a	432.51 a	333.54 a
Giza 10	4.07 c	3.63 b	6.83 c	5.23 bc	6.56 c	6.03 b	6.19 c	6.01 c	0.204 c	0.181 c	372.27 c	276.17 c
C- (A×B)	*	*	*	*	*	*	*	*	*	*	*	*

Seed yield and yield component traits in both growing seasons exhibited a positive response to the foliar application with drought-tolerance substances, characterized by initial increases under Se treatment, followed by subsequent increases under As, SA, and then KSi treatments. The 45-day + KSi treatment generally produced the highest values of seed yield and yield component attributes in both growth seasons. Compared with the 30-day treatment, the highest decrease in seed yield/fed (kg) was observed under the 45-day treatment with values of 21.43%, followed by the 45-day + Se treatment with values of 16.40%, and 45-day + As treatment with values of 12.19% as an average of the 2020/21 and 2021/22 growing seasons. The lowest decrease in seed yield/fed (kg) was observed under the 45-day + KSi treatment, with an average value of 3.42%, followed by the 45-day + SA treatment, which averaged 9.99%. This comparison is based on data from both the 2020/21 and 2021/22 growing seasons. Similar results as previously reported by Rashwan *et al.* (2016), Sadak and Bakry (2020), and El-Borhamy *et al.* (2022). Also, Bakry *et al.* (2015a and b) showed that the high rate of potassium silicate significantly raised flax-seed yield/fed by 17.9% compared with the control treatment. The yield of flax seeds and yield components were significantly impacted by potassium silicate (Bakry *et al.,* 2015b). Number of capsules/plant, number of seeds/capsule, number of seeds/plant, weight of the seeds/plant, 1000-seeds weight, and seed yield/fed are all significantly reduced by deficit irrigation, which is dependent on the intensity of the stress (Valipour *et al.,* 2025). Water stress hinders flowering and the development of the flower into a capsule, and its occurrence during flower and capsule formation results in capsules (Istanbulluoglu *et al.,* 2015). According to Fawaz and Alnuaimi (2025), the low seed weight is caused by a lack of water availability after the flowering stage and a decrease in photosynthesis and material transfer efficiency during the filling stage. According to Yusuf *et al.* (2013), exogenous SA application in flax plants promotes seed germination, growth, and flowering; boosts photosynthesis and the activity of enzymatic and non-enzymatic antioxidants to fight oxidative stress; and enhances yield components in the face of stressors like drought. By altering plant physiological and metabolic processes, such as regulating antioxidant systems and affecting the balance of plant hormones like auxins and gibberellins, SA is a powerful tool for sustainably mitigating environmental stresses in many plants, resulting in improved growth and increased fiber yields (Arif *et al.,* 2020). In order to control plant growth and resilience, SA affects ion uptake, stomatal movement, and the concentrations of photosynthetic pigments and compatible solutes such as proline (Yusuf *et al.,* 2013). Stress response-related transcription factors can be phosphorylated and activated by SA-activated protein kinases (Yang *et al.,* 2023). Plant immunity depends on several proteins that bind to SA (Decsi *et al.,* 2025).

Data in Table 6 indicated that genetic variations may be the cause of the variation in seed output and its constituent parts among flax cultivars. In comparison to the 2021/22 growing season, seed yield and yield component traits rose in the four flax cultivars in the 2020/21 growing season. Significant increases in seed yield and its component traits for the Sakha 6 cultivar were observed in both growing seasons, which represented increases of 7.66%, 18.47% and 30.00% compared to Giza 12, Giza 10, and Sakha 3 cultivars as an average of 2020/21 and 2021/22 growing seasons. These findings are consistent with those of El-Borhamy *et al.* (2022) and Sallam *et al.* (2023), who discovered that when compared to other cultivars grown in drought stress conditions, Sakha 6 is the best genotype for seed yield and the majority of yield component parameters. Remarkably, in both growing seasons, cultivar Sakha 3 had the lowest seed yield and yield component traits.

Significant interactions between irrigation regimes and flax cultivars were noticed for seed yield and yield component traits in both growing seasons, as shown in Table 7. The 30-day irrigation treatment resulted in higher seed yield and yield component traits for all four flax cultivars in both growing seasons, whereas the 45-day irrigation treatment (drought conditions) caused them to decline. Compared to 45 days of irrigation without foliar application in both growing seasons, the four flax cultivars' foliar application of drought-tolerant chemicals enhanced seed yield and yield component traits under study. Under the 45-day + KSi treatment, the four flax cultivars outperformed the other foliar spray treatments under drought conditions in terms of seed yield and yield component traits across both growth seasons. Similarly, the average 1000-seed weight and seed yield were significantly impacted by the interaction effect between the two experimental factors under study (Fawaz and Alnuaimi, 2025). Additionally, El-Borhamy *et al.* (2022) found that in both seasons, the number of capsules/plant and seed yield/fed were significantly impacted by the interaction between irrigation treatments and flax cultivars. There was a significant effect of interaction between the flax varieties and potassium silicate levels on seed yield and yield components (Bakry *et al.,* 2015a and 2015b). Potassium silicate outperformed all other treatments with flax cultivars in terms of seed output and its component traits (Bakry *et al.,* 2015b). Notably, in both growing seasons, Sakha 6 cultivar achieved its highest seed yield and yield component traits with each or all irrigation regimes, while the lowest values were recorded by Sakha 3 cultivar. In agreement with our results, El-Borhamy *et al.* (2022) stated that the highest number of capsules/plant was recorded by the Sakha 6 cultivar under control treatment in both seasons. Significant maximum seed yield and yield component traits for the Sakha 6 cultivar were observed at KSi foliar application with 45-day irrigation (drought conditions). The KSi foliar application on flax plants that grown under water stress (45-day) reduce the decline in the seed yield in Sakha 6 cultivar compared to normal irrigation with 3.95%, while represented increases about 6.23, 11.06, 20.48 and 23.75%, as an average of both seasons, compared to 45-day + SA, 45-day + As, 45-day + Se, and 45-day treatments, respectively. Similar to our results, El-Borhamy *et al.* (2022) and Valipour *et al.* (2025) observed significant effects of irrigation regimes and flax cultivars on seed yield and its related components. Also, 1000-seed weight and flax-seed yield were considerably impacted by irrigation treatments in both seasons (Fawaz and Alnuaimi, 2025).

Table 7. Effects of the interaction between irrigation regimes and flax cultivars on seed yield and its attributes during 2020/21 (S1) and 2021/22 (S2) seasons.

Interaction treatment		No. of apical branches/ plant		No. of capsules/plant		No. of seeds/capsule		1000-seed weight (g)		Seed yield/plant (g)		Seed yield/fed (kg)	
		S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
(I_1) 30 D	Sakha 3	3.83 cd	3.80 a-f	6.83 fg	6.20 c	7.57 bcd	6.20 c-g	5.57 j	5.46 h	0.198 e-i	0.189 c-g	375.04 ghi	280.30 g-l
	Giza 12	5.90 a	4.10 ab	10.13 b-e	8.77 a	7.60 a-d	7.50 ab	9.53 bc	9.43 bcd	0.320 ab	0.228 bc	451.63 bc	338.17 bcd
	Sakha 6	6.17 a	4.20 a	13.32 a	8.93 a	8.67 a	7.63 a	9.89 a	9.83 a	0.390 a	0.279 a	488.46 a	378.07 a
	Giza 10	4.53 b	3.97 abc	7.93 efg	7.57 b	7.50 bcd	6.75 a-d	6.45 f	6.25 f	0.231 d-h	0.223 bcd	417.79 cde	309.93 d-g
(I_2) 45 D	Sakha 3	3.47 d	3.30 f	5.43 g	3.60 h	4.60 g	3.87 j	5.11 l	5.02 i	0.143 i	0.121 j	307.92 l	230.13 n
	Giza 12	4.38 bc	3.63 b-f	7.73 efg	3.87 fgh	7.03 cd	5.23 ghi	9.03 e	8.90 e	0.240 c-h	0.159 g-j	351.89 h-k	256.67 k-n
	Sakha 6	4.72 b	3.60 b-f	9.03 c-f	4.07 fgh	7.73 a-d	5.47 f-i	9.35 cd	9.11 de	0.270 b-e	0.183 c-i	379.12 fgh	293.43 f-j
	Giza 10	3.60 d	3.40 ef	6.17 g	3.67 gh	4.70 g	4.70 ij	5.89 i	5.78 g	0.180 hi	0.136 ij	327.20 jkl	242.73 mn
(I_3) 45 D + SA	Sakha 3	4.27 bc	3.63 b-f	5.80 g	4.77 d-h	6.80 de	5.70 d-i	5.41 jk	5.26 hi	0.178 hi	0.174 d-i	339.14 i-l	253.47 lmn
	Giza 12	4.77 b	3.80 a-f	8.90 def	5.23 c-f	7.33 bcd	7.07 abc	9.38 cd	9.27 cd	0.275 b-e	0.205 c-g	421.40 cde	307.37 d-h
	Sakha 6	5.62 a	4.10 ab	11.93 ab	5.67 cde	8.10 abc	7.13 abc	9.69 ab	9.56 abc	0.298 bcd	0.230 bc	441.65 bc	341.83 bc
	Giza 10	4.30 bc	3.67 b-f	6.70 fg	5.03 c-g	7.00 cde	6.47 b-f	6.24 fgh	6.02 fg	0.213 e-i	0.193 c-g	362.97 g-j	269.27 j-m
(I_4) 45 D + Se	Sakha 3	3.52 d	3.43 def	5.53 g	4.53 e-h	5.40 fg	5.00 hi	5.21 kl	5.12 hi	0.148 i	0.141 hij	313.23 l	234.10 n
	Giza 12	4.53 b	3.70 a-f	7.87 efg	4.67 e-h	7.05 cd	5.53 e-i	9.22 de	9.13 de	0.262 b-g	0.187 c-h	384.76 e-h	287.53 g-k
	Sakha 6	4.80 b	3.77 a-f	10.73 bcd	4.90 c-h	7.80 a-d	5.57 e-i	9.50 bc	9.33 bcd	0.304 bcd	0.209 c-f	394.21 d-g	297.80 e-j
	Giza 10	3.76 cd	3.47 c-f	6.47 fg	4.57 e-h	5.95 ef	5.43 f-I	6.04 hi	5.91 fg	0.187 ghi	0.162 f-j	362.12 g-j	268.63 j-m
(I_5) 45 D + KSi	Sakha 3	4.37 bc	3.60 b-f	5.93 g	5.60 cde	7.00 cde	6.02 c-h	5.46 j	5.36 hi	0.190 f-i	0.176 d-i	367.86 ghi	274.93 h-m
	Giza 12	4.80 b	3.90 a-e	10.12 b-e	5.80 cde	7.40 bcd	7.33 ab	9.41 cd	9.29 cd	0.302 bcd	0.216 cde	443.47 bc	323.47 c-f
	Sakha 6	5.92 a	3.93 a-d	13.17 a	6.10 cd	8.20 ab	7.37 ab	9.78 a	9.65 ab	0.321 ab	0.262 ab	469.17 ab	363.13 ab
	Giza 10	4.39 bc	3.77 a-f	7.20 fg	5.70 cde	7.27 bcd	6.63 a-e	6.33 fg	6.16 f	0.215 e-i	0.198 c-g	398.92 d-g	295.93 e-j
(I_6) 45 D + As	Sakha 3	3.76 cd	3.50 c-f	5.63 g	4.70 d-h	6.77 de	5.15 ghi	5.40 jk	5.25 hi	0.182 hi	0.160 g-j	324.78 kl	242.73 mn
	Giza 12	4.51 b	3.77 a-f	7.97 efg	5.00 c-h	7.27 bcd	7.10 abc	9.32 cd	9.15 de	0.267 b-f	0.204 c-g	415.32 c-f	302.93 e-i
	Sakha 6	4.90 b	3.83 a-e	11.43 abc	5.10 c-f	7.88 a-d	7.07 abc	9.50 bc	9.35 bcd	0.315 bc	0.216 cde	422.44 cd	326.97 cde
	Giza 10	3.84 cd	3.53 c-f	6.50 fg	4.87 c-h	6.97 de	6.20 c-g	6.16 gh	5.92 fg	0.196 e-i	0.173 e-i	364.63 ghi	270.50 i-m

Responses of fiber and water traits

The main effects of irrigation regimes and flax cultivars, as well as their interaction, were observed to be significant on total fiber (%), fiber yield/fed (ton), total water applied (m^3/fed), and water productivity (kg/m^3) in both growing seasons, except total water applied by flax cultivars (Table 8). In both growing seasons, the 30-day treatment resulted in a substantial increase in total fiber (%), fiber yield/fed (ton), and total water applied (m^3/fed) when compared to the other irrigation regimes under study. As a result, in both growing seasons, these characteristics were diminished under drought conditions as opposed to the 30-day treatment. However, drought treatments considerably raised water productivity (kg/m^3) compared to the 30-day treatment in both growing seasons. On the other hand, total water applied (m^3/fed) has the opposite effect. Compared to 45 days of irrigation without foliar application, foliar application of drought-tolerant chemicals significantly improved the traits of total fiber (%), fiber yield/fed (ton), and water productivity (kg/m^3) in both growing seasons. When drought-tolerance substances were applied topically during both growing seasons, the traits of total fiber (%), fiber yield/fed (ton), and water productivity (kg/m^2) showed a response, where these traits first increased under Se treatment, then under As, SA, and finally KSi treatments. The fiber yield/fed (ton) was attained at the 45-day + KSi treatment, which corresponded to enhancements of 1.46, 3.54, 9.90, and 17.20% as an average of both seasons, in comparison to the 45-day + SA treatment, 45-day + As treatment, and 45-day + Se treatment, 45-day treatment, respectively. In both growing seasons, the highest total water applied (1414.16 and 1453.17 m^3/fed) were noticed with flax plants irrigated every 30 days, while the lowest ones (991.91 and 1014.87 m^3/fed) were registered from those irrigated every 30 days + KSi treatment which saved water about 29.86 and 30.16%, and increased water productivity by 34.43 and 35.45% in first and second seasons, respectively. These results were in agreement with Sallam *et al.* (2023), who reported a significant difference between irrigation rates and flax genotypes on fiber yields in both growing seasons, with fiber yields decreasing as water amounts decreased. Also, water productivity was affected by both irrigation water treatments and flax cultivars in both seasons (El-Borhamy *et al.,* 2022). Fiber % and fiber yield were significantly impacted by potassium silicate application (Bakry *et al.,* 2015b), which increased the fiber percentage and fiber yield/fed by 20.75% and 46.32% over the control, respectively. In both growth seasons, the 45-day + KSi treatment often yielded the highest values of water productivity (kg/m^3), fiber yield/fed (ton), and total fiber (%) when compared to other drought conditions. Plant growth was accelerated by the total water applied until it reached maturity, at which point it began to decline as the physiological characteristics of the plants changed (Bakry *et al.,* 2019). Since silica deposition thickens the cuticle layer, the application of silicon reduces the rate of transpiration by obstructing transpiration via the cuticles. Accordingly, it preserves the leaf water potential under drought. By preserving the buildup of organic solute, the silicon application controls the osmotic adjustments, enhancing the plants' tolerance to drought stress (Wang *et al.,* 202, and Xue *et al.,* 2023). From germination to vegetative growth and flowering, silicon helps reduce drought stress, which impacts a variety of morphological, biochemical, and physiological processes in plants (Pang *et al.,* 2019, and Abo-yousef *et al.,* 2025).

Except for total water applied (m^3/fed), all four flax cultivars showed increases in total fiber (%), fiber yield/fed (ton), and water productivity (kg/m^3) in the 2020/21 growing season compared to the 2021/22 growing season. Sakha 3 for total fiber (%), fiber yield/fed, and total water applied (m^3/fed) and Giza 12 cultivar for water productivity were recorded significantly higher values in both growing seasons. Sakha 3 cultivar outperformed Giza 10, Sakha 12, and Sakha 6 cultivars in terms of fiber yield/fed (ton) by 5.50, 6.72, and 51.41% respectively, on average across both growing seasons.

Table 8. Effects of irrigation regimes and flax cultivars on fiber and water relation characters during 2020/21 (S1) and 2021/22 (S2) seasons.

Treatments	Total fiber (%)		Fiber yield/fed (ton)		Total water applied (m^3/fed)		Water productivity (kg/ m^3)	
	S1	S2	S1	S2	S1	S2	S1	S2
A- Irrigation regimes								
(I_1) 30 D	19.56 a	19.19 a	0.683 a	0.612 a	1414.16 a	1453.17 a	0.790 c	0.646 c
(I_2) 45 D	19.10 d	18.83 f	0.538 c	0.485 d	1090.85 b	1108.13 b	0.806 c	0.668 c
(I_3) 45 D + SA	19.36 bc	19.04 c	0.624 b	0.558 b	1009.36 bc	1034.24 bc	1.008 ab	0.824 ab
(I_4) 45 D + Se	19.17 d	18.92 e	0.574 c	0.517 cd	1018.61 bc	1038.92 bc	0.927 b	0.764 b
(I_5) 45 D + KSi	19.45 b	19.11 b	0.631 b	0.568 b	991.91 c	1014.87 c	1.062 a	0.875 a
(I_6) 45 D + As	19.28 c	18.98 d	0.610 b	0.548 bc	1015.37 bc	1042.79 bc	0.979 ab	0.808 ab
B- Cultivars								
Sakha 3	23.07 a	22.66 a	0.691 a	0.616 a	1092.91 a	1117.83 a	0.956 a	0.789 a
Giza 12	19.03 c	18.89 c	0.640 b	0.584 b	1092.71 a	1115.84 a	0.974 a	0.807 a
Sakha 6	13.94 d	13.79 d	0.454 c	0.409 c	1085.31 a	1111.24 a	0.827 b	0.677 b
Giza 10	21.24 b	20.71 b	0.656 b	0.583 b	1089.25 a	1116.50 a	0.957 a	0.783 a
C- (A×B)	*	*	*	*	*	*	*	*

Table 9 shows how irrigation regimes and flax cultivars interact to affect total fiber, fiber yield/fed, total water applied, and water productivity in both seasons. All four flax cultivars showed significantly increased total fiber (%) and fiber yield/fed (ton) attributes under the 30-day irrigation treatment, while these traits decreased under the 45-day irrigation treatment (drought conditions) in both growing seasons. Total water applied (m^3/fed) increased under 30-day irrigation treatment and decreased under 45-day + KSi treatment for all four flax cultivars, while the opposite is true for water productivity (kg/m^3). The foliar application of drought-tolerant chemicals to four flax cultivars improved the following traits: total fiber (%), fiber yield/fed (ton), and water productivity (kg/m^3), compared to 45 days of irrigation without foliar application in both growing seasons. In terms of total fiber (%), fiber production/fed (ton), and water productivity (kg/m^3) traits, the four flax cultivars fared better under drought conditions under the 45-day + KSi treatment than the other foliar spray treatments during both growth seasons. Potassium silicate foliar application of flax cultivars at a high rate gave the highest values for the fiber % and fiber yield (Bakry *et al.,* 2015b). Sakha 3 cultivar notably attained the highest total fiber (%) and fiber yield/fed (ton) attributes with each or all irrigation regimes in both growing seasons, but Sakha 6 cultivar recorded the lowest results. In terms of water productivity, the best cultivar was Sakha 3 under 45-day and 45-day + SA treatments, and Giza 12 cultivar under 45-day + Se, 45-day + KSi, and 45-day + As treatments, but Sakha 6 cultivar recorded the lowest values under all irrigation treatments. Under KSi foliar spray with 45-day irrigation (drought stress), the highest significant values were observed by Sakha 3 cultivar for total fiber (%) and fiber yield/fed (ton) traits, and by Giza 12 cultivar for water productivity in both growing seasons.

Table 9. Effects of the interaction between irrigation regimes and flax cultivars on fiber and water relation characters during 2020/21 (S1) and 2021/22 (S2) seasons.

Interaction Treatments		Total fiber (%)		Fiber yield/fed (ton)		Total water applied (m^3/fed)		Water productivity (kg/ m^3)	
		S1	S2	S1	S2	S1	S2	S1	S2
(I_1) 30 D	Sakha 3	23.32 a	22.90 a	0.751 a	0.669 a	1419.33 a	1456.54 a	0.793 gh	0.653 fg
	Giza 12	19.23 i	19.01 l	0.714 abc	0.649 abc	1418.07 a	1457.59 a	0.823 gh	0.683 efg
	Sakha 6	14.12 m	13.94 p	0.524 ij	0.471 jk	1408.01 a	1453.01 a	0.721 h	0.585 g
	Giza 10	21.57 e	20.90 f	0.744 a	0.657 ab	1411.24 a	1455.53 a	0.823 gh	0.665 fg
(I_2) 45 D	Sakha 3	22.88 c	22.43 e	0.599 fgh	0.533 hi	1098.85 b	1118.39 b	0.825 gh	0.682 efg
	Giza 12	18.80 l	18.74 o	0.591 gh	0.541 ghi	1090.25 b	1106.58 b	0.865 fg	0.721 c-g
	Sakha 6	13.76 p	13.66 s	0.390 l	0.353 m	1078.33 b	1097.94 b	0.714 h	0.589 g
	Giza 10	20.96 h	20.50 k	0.573 hi	0.511 ij	1095.97 b	1106.60 b	0.822 gh	0.680 efg
(I_3) 45 D + SA	Sakha 3	23.11 b	22.69 c	0.721 ab	0.640 a-d	1005.41 b	1030.90 b	1.058 a-d	0.867 ab
	Giza 12	19.07 ijk	18.90 m	0.637 d-h	0.581 e-h	1014.01 b	1038.07 b	1.044 a-d	0.857 abc
	Sakha 6	13.99 mno	13.81 q	0.466 jk	0.414 l	1006.42 b	1033.73 b	0.902 efg	0.731 b-f
	Giza 10	21.28 f	20.76 h	0.671 b-f	0.598 c-g	1011.62 b	1034.25 b	1.028 a-d	0.844 abc
(I_4) 45 D + Se	Sakha 3	22.91 c	22.58 d	0.647 c-g	0.579 e-h	1021.75 b	1042.48 b	0.947 def	0.786 a-f
	Giza 12	18.89 kl	18.82 n	0.603 fgh	0.553 f-i	1015.87 b	1035.08 b	0.973b-f	0.812 a-e
	Sakha 6	13.81 op	13.70 rs	0.436 kl	0.394 lm	1021.40 b	1040.16 b	0.820 gh	0.672 fg
	Giza 10	21.07 gh	20.59 j	0.608 e-h	0.542 ghi	1015.42 b	1037.96 b	0.967 c-f	0.788 a-f
(I_5) 45 D + KSi	Sakha 3	23.19 ab	22.75 b	0.721 ab	0.645 abc	998.83 b	1016.53 b	1.091 abc	0.907 a
	Giza 12	19.18 ij	18.98 l	0.662 b-g	0.602 b-f	998.22 b	1020.65 b	1.112 a	0.910 a
	Sakha 6	14.06 mn	13.88 p	0.462 jk	0.422 kl	983.83 b	1006.24 b	0.950 def	0.782 a-f
	Giza 10	21.37 f	20.83 g	0.680 a-e	0.605 b-f	986.78 b	1016.05 b	1.097 ab	0.899 a
(I_6) 45 D + As	Sakha 3	23.03 bc	22.62 d	0.707 a-d	0.630 a-e	1012.09 b	1042.14 b	1.019 a-e	0.840 a-d
	Giza 12	19.01 jk	18.90 m	0.631 e-h	0.577 e-h	1021.03 b	1047.04 b	1.029 a-d	0.862 ab
	Sakha 6	13.90 nop	13.74 r	0.444 kl	0.400 lm	1013.89 b	1036.38 b	0.858 fg	0.706 d-g
	Giza 10	21.19 fg	20.68 i	0.658 b-g	0.586 d-h	1014.49 b	1045.61 b	1.008 a-e	0.823 a-d

Correlation analysis

Correlation coefficients among straw, seed, fiber yields, water productivity, and other studied traits across the effects of irrigation regimes and flax cultivars in both growing seasons (overall) are presented in Figure 1. Positive and significant correlations ($P < 0.05$ or 0.01) were noticed among PH, SD, SY/P, SY/F, NAB/P, NC/P, NS/C, 1000-SW, SeY/P, and SeY/F traits. TL correlated significantly and positively with PH, SD, SY/P, SY/F, NC/P, NS/C, SeY/F, FY/F, and TWA traits ($P < 0.05$). TF correlated positively with FY/F ($P < 0.05$) and negatively with NAB/P, NC/P, SeY/P, and SeY/F traits ($P < 0.05$). A significant and negative correlation was observed between TWA and WP traits. Our study's findings are consistent with those of many other studies. All straw yield parameters, including fiber yield/fed, straw yield/plant, total and technical length/plant, and fiber %, exhibited positive and highly significant association coefficients with straw yield/fed, according to the results of simple correlation coefficients (EL-Shimy *et al.,* 2015). There is a favorable correlation between flax fiber and straw yield, plant height, and technical length (Fila *et al.,* 2018). Characteristics that contribute to straw yield, such as plant height, technical length, stem diameter, and total fiber yield, showed strong positive associations (Anwar *et al.,* 2025). All seed yield characteristics, including seed yield/plant, number of capsules/plant, number of seeds/capsule, 1000-seed weight, and oil content, showed positive and highly significant correlations with seed yield (EL-Shimy *et al.,* 2015; Anwar *et al.,* 2025; and Valipour *et al.,* 2025). According to Arslanoglu *et al.* (2022), there was a substantial positive link between plant density and technical length, plant height, and the yields of seeds, fiber, and straw. The degree and direction of the association between several flax properties are indicated by the correlation coefficients (Barbaś *et al.,* 2025). Consequently, it is suggested that these characteristics are closely related and might be addressed in breeding plans at the same time (Anwar *et al.,* 2025).

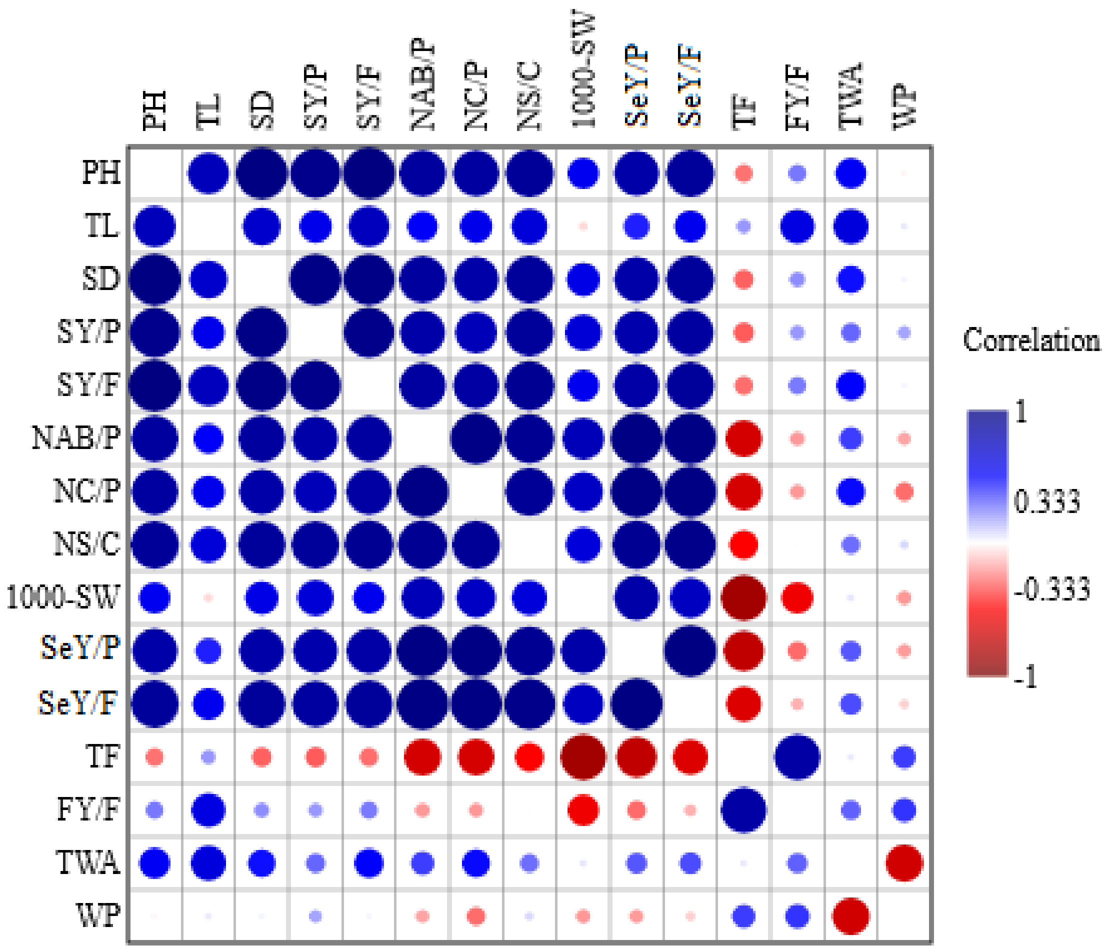

Figure 1. Correlation plot describing Pearson's correlation among straw, seed, fiber yields, water productivity, and other studied traits across the effects of irrigation regimes and flax cultivars in both growing seasons (overall). PH: Plant height (cm); TL: Technical length (cm); SD: Stem diameter (mm); SY/P: Straw yield/plant (g); SY/F: Straw yield/fed (ton); NAB/P: No. of apical branches/plant; NC/P: No. of capsules/plant; NS/C: No. of seeds/capsule; 1000-SW: 1000-seed weight (g); SeY/P: Seed yield/plant (g); SeY/F: Seed yield/fed (kg); TF: Total fiber (%); FY/F: Fiber yield/fed (ton); TWA: Total water applied (m^3/fed); WP: Water productivity (kg/m^3).

Principal component analysis (PCA)

PCA was used to assess the associations among straw, seed, fiber yields, water productivity, and other studied traits across the effects of irrigation regimes and flax cultivars, as well as their interactions in both growing seasons (overall). The eight PCAs for the investigated traits affected by the irrigation regimes and flax cultivars, as well as their interactions, are given in Table 10, which contains 100% of the total variance. The eigenvalues of the recovered first three PCs (PC1, PC2, and PC3) were more than one, with values of 9.66, 3.13, and 1.68, respectively. PC1, PC2, and PC3 account for 96.42% of the variables' overall variability under study. The eigenvalues of the other five PCs, however, were less than one (Eigenvalue <1), which accounts for 3.58% of the total variance. Based on Jan *et al.* (2018), the PCs with eigenvalue > 1 showed more variability than the PCs with eigenvalue < 1. PC1, PC2, and PC3 explained 64.38%, 20.84%, and 11.20% of the total variation of the variables under study. The first two PCs accounted for 85.22% of the total variation of the variables under investigation. According to Anwar *et al.* (2025), Aybar *et al.* (2025), and Dąbrowski *et al.* (2025), the top two PCs were shown in the PC biplot and explained a significant amount of the variance (more than 80%). While principal component analysis results under water stress conditions revealed that the first two components accounted for over 46.84% of the variance, according to Zare *et al.* (2023). Therefore, PC1 and PC2 can be used as the basis for assessing the relationship between the features being studied under the main influence of irrigation regimes and flax cultivars, as well as their interactions.

Table 10. Eigenvalue, percentage of variance (%), and cumulative% for PCs.

Principal Component Number	Eigenvalue	Percentage of Variance (%)	Cumulative (%)
PC1	9.66	64.38	64.38
PC2	3.13	20.84	85.22
PC3	1.68	11.20	96.42
PC4	0.42	2.77	99.19
PC5	0.05	0.37	99.55
PC6	0.03	0.23	99.78
PC7	0.02	0.16	99.95
PC8	0.01	0.05	100.00

The interrelationships between the flax genotypes and the assessed traits were better understood thanks to PCA (Yadav *et al.,* 2024). The relationships among the straw, seed, fiber yields, water productivity, and other studied traits were determined under the primary effects of irrigation regimes and flax cultivars by a biplot created using PC1 and PC2 (Figure 2). Although the degree and consistency of the quantity varied, most features in this study exhibited a steep angle under the effect of the experimental conditions considered, indicating a positive link between them. These findings are comparable to those of the correlation coefficient mentioned above. Based on the degree of relationship between the principal effects of irrigation regimes and flax cultivars in the biplot analysis, PC1 and PC2 mainly distributed and divided the studied traits into two groups. Seed yield would be enhanced by selecting flax genotypes with low (near-zero) PC1 and high-positive PC2 (Zare *et al.,* 2021). In the first group, the Giza 12 cultivar under I_1, I_3, and I_5 (first quarter) and the Sakha 3 and the Giza 10 cultivars (second quarter) showed a high positive association with PC2 and comprised TF, FY/F, and WP traits. As for the second group, all other examined features are strongly positively associated with Sakha 6 (fourth quarter) and Giza 12 cultivars, as well as the application of I_1, I_3, and I_5 (first quarter), which was linked to PC1. PC1 has a high percentage of variance capture, indicating that it is successful in differentiating flax genotypes based on how well they perform in straw and seed traits (Anwar *et al.,* 2025). PC1 positively correlated with all studied traits except TF, FY/F, and WP traits. The variables displayed strong positive loadings in PC1, suggesting that they can be selected simultaneously for shaping early maturing high-yielding genotypes under drought stress and that they significantly contribute to the phenotypic variability of linseed genetic resources. During drought stress, Giza 12 was the best for straw yield, Sakha 6 for seed yield, and Sakha 3 for fiber yield under 45-day + KSi treatment. This is due to their closeness. According to the criteria on which they are positioned, varieties that are close to particular qualities yield favorable outcomes (Aybar *et al.,* 2025). According to Anwar *et al.* (2025), the PC biplot effectively distinguished between genotypes linked to higher seed yield and related features on the negative side of PC1 and those linked to higher straw yield and related attributes on the positive side of PC1.

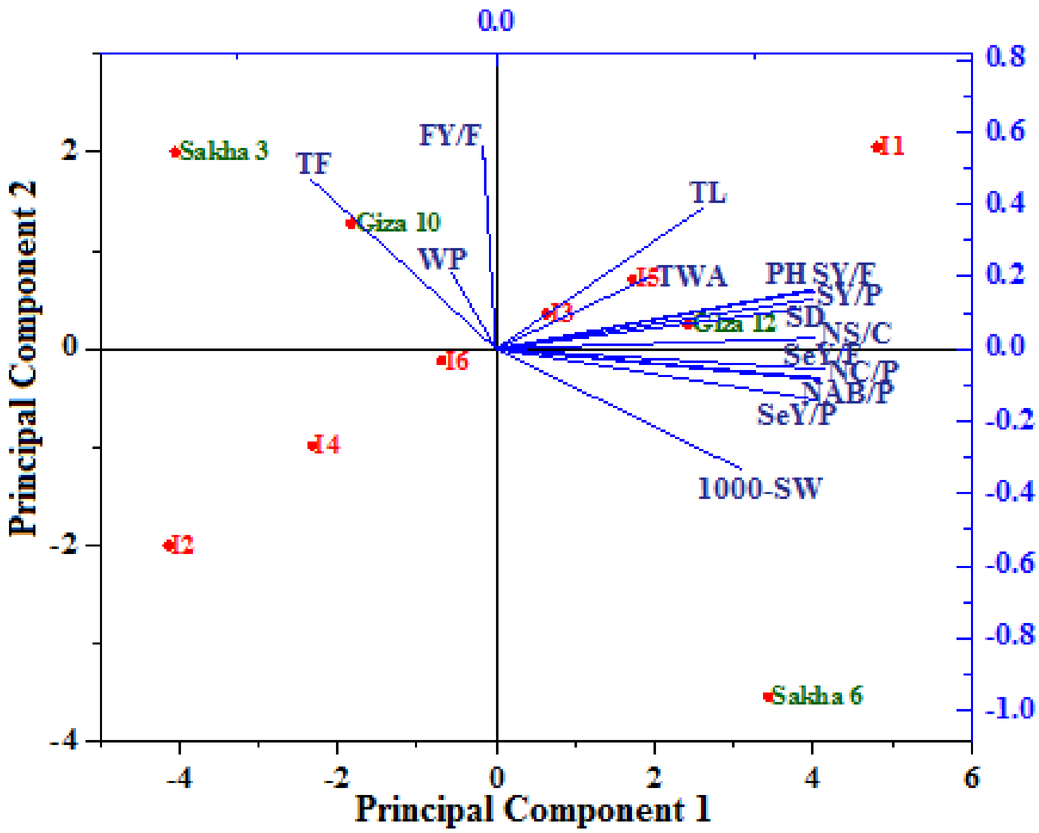

Figure 2. PCA among straw, seed, fiber yields, water productivity, and other studied traits across the effects of irrigation regimes and flax cultivars. PH: Plant height (cm); TL: Technical length (cm); SD: Stem diameter (mm); SY/P: Straw yield/plant (g); SY/F: Straw yield/fed (ton); NAB/P: No. of apical branches/plant; NC/P: No. of capsules/plant; NS/C: No. of seeds/capsule; 1000-SW: 1000-seed weight (g); SeY/P: Seed yield/plant (g); SeY/F: Seed yield/fed (kg); TF: Total fiber (%); FY/F: Fiber yield/fed (ton); TWA: Total water applied (m3/fed); WP: Water productivity (kg/m3); I_1:30 D; I_2: 45 D, I_3: 45 D + SA; I_4: 45 D + Se; I_5: 45 D + KSi; I_6: 45 D + As.

Conclusion

Application of irrigation regimes with drought tolerance substances on flax cultivars had significant effects on straw, seed, fiber yields, water productivity, and most evaluated traits in both growing seasons. Relative to the 30-day irrigation treatment (normal irrigation), deficit irrigation significantly reduced the yields of straw, seed, and fiber, along with all other assessed qualities. The application of foliar sprays containing drought-tolerant substances resulted in a marked enhancement in straw, seed, and fiber yields, along with all examined traits, compared to the absence of such application, while conserving irrigation water across both growing seasons. These findings suggest that a deficit irrigation regime combined with KSi treatment is an effective way to save water applied and improve water productivity. Furthermore, they have increased resilience to drought. The varieties differed in their characteristics. Superiority of Giza 12 cultivar for straw yield, Sakha 6 cultivar for seed output, and Sakha 3 cultivar for fiber yield, and they are suggested for growing in areas with inadequate irrigation. These results shed insight into the potential of applying KSi as a successful strategy to increase flax's tolerance to the impacts of water stress in regions that are susceptible to drought.

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تأثير الرش الورقي بمركبات تحمل الجفاف على الصفات الكمية لبعض أصناف الكتان المزروعة تحت ظروف الجفاف

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الملخص العربى

يُعد الإجهاد الناتج عن الجفاف أحد أكبر المخاطر التي تهدد الأمن الغذائي في ظل تغير المناخ. ومن المتوقع أن يؤدى تعرض محصول الكتان للجفاف إلى انخفاض صفات النمو وإنتاجية البذور والألياف وجودتها. لذا فمن الضروري تقليل الآثار الضارة لإجهاد الجفاف على إنتاجية محصول الكتان . وعليه فكان الهدف من الدراسة هو تحديد كفاءة أداء أربعة أصناف من الكتان المعرضة لإجهاد الجفاف، مع أو بدون رش الأوراق بمواد تحمل للجفاف، من حيث خصائص إنتاجية القش والبذور والألياف والمياه. وأُجريت التجارب الحقلية في محطة البحوث الزراعية بالجميزة بمحافظة الغربية بمصر خلال موسمي الشتاء ٢٠٢١/٢٠٢٠ و٢٠٢٢/٢٠٢١. وقد أثرت نظم الري وأصناف الكتان وتفاعلاتها بصورة معنوية على إنتاجية القش والبذور والألياف وإنتاجية المياه ومعظم الصفات المدروسة في كلا موسمي الزراعة. أدى تعريض الكتان للجفاف إلى انخفاض معنوى فى جميع صفات انتاجية القش والبذور والألياف، مقارنة بالرى كل ٣٠ يومًا . هذا وقد أدى الري كل ٤٥ يومًا مع الرش الورقي لمركبات تحمل الجفاف إلى تقليل تأثير الاجهاد مع زيادة معنوية في انتاجية القش والبذور والألياف والصفات المدروسة وذلك مقارنةً بالري كل ٤٥ يومًا دون رش ورقي في كلا موسمي الزراعة. وقد أسفرت المعاملة بسيلكات البوتاسيوم للنباتات التى تروى كل ٤٥ يومًا عن أعلى قيم لانتاجية القش والبذور والألياف بالإضافة إلى جميع الصفات المقيمة في كلا موسمي الزراعة وذلك عند مقارنتها بمعاملات الإجهاد الأخرى وخاصة الكنترول. أظهرت هذه النتائج الآثار المفيدة والدور الإيجابي للمعاملة بسيلكات البوتاسيوم على نمو وتطور نباتات الكتان أثناء ظروف الجفاف وقد ساهمت هذه المعاملة فى توفير ماء الرى بمعدل ٢٩,٨٦ ، ٣٠,١٦٪ خلال الموسم الأول والثانى على الترتيب، وبمقارنة الأصناف المختبرة، تحققت أعلى القيم لمحصول القش وإنتاجية المياه بزراعة صنف جيزة ١٢ ، انتاجية البذور بزراعة صنف سخا ٦، انتاجية الألياف بزراعة صنف سخا ٣. وبناءً على نتائج التفاعل بين نظم الري وأصناف الكتان وتحليل المكونات الرئيسية (PCA) ، لوحظ تفوق أصناف جيزة ١٢ في إنتاجية القش، وسخا ٦ في إنتاجية البذور، وسخا ٣ في إنتاجية الألياف، عند رشها بسيليكات البوتاسيوم ورقيًا تحت ظروف الجفاف، مقارنةً بالأصناف الأخرى التي رشت بأنواع أخرى في كلا موسمي النمو. تُلقي هذه النتائج الضوء على إمكانية تطبيق سيليكات البوتاسيوم كإستراتيجية ناجحة لزيادة قدرة نباتات الكتان على تحمل تأثير الإجهاد المائى فى المناطق المعرضة للجفاف.