THE EFFECTS OF POTASSIUM FERTILIZERS ON FLOWERING, VEGETATIVE GROWTH, AND DAUGHTER CORM YIELD OF POTTED SAFFRON

SELIEM, M. K.[1] – DEWIR, Y. H.[2*] – EL-MAHROUK, M. E.[3] – EL-RAMADY, H.[4,5] – FATHY ELBEHIRY, F.[6]

[1]*Ornamental and Floriculture Dept., Horticulture Research Institute, Antoniades, Alexandria 21599, Egypt*

[2]*Plant Production Department, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia*

[3]*Horticulture Department, Faculty of Agriculture, Kafrelsheikh University, Kafr El-Sheikh 33516, Egypt*

[4]*Institute of Animal Science, Biotechnology and Nature Conservation, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi Street, Debrecen 4032, Hungary*

[5]*Soil and Water Department, Faculty of Agriculture, Kafrelsheikh University, Kafr El-Sheikh 33516, Egypt*

[6]*Department of Basic and Applied Sciences, Higher Institute for Agricultural Cooperation, Cairo 11241, Egypt*

[*]*Corresponding author*
e-mail: ydewir@ksu.edu.sa

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Abstract. Saffron is a highly priced crop that could be potentially produced in the arid and semi-arid areas due to its low water requirements. Fertilization is an important agricultural practice that affects saffron production. Saffron productivity is mainly depending on the number of produced stigma and desirable size of daughter corms. Therefore, the current study was carried out to investigate two different potassium-fertilizers (K-silicate and K-sulphate) at four applied doses (0.5, 1.0, 1.5, and 2.0 g L^{-1}) on growth and productivity of two corm sizes (2.2 – 2.5 and 3.2 – 3.5 cm diameter) of potted saffron. Flowering parameters (number of flowers per plant, and stigma fresh and dry weight) and vegetative growth parameters (plant height, number of leaves, plant fresh and dry weight, and root fresh and dry weight) were recorded. K-silicate fertilizer exhibited the highest values in terms of flowering and vegetative growth parameters compared to K-sulphate, especially when utilizing larger corm sizes. However, a lower dosage of K-sulphate (0.5 g. L^{-1}) enhanced the fresh weight of the stigma. Both sources of potassium improved root growth when compared to the control. Similarly, the utilization of K-silicate fertilizers resulted in higher values of nutrient content and uptake by leaves, corm diameter, and corm fresh weight. Saffron plants that were fertilized with K-sulphate demonstrated higher values of chlorophyll fluorescence and the total number of daughter corms compared to those fertilized with K-silicate, with a preference for larger corm sizes. Our findings indicate that there is a correlation between the type of K-fertilizer and corm size in saffron production. Additionally, a significant improvement in growth and yield of potted saffron was observed with the application of K-silicate.

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Introduction

Saffron (*Crocus sativus* L.) is a perennial plant with medicinal properties, renowned worldwide for its significant economic value as a spice. This particular crop, commonly referred to as "red gold," thrives in arid and semi-arid regions characterized by high altitudes, cold winters, low annual rainfall, and hot summers (Azari et al., 2023). Saffron finds various applications in agriculture, medicine, and nutrition, serving diverse industries such as cosmetics, fabric dyeing, perfumery, decorative fibers, and colored papers (Koocheki and Khajeh-Hosseini, 2020; Jazani et al., 2022). Recently, saffron has gained significant attention as the most expensive agricultural commodity, prompting numerous researchers to focus on exploring its medicinal properties (Sarwat et al., 2020), technological potential (Koocheki and Khajeh-Hosseini, 2020), and genome (Vakhlu et al., 2022). The primary method of propagating saffron involves the use of corms, which provide all the necessary nutrients for flower production in the initial year (Esmaeilian et al., 2022a). Additionally, saffron exhibits low water requirements, minimal fertilizer needs, and can thrive in a wide range of soil textures, from sandy to sandy/loamy, thereby facilitating high-quality yield (Shajari et al., 2020; Esmaeilian et al., 2022b; Aboueshaghi et al., 2023; El-Mahrouk et al., 2023). However, challenges faced by saffron production include high labor costs, low productivity, insufficient adoption of agricultural practices (particularly in irrigation and fertilization programs), and unpredictable climatic conditions (Hourani, 2022).

Recently, there has been an escalated concern regarding the fertilization methods employed in the cultivation of saffron. This concern has primarily revolved around various issues associated with this agricultural practice. These issues include the utilization of fertilizers to enhance saffron productivity (Hourani, 2022), the management of nutrients to improve saffron quality (Shajari et al., 2022; Azari et al., 2023), the implementation of fertilizers in saffron organic farming (Esmaeilian et al., 2022a), the application of biofertilizers in field conditions (Chamkhi et al., 2023), the utilization of organic wastes and protective osmolytes to mitigate P deficiency stress in calcareous soils (Afshari et al., 2023), and the potential of organic fertilizers under drought stress (Aboueshaghi et al., 2023). Numerous published articles have delved into these matters in order to ascertain the appropriate quantity and type of fertilizers for saffron cultivation. Some of these articles have focused on organic fertilizers such as humic acid (Shajari et al., 2022), the combination of manure and biological fertilizers (Esmaeilian et al., 2022a), mineral fertilizers (Khorramdel et al., 2015; Azari et al., 2023), and nano-based nutrients (Rikabad et al., 2019; Mahmoodi et al., 2021; Khoshpeyk et al., 2022).

Several studies have established that the productivity of saffron corms and the yield of flowers are contingent upon the nutrient content of the growing media and the application of amendments (Dewir et al., 2022a,b; Esmaeilian et al., 2022b; Hourani, 2022; El-Mahrouk et al., 2023). Numerous researchers have attested to the significance of potassium fertilizers as a vital source for providing saffron plants with the necessary potassium (Zabihi and Feizi, 2014; Basatpour et al., 2022; Johnson et al., 2022). Potassium serves as an essential nutrient in regulating various biological processes in plants, acting as a principal constituent in over 60 enzymes that govern plant growth and productivity, particularly in the face of stress (Johnson et al., 2022). It is reported that K can stimulate saffron flowering and mitigate the higher yield under stressful conditions by increasing yield and yield components of flowers and corms (Hourani, 2022).

Saffron exhibits great potential as a promising crop for cultivation in arid and semi-arid regions, provided that the necessary cold requirements are fulfilled. However, it is imperative to possess a comprehensive understanding of various agricultural practices, particularly in regards to the fertilization needs. Consequently, the present research endeavor sought to assess the influence of diverse sources of potassium fertilizers and their respective application rates on the yield and quality of potted saffron. This investigation also incorporated two distinct corm sizes, namely 2.2 – 2.5 cm and 3.2 – 3.5 cm in diameter, in order to provide a comprehensive analysis.

Materials and Methods

Plant materials

Saffron corms of varying sizes, specifically 2.2-2.5 and 3.2-3.5 cm in diameter, along with corresponding circumferences of 7-8 and 10-11 cm, were procured from Bloembollenbedrijf J. C. Koot, located in Vennewatersweg, The Netherlands. These corms underwent peeling and were subsequently subjected to a fungicide treatment using a solution containing 0.5 g L^{-1} of Rizolex-T 50% WP. This particular solution comprises 20% (w/w) Tolclofos-methyl and 30% (w/w) thiuram and is manufactured by the Kafr El-Zayat Company in El-Gharbia, Egypt. The purpose of this treatment was to safeguard against any potential fungal infestation. Subsequently, the corms were dried before being planted.

Fertilizer treatments and growth conditions

Saffron corms were planted in plastic pots with a diameter of 12 cm, with one corm per pot. These pots were filled with a mixture of peatmoss and foam in a 1:1 ratio. The transplantation of the corms took place on November 15, 2021, in the open field of Kafr El-Zayat city. Subsequently, the plants were cultivated for a duration of 18 weeks, during which daughter corms were harvested. Following a period of fifteen days after cultivation, the plants were subjected to weekly sprayings with varying doses of potassium silicate and potassium sulfate. These doses included concentrations of 0.0, 0.5, 1.0, 1.5, and 2.0 g L^{-1} for both K-fertilizers. Fertilization was implemented via water irrigation, conducted once in the months of December, January, and February, and twice in the months of March, April, and May. The solution of fertilizers was prepared by dissolving 0.25 grams per liter of complete fertilizer with a composition of Nitrogen, Phosphorus, and Potassium in the ratio of 19:19:19, along with the addition of the following fertilizers: 0.2 grams per liter of Calcium Nitrate ($CaNO_3$), 0.15 grams per liter of Magnesium Sulfate ($MgSO_4$), and 0.1 grams per liter of chelated micro-nutrients. This solution was thoroughly dissolved in a tank and subsequently applied directly to the experimental plots during the irrigation process (*Table 1, Figure 1*). The experimental pots were subjected to irrigation every 7 to 10 days from November to March, and every 4 to 6 days in the month of April. In May, the pots were manually irrigated every 2 to 3 days using a 10-liter watering can. Changes in atmospheric temperature, moisture levels, and precipitation were documented (*Figure 2*; https://www.worldweatheronline.com/kafr-el-zayat-weather-history/al-gharbiyah/eg.aspx). Weeding was performed by hand during the growing period. Crust breaking operations were applied using a trowel after both full

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flower harvests. A thorough examination revealed the absence of any disease or insect infestation; thus, no control chemicals were utilized.

Table 1. *List of used fertilizers that were applied to saffron during the study, and their composition and sources*

Fertilizer type	Nutrient content in fertilizer (%)	Source or the company
Potassium sulfate (K_2SO_4)	K_2O= 50 and S= 17%	Evergrow company, El-Giza, Egypt
Potassium silicate (K_2SiO_3)	K_2O = 61 %, and SiO_2=38.95%	Technogen, Cairo, Egypt
Calcium nitrate ($CaNO_3$)	N= 15.5 and CaO = 26.3%	Yara company, Cairo, Egypt
Magnesium sulfate ($MgSO_4$)	Mg= 16 and S= 12.5%	Queisna for Agriculture Development, Menofia, Egypt
Chelated microelements	Fe= 4; Zn= 4; Mn= 3; Cu= 0.1; B= 1.5 and Mo= 0.5%	Queisna for Agriculture Development, Menofia, Egypt
Complete fertilizer	N: P_2O_5: K_2O= 19:19:19 %	Yara company, Cairo, Egypt

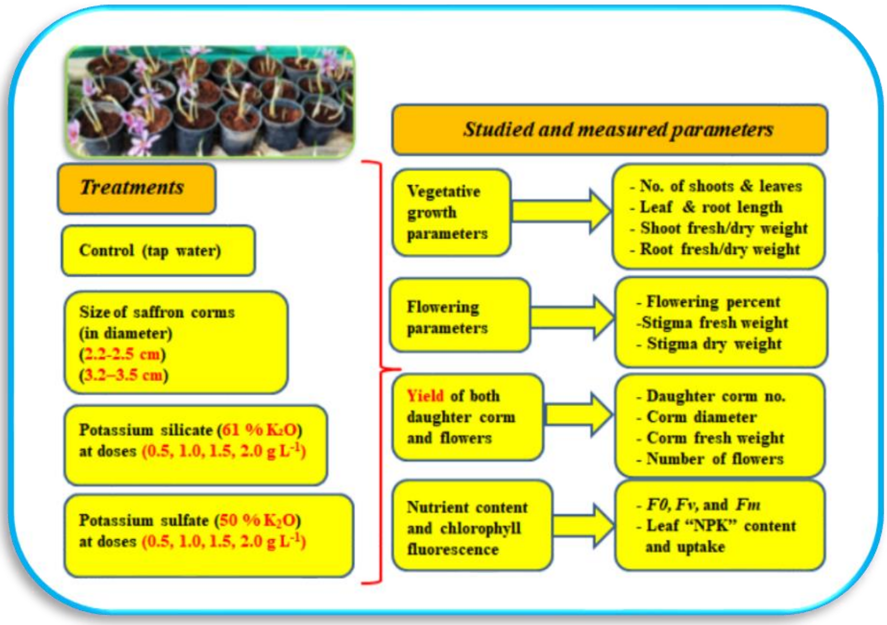

Figure 1. *An overview on the experimental design, treatments, and applied doses of K-fertilizers*

Measurements of flowering and growth parameters

The evaluation of flowering parameters, specifically the count of flowers per plant and the fresh and dry weight of the stigma, was conducted 29 days subsequent to the transplantation of the corm. Furthermore, the duration of the flowering period was observed to span a total of 8 days. In order to determine the dry weight of the stigma, it was dried for 1 hour at a temperature of 40 °C, as stated by Dewir et al. (2022a) and Maggio et al. (2006). On the other hand, the assessment of vegetative growth parameters, encompassing plant height, leaf count, fresh and dry weight of the plant, and fresh and dry weight of the root, was performed 9 weeks subsequent to the sprouting of the corm.

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The dry weight of both the plant and root were determined after being subjected to an oven drying procedure for a total of 48 hours, with the temperature set at 65 °C. Following the occurrence of leaf senescence, the plants were extracted from the ground, the mother corm sections were eliminated, and the daughter corms were separated. Subsequently, the evaluation of corm formation parameters, including the count of corms per plant, the diameter of the corm, and the fresh weight of the corm, was carried out 18 weeks after the sprouting of the corm.

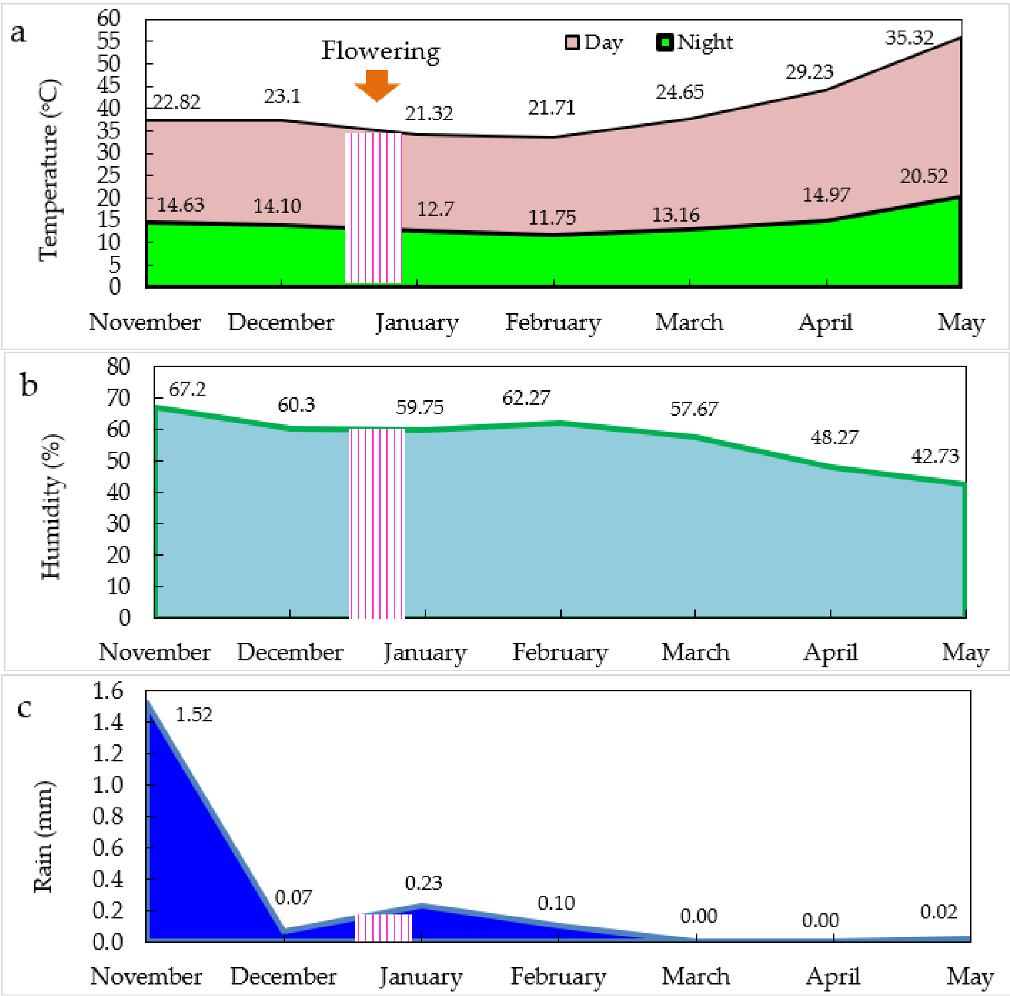

Figure 2. *Changes in the average diurnal and nocturnal temperature (a), atmospheric moisture content (b) and rainfall (c) from November, 2020 through May 2021*

Determination of chlorophyll fluorescence

Chlorophyll fluorescence parameters were assessed on the abaxial surface of freshly obtained leaf samples, with the additional step of subjecting the plants to a period of 30 minutes of darkness prior to measurement. The fluorescence was analyzed using a portable chlorophyll fluorescence instrument (OS30P, Labo Amirica, USA). The initial fluorescence (F0) was measured for a duration of 30 minutes in leaves that were adapted to darkness, utilizing light of an intensity lower than 0.1 µmol m^{-2} s^{-1}, while the maximum fluorescence (Fm) was measured after applying a saturating pulse of light

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(> 3500 µmol m^{-2} s^{-1}) for one second (s) on the same leaves. The maximal variable fluorescence (Fv = Fm - F0) and the photochemical efficiency of photosystem II (Fv/Fm) were calculated for the dark-adapted leaves, following the methodology described by Dewir et al. (2005), using a random selection of three plants, specifically the fully expanded young leaves, and employing a standard leaf chamber. Each treatment consisted of three separate replications, each involving a single leaf.

Plant chemical composition

Plant samples (leaves, corms, and roots) were oven-dried at 65 °C for 48 h. Dry samples were ground to a homogenous powder in a metal-free mill (IKa-Werke, M 20, Staufen, Germany). Concentrated sulfuric acid (95%, 5 mL) was added to plant sample (0.2 g), and the mixture was heated for 10 min on a sand hotplate. Then, 0.5 mL of perchloric acid was added, and heating was continued until a clear solution was obtained. The solution was left to cool before it was filtered and diluted to 50 mL with distilled water. The digested samples were prepared for nitrogen measurement (%) using a modified micro-Kjeldahl method., whereas P (%) and K (%) were measured colorimetrically using a spectrophotometer (GT 80+, Leicestershire, UK), and using an atomic absorption spectrophotometer (Avanta E; GBC, Victoria, Australia), respectively according to Sparks et al. (2020). The nutrient uptake (NPK) by leaves was calculated using the following equation:

$$\text{Nutrient uptake} = \text{Leaf dry weight} \times \text{nutrient concentration} \qquad \text{(Eq.1)}$$

Experimental design and statistical analyses

The experiment was set up in a factorial completely randomized design with three factors (two corms size, two fertilizers and five applied doses). Each treatment had 3 replicates and each replicate was represented by 6 pots; each pot contained one plant. The mean separations were performed using Tukey’s multiple range test using the SAS program (SAS ver. 9.4; SAS Institute, Cary, NC). Principal component analysis (PCA) with clustering was performed to integrate growth and yield parameters with different treatments and explain the largest proportion of variability among variables. This analysis was carried out using the XLSTAT statistical package software (Ver. 2019.1, Excel Add-ins soft SARL, New York, NY, USA).

Results

Response of flowering to corm size and applied K-fertilizers

Corm size and K fertilizers significantly influenced the flowering parameters (i.e., flowering percentage, number of flowers per plant, the fresh and dry weight of stigma) (*Table 2*). The corm size of 3.2 – 3.5 cm diameter recorded higher values of flowering parameters compared to the smaller corm size (2.2 – 2.5 cm). Potassium silicate dose of 1-1.5 mg L^{-1} recorded highest values of number of flowers (2.33 and 2.0, respectively) while1.5 mg L^{-1} recorded the highest stigma dry weight (5.933 mg). Potassium sulphate at doses ≥ 0.5 mg L^{-1} recorded lower values of flowering parameters as compared with their respective doses of potassium silicate.

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Table 2. *Effect corm size, potassium silicate and sulfate on flowering of saffron*

Corm size	Fertilizer type	Foliar dose (g L^{-1})	Flowering (%)	Number of flowers	Stigma fresh weight (mg)	Stigma dry weight (mg)
2.2 -2.5 cm diameter	Control	0.0	0.00 g	0.00 e	0.000 d	0.000 f
	K_2SiO_3	0.5	0.00 g	0.00 e	0.000 d	0.000 f
		1.0	0.00 g	0.00 e	0.000 d	0.000 f
		1.5	0.00 g	0.00 e	0.000 d	0.000 f
		2.0	0.00 g	0.00 e	0.000 d	0.000 f
	K_2SO_4	0.5	0.00 g	0.00 e	0.000 d	0.000 f
		1.0	0.00 g	0.00 e	0.000 d	0.000 f
		1.5	0.00 g	0.00 e	0.000 d	0.000 f
		2.0	0.00 g	0.00 e	0.000 d	0.000 f
3.2 -3.5 cm diameter	Control	0.0	81.67 c	1.33 cd	0.021 bc	5.733 ab
	K_2SiO_3	0.5	100.00 a	1.67 bc	0.025 ab	3.633 d
		1.0	76.67 c	2.33 a	0.023 abc	5.333 b
		1.5	96.67 ab	2.00 ab	0.022 abc	5.933 a
		2.0	93.33 b	1.33 cd	0.019 c	4.033 cd
	K_2SO_4	0.5	61.67 e	1.00 d	0.027 a	4.100 c
		1.0	41.67 f	1.00 d	0.018 c	1.100 e
		1.5	68.33 d	1.33 cd	0.019 c	1.233 e
		2.0	63.33 de	1.00 d	0.019 c	0.850 e
***P*-values**						
Corm size			<.0001***	<.0001***	<.0001***	<.0001***
Fertilizer type			<.0001***	<.0001***	0.3208 NS	<.0001***
Fertilizer doses			<.0001***	0.1015 NS	0.0090**	<.0001***
Corm size × Fertilizer type			<.0001***	<.0001***	0.3208 NS	<.0001***
Corm size × fertilizer doses			<.0001***	0.1015 NS	0.0090**	<.0001***
Fertilizer type × Fertilizer doses			0.2095NS	0.2126 NS	0.4113 NS	<.0001***
Corm size × Fertilizer type × Fertilizer doses			0.2095 NS	0.2126 NS	0.4113 NS	<.0001***

Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test. NS, ** and ***= nonsignificant, significant at $P \leq 0.01$ and $P \leq 0.001$, respectively

Response of saffron vegetative growth to corm size and applied K-fertilizers

The number of leaves and shoots of the big size of saffron corm were higher comparing with the small size under different applied potassium fertilizers (*Table 3*). The same trend was observed also in general for the leaf length besides both fresh and dry weight of shoots. For all studied vegetative growth parameters, there is no continues increase after applying different doses of potassium fertilizers, but a slight increase, then decrease. Interestingly, there is a highly significant difference among the combined interactions of

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treatments for both fresh and dry shoot weight. The highest values of leaf length, shoot fresh and dry weight (28.67, 27.53, and 7.59, respectively) were recorded after applying dose of 0.5 g L^{-1} K_2SiO_3 for the bigger corm size (3.2 – 3.5 cm diameter), whereas the highest number of leaves was resulted by 2.0 g L^{-1} K_2SiO_3 treatment.

Table 3. *Effect of corm size, potassium silicate and sulfate on vegetative growth of saffron*

Corm size	Fertilizer type	Foliar dose (g L^{-1})	Number of shoots	Number of leaves	Leaf length (cm)	Shoot fresh weight (g)	Shoot dry weight (g)
2.2 -2.5 cm diameter	Control	0.0	4.67 efg	5.67 ef	25.33 bcd	7.55 l	1.90 hi
	K_2SiO_3	0.5	5.00 def	6.33 e	25.33 bcd	6.86 m	1.93 hi
		1.0	5.00 def	6.33 e	25.00 bcde	6.66 m	1.76 ij
		1.5	4.00 g	6.33 e	24.33 cde	9.30 i	2.16 g
		2.0	3.00 h	6.00 ef	26.33 bc	8.30 jk	1.99 gh
	K_2SO_4	0.5	4.00 g	5.67 ef	21.00 fg	7.97 kl	1.60 j
		1.0	4.67 efg	5.67 ef	20.33 g	8.57 j	1.60 j
		1.5	4.33 fg	5.33 f	23.00 ef	8.40 jk	1.89 hi
		2.0	4.33 fg	6.00 ef	25.67 bcd	9.73 i	2.20 g
3.2 -3.5 cm diameter	Control	0.0	5.00 def	9.00 cd	25.33 bcd	19.57 d	5.03 b
	K_2SiO_3	0.5	5.00 def	10.33 ab	28.67 a	27.53 a	7.59 a
		1.0	5.67 bcd	9.67 bc	26.33 bc	20.16 c	4.64 c
		1.5	6.00 abc	10.00 ab	25.33 bcd	19.10 e	4.16 d
		2.0	5.67 bcd	10.33 ab	27.00 ab	17.80 g	4.56 c
	K_2SO_4	0.5	5.33 cde	8.67 d	27.00 ab	18.63 f	3.60 e
		1.0	6.33 ab	10.00 ab	25.67 bcd	20.45 c	4.51 c
		1.5	6.00 abc	10.00 ab	25.33 bcd	14.55 h	3.03 f
		2.0	6.67 a	10.67 a	24.00 de	20.94 b	4.53 c
***P*-values**							
Corm size			<.0001***	<.0001***	<.0001***	<.0001***	<.0001***
Fertilizer type			0.0427*	0.0117*	<.0001***	<.0001***	<.0001***
Fertilizer doses			0.0270*	0.1653 NS	0.0460*	<.0001***	<.0001***
Corm size × Fertilizer type			0.1415 NS	0.2930 NS	0.0940NS	<.0001***	<.0001***
Corm size × fertilizer doses			0.0003***	0.1487 NS	0.0007***	<.0001***	<.0001***
Fertilizer type × Fertilizer doses			0.0050**	0.0316*	0.2076NS	<.0001***	<.0001***
Corm size × Fertilizer type × Fertilizer doses			0.0759 NS	0.0976 NS	0.0582NS	<.0001***	<.0001***

Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test. NS, *, ** and ***= nonsignificant, significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively

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Response of saffron root growth to corm size and applied K-fertilizers

All studied fibrous root growth parameters have a positive response after applying K-fertilizers and higher in case of the bigger size of corm (3.2 – 3.5 cm) comparing to the smaller size (2.2 – 2.5 cm), as tabulated in *Table 4*. Under the same size of saffron corm, the obtained results after applying K-sulphate in general were higher than K-silicate. After applying the increased doses of K-fertilizers, the recorded root parameters did not take a stable trend among all treatments. Impacts of different doses of potassium fertilizers under the studied size of saffron corm on could be noticed in both vegetative and corm growth.

***Table 4.** Effect of K-silicate and sulfate on fibrous root growth of two corm sizes of saffron*

Corm size	Fertilizer type	Foliar dose (g L^{-1})	Root fresh weight (g)	Number of roots	Root length (cm)	Root dry weight (g)
2.2 -2.5 cm diameter	Control	0.0	1.56 j	72.67 de	8.03 i	0.157 i
	K_2SiO_3	0.5	2.20 i	53.67 g	12.50 f	0.207 h
		1.0	2.43 hi	57.67 g	11.13 gh	0.280 g
		1.5	3.73 f	87.67 c	15.00 de	0.373 f
		2.0	4.23 e	59.00 g	17.00 b	0.427 e
	K_2SO_4	0.5	4.03 e	74.67 de	10.67 h	0.433 e
		1.0	3.76 f	76.00 de	12.03 fg	0.303 g
		1.5	2.53 h	53.67 g	12.40 f	0.310 g
		2.0	3.09 g	71.00 e	15.67 d	0.220 h
3.2 -3.5 cm diameter	Control	0.0	4.17 e	97.67 b	10.93 gh	0.490 d
	K_2SiO_3	0.5	6.13 b	95.67 b	14.83 de	0.680 a
		1.0	6.36 ab	89.00 c	12.50 f	0.593 c
		1.5	5.70 c	104.33 a	15.50 d	0.627 bc
		2.0	4.53 d	95.33 b	15.83 cd	0.647 ab
	K_2SO_4	0.5	5.53 c	97.33 b	16.83 bc	0.680 a
		1.0	6.48 a	108.67 a	14.07 e	0.630 bc
		1.5	3.19 g	65.33 f	10.03 h	0.193 hi
		2.0	3.31 g	77.00 d	18.93 a	0.620 bc
***P*-values**						
Corm size			<.0001***	<.0001***	<.0001***	<.0001***
Fertilizer type			<.0001***	0.0089**	0.0308*	<.0001***
Fertilizer doses			<.0001***	<.0001***	<.0001***	<.0001***
Corm size × Fertilizer type			<.0001***	<.0001***	0.0007***	<.0001***
Corm size × fertilizer doses			<.0001***	<.0001***	<.0001***	<.0001***
Fertilizer type × Fertilizer doses			<.0001***	<.0001***	<.0001***	<.0001***
Corm size × Fertilizer type × Fertilizer doses			<.0001***	<.0001***	<.0001***	<.0001***

Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test *, ** and ***= significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively

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Response of saffron daughter corm formation to corm size and applied K-fertilizers

As daughter corms formation are important component of saffron yield, their weight and size were measured at harvest to evaluate their response to applied K-fertilizers (*Table 5*). Total number of daughter corms, diameter and fresh weight were the main measured parameters. Production of saffron corms is needed when the size of daughter corms will be more than 2 mm for the cultivation in the next season. The applying K-fertilizers increased the obtained saffron corm parameters with priority to the bigger size than the smaller one. All studied parameters of saffron corm recorded the highest values for the bigger size (3.2 -3.5) than the smaller one. Corm fresh weight was the only parameter, which recorded by all combined interactions in a highly significant difference, whereas most non-significant responses within these combined interactions were recorded for the daughter corms (≥ 2 mm).

Table 5. *Effect of corm size, potassium silicate and sulfate on daughter corm formation of saffron*

Corm size	Fertilizer type	Foliar doses (g L^{-1})	Total number of daughter corms	Daughter corms (≥ 2 mm)	Corm diameter (mm)	Corm fresh weight (g)
2.2 -2.5 cm diameter	Control	0.0	3.00 cdef	0.67 c	11.54 h	1.317 k
	K_2SiO_3	0.5	2.67 def	1.00 bc	12.90 g	1.356 jk
		1.0	3.00 cdef	1.00 bc	13.43 f	2.047 f
		1.5	3.67 bcdef	1.00 bc	11.76 h	1.483 i
		2.0	2.00 f	1.00 bc	12.82 g	1.924 g
	K_2SO_4	0.5	2.33 ef	1.00 bc	14.82 e	1.765 h
		1.0	3.67 bcdef	0.67 c	11.07 h	1.399 j
		1.5	2.00 f	1.33 abc	16.47 c	2.855 b
		2.0	2.33 ef	1.00 bc	12.66 g	1.873 g
3.2 -3.5 cm diameter	Control	0.0	4.00 abcde	2.00 a	15.42 d	2.306 d
	K_2SiO_3	0.5	4.00 abcde	1.33 abc	16.83 c	2.232 e
		1.0	2.33 ef	1.67 ab	19.98 a	3.750 a
		1.5	4.67 abc	1.33 abc	15.43 d	2.008 f
		2.0	4.33 abcd	1.00 bc	14.51 e	1.727 h
	K_2SO_4	0.5	5.67 a	1.33 abc	14.53 e	1.460 i
		1.0	4.67 abc	1.33 abc	13.86 f	1.346 jk
		1.5	3.33 bcdef	1.33 abc	17.92 b	2.643 c
		2.0	5.00 ab	1.67 ab	15.74 d	2.028 f
***P*-values**						
Corm size			<.0001***	0.0052**	<.0001***	<.0001***
Fertilizer type			0.3435 NS	0.7411 NS	0.1456 NS	<.0001***
Fertilizer doses			0.9160 NS	0.9530 NS	<.0001***	<.0001***
Corm size × Fertilizer type			0.0836 NS	0.7411 NS	<.0001***	<.0001***
Corm size × fertilizer doses			0.0349*	0.5568 NS	<.0001***	<.0001***
Fertilizer type × Fertilizer doses			0.0106*	0.2926 NS	<.0001***	<.0001***
Corm size × Fertilizer type × Fertilizer doses			0.6702 NS	0.5568 NS	<.0001***	<.0001***

Values followed by the same letter in the same column are not significantly different at P ≤ 0.05 level, according to Tukey's multiple range test. NS, *, ** and ***= nonsignificant, significant at P ≤ 0.05, P ≤ 0.01 and P ≤ 0.001, respectively

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Response of chlorophyll fluorescence to corm size and applied fertilizers

The response of chlorophyll fluorescence in saffron leaves to corm size and applied different doses of K-fertilizers is presented in *Figure 3*. Applied doses of potassium sulphate recorded the significant higher values of chlorophyll fluorescence in saffron leaves compared to potassium silicate, with priority to the bigger corm size. The significant highest values (up to 0.78 and 0.77) were obtained after applying the dose of 1.0 and 2.0 g L^{-1} potassium sulphate using the bigger corm size. Under low applied K doses (control and 0.5 g L^{-1}), chlorophyll fluorescence values in saffron leaves were higher for the smaller corm size comparing with biggest one, whereas the higher applied K doses recorded the opposite results for both applied K-fertilizers.

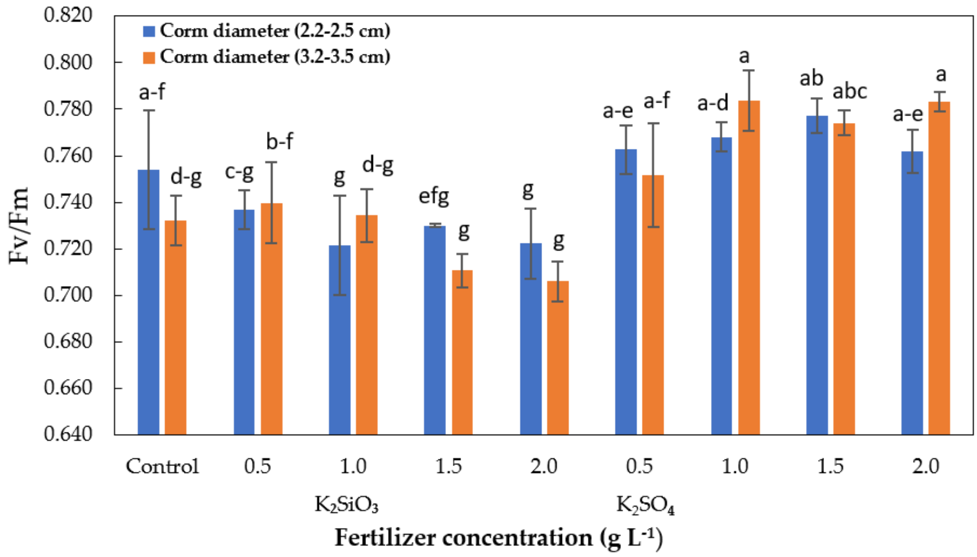

Figure 3. *Effect of different applied doses of potassium fertilizers (silicate and sulfate) on Fv/Fm of two bulb size (2.2 -2.5 and 3.2-3.5) of saffron. Data presented are means ± standard error. Values followed by the same letter in the same column are not significantly different at P ≤ 0.05 level*

Impact of applied fertilizers on nutrient contents and uptake by saffron leaves

In general, applying K-fertilizers led to increase saffron leaf content of nutrients, especially the K content in leaves for both used corm sizes, whereas the K-higher values belonged the bigger corm size (*Table 6*). Under different applied K-fertilizers, the applied dose of 2.0 g L^{-1} of both K-fertilizers recorded the highest K contents in saffron leaves for two corm sizes (0.48 and 0.45% for the first and second size, respectively). This same trend was observed somehow for the N content, whereas this trend was not clear for P contents in saffron leaves under different corm size and applied K-fertilizers. Concerning N content in saffron leaves, the highest values (3.03 and 3.35 %) were recorded for the bigger corm size and 1.72 and 1.41 % for smaller one after applying dose of 1.5 g L^{-1} for both K silicate and sulphate, respectively for both corm sizes. Regarding saffron P content in leaves, almost all combined interactions were in a highly significant difference followed by N and K contents, respectively.

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Table 6. *Effect of corm size, potassium silicate and sulfate on NPK content (%) of saffron leaves*

Corm size	Fertilizer type	Foliar doses (g L^{-1})	N (%)	P (%)	K (%)
2.2 -2.5 cm diameter	Control	0.0	1.04 i	0.260 bc	0.42 i
	K_2SiO_3	0.5	0.99 i	0.215 g	0.43 gh
		1.0	1.04 i	0.250 bcd	0.45 cd
		1.5	1.68 g	0.227 def	0.47 b
		2.0	1.72 g	0.231 fg	0.48 a
	K_2SO_4	0.5	1.59 gh	0.306 a	0.44 efg
		1.0	2.36 e	0.246 cdef	0.44 ef
		1.5	1.61 gh	0.190 h	0.44 fg
		2.0	1.41 h	0.191 h	0.45 de
3.2 -3.5 cm diameter	Control	0.0	2.45 de	0.190 h	0.43 hi
	K_2SiO_3	0.5	2.81 bc	0.196 h	0.42 i
		1.0	2.26 e	0.266 b	0.44 efg
		1.5	3.03 b	0.241 def	0.47 b
		2.0	1.96 f	0.186 h	0.48 a
	K_2SO_4	0.5	2.66 cd	0.266 bcd	0.44 fgh
		1.0	2.98 b	0.261 bc	0.44 efg
		1.5	3.35 a	0.248 cde	0.46 cd
		2.0	1.77 fg	0.233 ef	0.46 bc
***P*-values**					
Corm size			<.0001***	0.6451 NS	0.9581 NS
Fertilizer type			<.0001***	0.0001***	<.0001***
Fertilizer doses			<.0001***	<.0001***	<.0001***
Corm size × Fertilizer type			0.0213 *	<.0001***	0.0054**
Corm size × fertilizer doses			<.0001***	<.0001***	0.0004***
Fertilizer type × Fertilizer doses			<.0001***	<.0001***	<.0001***
Corm size × Fertilizer type × Fertilizer doses			<.0001***	<.0001***	0.8555 NS

Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test. NS, ** and ***= nonsignificant, significant $P \leq 0.01$ and $P \leq 0.001$, respectively

The total uptake of studied nutrients (NPK) by saffron leaves was calculated and presented in *Table 7*. In general, the K-uptake by saffron leaves increased by increasing applied K-fertilizer doses for both two corm sizes. The highest values in K uptake by saffron leaves (1257 and 1212 mg kg^{-1} as well as 4060 and 2542 mg kg^{-1}, for the small and big corm size, respectively) were obtained after applying both K-fertilizers. These previous values were obtained after applying K-silicate at dose of 1.5 and 2.0 g L^{-1}, and 1.0 and 2.0 g L^{-1} of K-sulphate for smaller and bigger corm size, respectively. All combined interactions were in a highly significant difference for the uptake of N and K by saffron leaves, whereas this trend was achieved only for corm size for P uptake.

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Table 7. *Effect of corm size, potassium silicate and potassium sulfate on NPK uptake (mg kg^{-1} dry weight) by saffron leaves*

Corm size	Fertilizer type	Foliar doses (g L^{-1})	N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
2.2 -2.5 cm diameter	Control	0.0	197 kl	50.0 fg	981 l
	K_2SiO_3	0.5	192 l	41.6 g	1024 k
		1.0	183 l	44.4 g	979 l
		1.5	363 hi	50.0 fg	1257 h
		2.0	341 hi	47.2 g	1169 j
	K_2SO_4	0.5	255 jk	50.0 fg	864 m
		1.0	377 h	38.8 g	868 m
		1.5	305 ij	36.1 g	1024 k
		2.0	312 ij	41.6 g	1212 i
3.2 -3.5 cm diameter	Control	0.0	1234 c	97.2 cde	2630 b
	K_2SiO_3	0.5	2133 a	150.0 a	2579 c
		1.0	1050 d	125.0 ab	4060 a
		1.5	1261 c	100.0 bcde	2636 b
		2.0	894 f	86.1 de	2479 d
	K_2SO_4	0.5	958 e	97.2 cde	1922 f
		1.0	1344 b	116.6 bc	2435 e
		1.5	1016 de	75.0 ef	1671 g
		2.0	802 g	105.5 bcd	2542 c
***P*-values**					
Corm size			<.0001***	0.0325 *	<.0001***
Fertilizer type			<.0001***	0.2345 NS	<.0001***
Fertilizer doses			<.0001***	0.2928 NS	<.0001***
Corm size × Fertilizer type			<.0001***	0.2665 NS	<.0001***
Corm size × fertilizer doses			<.0001***	0.3115 NS	<.0001***
Fertilizer type × Fertilizer doses			<.0001***	0.3290 NS	<.0001***
Corm size × Fertilizer type × Fertilizer doses			<.0001***	0.2705 NS	<.0001***

Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test. NS, * and ***= nonsignificant, significant at $P \leq 0.05$ and $P \leq 0.001$, respectively

Principle component analysis

The PCA biplot of flowering, vegetative growth and daughter corms formation parameters visually represents that the first and second components account for 71.40% variability observed among all parameters when considering both corm size and K-fertilizer treatments (*Figure 4*). Specifically, the first component accounts for 60.25% of the variability, while the second component accounts for 11.15% of the variability among the parameters. K-fertilizer exhibited strong correlation with big size of saffron corms (corm size 3.2 -3.5 cm diameter; S2) rather than the small corm size (corm size 2.2 -2.5 cm diameter; S1). Furthermore, the biplot from the PCA analysis demonstrates that the vegetative parameters exhibit positive correlation with one another and with uptake of N, P and K and content of N rather than content of P and K. P content was negatively correlated with other parameters.

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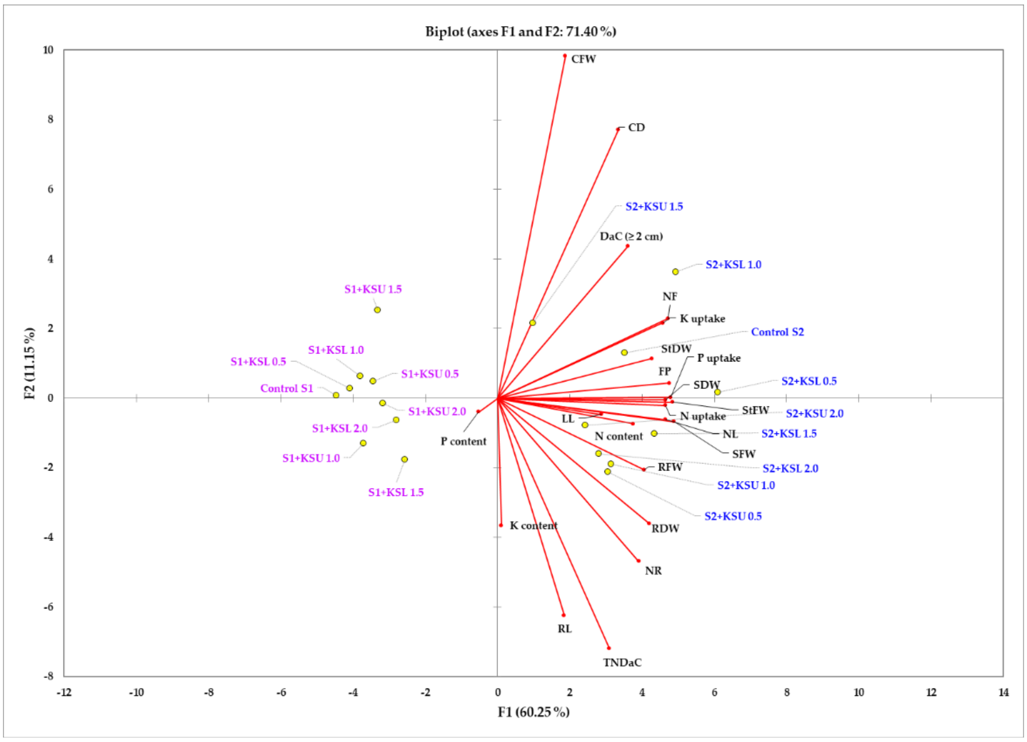

***Figure 4.** Biplot of principal component analysis of flowering, vegetative growth, and daughter corms formation parameters of saffron as influenced by corm size and different treatments of K-fertilizers. Abbreviations in the figure indicate corm fresh weight (CFW), corm diameter (CD), daughter corm ≥ 2 cm (DaC ≥ 2 cm), number of flowers (NF), stigma dry weight (StDW), flowering percentage (FP), stigma fresh weight (StFW), shoot dry weight (SDW), number of leaves (NL), leaf length (LL), root dry weight (RDW), shoot fresh weight (SFW), root fresh weight (RFW), number of roots (NR), total number of daughter corms (TNDaC), root length (RL), corm size 2.2 -2.5 cm diameter (S1), corm size 3.2 -3.5 cm diameter (S2), K_2SiO_3 treatments (KSL 0, 0.5, 1.0 and 2.0 $g.L^{-1}$) and K_2SO_4 treatments (KSU 0, 0.5, 1.0 and 2.0 $g.L^{-1}$)*

Discussion

Fertilization plays a critical role in saffron production, encompassing various agricultural practices. Our previous research has emphasized the impact of the growing substrate, the electrical conductivity (EC) of the nutrient medium, and the pH and texture of the soil on saffron yield (Dewir and Alsadon, 2022; Dewir et al., 2022a; El-Mahrouk et al., 2023). Potassium, being a vital nutrient, must be incorporated into the fertilization regimen. Inadequate or excessive levels of potassium can disrupt numerous biological processes in plants (Johnson et al., 2022). Consequently, potassium was chosen as a crucial element in our present investigation to establish an optimal fertilizer program specifically tailored for arid and semi-arid regions. Our study primarily focuses on saffron yield, encompassing both flowers and daughter corms, under varying doses of potassium and two different corm sizes. Potassium occupies a distinctive position among all essential nutrients, as it plays a crucial role in facilitating plant growth. However, it is noteworthy that potassium is not found in any plant components, such as proteins, fats, or carbohydrates. Furthermore, numerous plant biological processes are partially or wholly regulated by potassium, as extensively examined in recent studies investigating its various roles in plant growth, particularly under stressful conditions (Cui and

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Tcherkez, 2021; Johnson et al., 2022; Mostofa et al., 2022; Soumare et al., 2022). Specially selected potassium-based fertilizers possess unique characteristics that are particularly beneficial for cultivating saffron in arid environments. Potassium sulphate, for instance, serves as a valuable source of sulfur, which can be converted into H_2SO_4 to address saline/alkaline soils in arid regions. While the acidic behavior of silicate also could be expected when this fertilizer added to such soils. The potassium content present in each potassium-based fertilizer may provide an explanation for the results obtained in our research. Specifically, our findings suggest a higher preference for silicate fertilizer, containing 61% potassium oxide (K_2O), compared to sulphate fertilizer, which only contains 50% potassium oxide (K_2O), when applied at equivalent doses.

A robust correlation between the cultivation of saffron and the process of fertilization has been documented in scientific literature, encompassing various types of fertilizers such as organic fertilizers (Aboueshaghi et al., 2023), biofertilizers (Esmaeilian et al., 2022a), mineral fertilizers (Azari et al., 2023), and nanofertilizers (Khoshpeyk et al., 2022). Within the category of mineral fertilizers, potassium (K) fertilizers assume a crucial role in providing saffron with the necessary potassium to support its biological functions (Basatpour et al., 2022). Interestingly, our findings have revealed that different doses of K-silicate proved to be more effective in promoting the vegetative growth of saffron compared to K-sulphate. This observation can be attributed to the higher potassium content present in K-silicate, which enhances the biological activities and metabolism of saffron, resulting in the generation of a greater number of leaves, shoots, roots, and daughter corms, with priority given to the development of larger saffron daughter corms. It is worth noting that saffron corms of larger size exhibit superior growth and yield when compared to smaller corms due to their enhanced nutrient storage capacity, enabling them to provide ample nutrients to the transplants, particularly during the initial stages of growth.

The present study demonstrated that saffron corms with a larger size (3.2 – 3.5 cm) exhibited the highest values in terms of flowering, vegetative growth, and the formation of daughter corms, in comparison to smaller-sized corms. This can be attributed to the higher nutrient content present in the larger mother corms, which provide ample support for superior growth and yield. These findings align with the previous research conducted by Cardone et al. (2021), who emphasized the significance of mother corm size in controlling the various attributes of flowering and production, including the yield of both stigma and daughter corm. It was also observed that corms measuring up to 3.5 cm achieved the highest number of flowers and stigma yield, while an increase in size up to 4.5 cm resulted in a decrease in these parameters due to increasing the crop cycle. Similar studies, such as those conducted by Koocheki et al. (2019) and Zhu et al. (2022), have reported on the appropriate size of corms in saffron cultivation. These studies confirm that the yield of daughter corms, as well as the number of flowers in saffron, are primarily regulated by genetic attributes and/or agronomic practices, which play a role in governing the biochemical processes during both vegetative and reproductive growth periods. However, the introduction of chemical fertilizers, such as K-fertilizers, may serve to stimulate the saffron buds, enabling them to absorb a greater amount of nutrients from the mother corm reserves and/or from K-foliar solution. This hypothesis is supported by the presence of nutrient-rich big-sized daughter corms, which exhibit a significant increase in both vegetative and yield attributes. In our study, the size range of 3.2 – 3.5 cm yielded the highest number of flowers and dry weight of stigma.

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Zabihi and Feizi (2014) emphasized the significant impact of K sources on the yield of dry saffron stigmas. The study demonstrated that the application of K in the form of K_2SO_4 resulted in a higher yield of dry stigmas compared to muriate of KCl. The authors also found that the rate of potassium had a notable effect on the dry stigma yield of saffron, with the highest yield observed when 20.75 Kg K ha^{-1} was applied. Previous research by Basatpour et al. (2022) reported that the application of 100 kg ha^{-1} of potassium sulfate led to the highest fresh weight of saffron flowers. Additionally, Akram et al. (2014) found that a rate of 200 kg ha^{-1} of potassium sulfate resulted in a significant increase in flower number (5.5%), flower weight (5.6%), fresh weight of stigma (10%), and dry weight of stigma (8.5%) compared to the control. A greenhouse experiment revealed that higher levels of potassium effectively mitigated the negative effects of NaCl on root length, root number, fresh weight, and leaf number per saffron plant. Furthermore, in the presence of salinity, the introduction of 50% extra potassium in the rhizosphere of saffron, based on Hoagland's nutrient solution, improved the detrimental effects of NaCl up to 9.4 dS m^{-1} of soil solution (Avarseji et al., 2013). The application of K-fertilizer in the silicate form, which possesses a higher K_2O content, resulted in the highest flower yield and dry weight of stigma when compared to the sulphate source at various applied doses. When considering the role of potassium (K) in saffron flowering, it is noteworthy that K can mitigate higher yields under stressful conditions by enhancing the yield and yield components of flowers and corms (Hourani, 2022).

The findings of our study validate the influence of different applied K-fertilizers on the productivity of saffron. In general, both forms of applied K-fertilizers increased the content and uptake of nitrogen, phosphorus, and potassium (NPK) in saffron leaves, particularly in corms of larger sizes, when compared to the control group. These results align with the findings of Zabihi and Feizi (2014) and Basatpour (2022) under similar climatic conditions in Iran, which resemble the arid zones of Egypt. It is worth noting that all saffron parameters were enhanced following the application of K-silicate, with the exception of chlorophyll fluorescence, which was found to be more favorable when K-sulphate was utilized. The reason behind the effectiveness of K-silicate can be attributed to its higher K content (61%), while the impact of K-sulphate on chlorophyll fluorescence may be attributed to the role of sulfur (S) in such biological activities. Previous studies have reported that S plays a crucial role in the photosynthetic apparatus, as it regulates chlorophyll content, grana size, and electron transport rate (Samborska et al., 2019). This study has also raised several questions regarding other sources of K-fertilizers and other types of fertilizers, particularly nanofertilizers, which will be addressed in our future research on this important crop.

Conclusions

The current investigation revealed that the application of K-fertilizer and the size of the corm have exerted a significant influence on the saffron yield and growth. Saffron corms with a smaller size (ranging from 2.2 to 2.5 cm in diameter) did not undergo flowering and displayed a diminished yield of daughter corms. Both sources of potassium have exhibited a positive impact on the growth and productivity of saffron in comparison to the control group. Furthermore, it has been found that the usage of K-silicate has yielded superior results when compared to K-sulphate. These findings have the potential to make a substantial contribution to the overall production of saffron.

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