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Optimizing saffron cultivation in Lebanon: Effects of crop density and fertilization on yield and corm growth

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Abstract

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Saffron production in Lebanon is gaining attention as a profitable alternative crop, particularly in the central Bekaa Valley. To enhance yield, a customized fertilization regimen is essential. This study evaluated four levels of KNO_3 (0, 5, 10, and 15 units), with or without vegetative organic matter (VOM) under two cultivation densities: 20 cm x 20 cm (30 corms/m^2) and 14.3 cm x 14.3 cm (56 corms/m^2). Results showed that flower production in the second year was primarily influenced by plant density, while in the third year, fertilization had a more significant impact. Treatment T'7 (10NK) under higher crop density produced the highest flower numbers in both years. Leaf length increased over the two years, with the longest leaves observed in lower crop density (T4: 15NK + VOM) and higher crop density (T'4: 15NK + VOM). Corm multiplication and individual corm weight were higher in lower-density cultivation, with T5 (0NK) and T8 (15NK) showing the highest corm multiplication, and T2 (5NK + VOM) and T3 (10NK + VOM) producing the heaviest corms. The highest saffron yield in both years was recorded in T'7, followed by T'4. The strong correlations between corm number, flower production, and saffron yield underscore the need to optimize corm density and fertilization practices. However, the inverse relationship with individual corm weight suggests that further research is required to refine strategies for maximizing both corm and flower productivity.

Keywords: Saffron; crop density, fertilization; organic matter; Lebanon

Introduction

Saffron *Crocus sativus* L. (Iridaceae) is among the most valuable and expensive medicinal plants globally (Nazarian et al., 2024), with its market expected to grow by 12.09% from 2020 to 2027 (Kothari et al., 2021). This historical crop has not significantly benefited from modern technology and still relies predominantly on traditional knowledge. It requires minimal water, making it a viable option for farmers to generate relatively satisfactory income under challenging conditions (Rashed-Mohassel, 2020). Climate, crop density, irrigation, and other agricultural practices all impact saffron cultivation (Al Madini et al., 2019; Rezvani-Moghaddam, 2020), but achieving the highest output and quality of saffron necessitates a balanced and timely supply of fertilizer (Ghanbari and Khajoei-Nejad, 2021).

In regions where saffron is cultivated, the absence of specific fertilizer recommendations is notable due to variations in soil organic matter, climate, and agricultural practices (WBSiE, 2006). Some researchers argue that fertilization may not be essential for successful saffron production in fertile soils, as saffron corms have the capacity to store ample nutrients. This view is supported by the relatively low level of nutrient absorption observed in saffron (Shahandeh, 2020). Consequently, the economic yield, particularly the stigmas, relies more on corm nutrient reserves than on direct soil conditions. Therefore, when evaluating saffron's nutrient requirements, it is crucial to consider both stigma and corm yield, whether based on yield goals, mathematical response curves, or balance sheets (Douglas et al., 2014).

To optimize saffron growth and yield, emphasis is placed on the importance of fertilization and proper nutrition to balance vegetative and reproductive growth in the saffron plant (Koocheki, 2004). Studies indicate that soil physicochemical and biological properties are essential indicators for designing crop yield plans, guiding the selection of manure to improve soil properties and, consequently, crop yield (Ma et al., 2021). Soil properties have been shown to account for a significant percentage of changes in saffron flower yield, underscoring the pivotal role of soil conservation in achieving high-quality production (Aghhavani et al., 2018; Cardone et al., 2020).

Moreover, optimal formation of new (replacement) corms can improve saffron flower growth and yield in subsequent years through proper agronomic management (de Juan et al., 2009). Integrated nutrient management, through the effective combination of different fertilizers, ensures balanced nutrient uptake at critical growth stages, ultimately enhancing plant growth and yield (Selim, 2020; Ahmadian et al., 2024).

Therefore, in the following study, we aim to determine the effects of crop density and different fertilization regimes on yield and corm growth under the climate conditions of Lebanon's central Bekaa Valley (arid and semi-arid region). This research seeks to contribute to a reliable long-term strategy for addressing current challenges in saffron cultivation, specifically in Lebanon.

Materials and Methods

Experimental site

The experiment was carried out in Deir El Ghazel, a village in Lebanon's Central Bekaa Valley, over three consecutive years (2019–2022). This study focuses on evaluating the results from the second and third years. A total of 9000 corms were initially selected from Qaa Farm in northern Lebanon, and 6000 healthy corms, each with a diameter of 2.8 cm, were carefully sorted for the experiment.

The pedo-climatic conditions of the experimental site

Data from the International Centre for Agricultural Research in the Dry Areas (ICARDA) shows that Deir el Ghazel experiences a hot, dry season from May to September and very cold weather the rest of the year. The average rainfall is 450 mm, with 80% falling between November and March, and no rain typically occurs in the Central Bekaa Valley from June through September.

Soil samples were collected from the plot at depths of 0–30 cm, where most root activity occurs and tillage mixes nutrients. Samples were taken randomly using the zigzag method and analyzed at the Lebanese Agricultural Research Institute (LARI), Tal Amara station. The soil is clayey (64% clay) with moderate drainage, a bulk density of 1.41 g/cm³, and low organic matter (≤1.0%). Key characteristics include a field capacity of 29.5%, a permanent wilting point of 16.0%, and an extractable water capacity of 190 mm for a 1 m rooting depth. The soil has a pH of 7.4, EC of 0.21 mS/cm, and is rich in potassium (1529 ppm) and calcium (16 587 ppm), with moderate levels of organic matter (3.23%), nitrogen (0.194%), and phosphate (274 ppm).

6000 saffron bulbs were planted at a 15 cm depth. Drip irrigation (30–40 mm) was applied twice in September, 20 days apart, with weeds removed after the first irrigation. Irrigation ceased in winter, relying solely on rainfall.

Experimental set up

The experiment investigated the individual and combined effects of "Corm Density," "Vegetal Organic Matter" (VOM), and "Potassium Nitrogen Fertilization" (KNO_3).

KNO_3 was applied at 4 levels 0, 5, 10, and 15 units as follows:

– 0NK: No fertilizer.

– 5NK: 5 units of KNO_3 (13.7-0-46.3) per 1000 m² = 6.26 kg/1000 m² or 18.78 g for a 3 m² block.

– 10NK: 10 units of KNO_3 per 1000 m² = 12.52 kg/1000 m² or 37.56 g for a 3 m² block.

– 15NK: 15 units of KNO_3 per 1000 m² = 18.78 kg/1000 m² or 56.34 g for a 3 m² block.

VOM was applied at a rate of 1% in its respective treatments, equivalent to 5.2 kg per 3 m².

The experimental design consisted of 16 treatments, evenly split between two bulb density categories (30 corms/m² and 56 corms/m²), with three replicates each, following a Randomized Complete Block Design (RCBD). The control treatments, T5 (0NK) and T'5 (0NK), in both density categories, were not treated with KNO_3 or VOM.

The treatments were as follows:

– Low-density cultivation (T): T1 (0NK + VOM), T2 (5NK + VOM), T3 (10NK + VOM), T4 (15NK + VOM), T5 (0NK), T6 (5NK), T7 (10NK), and T8 (15NK).

– High-density cultivation (T'): T'1 (0NK + VOM), T'2 (5NK + VOM), T'3 (10NK + VOM), T'4 (15NK + VOM), T'5 (0NK), T'6 (5NK), T'7 (10NK), and T'8 (15NK).

Ultra Sol fertilizer (KNO_3) and Domoflor mix 1 (VOM) were manually applied three times: in February 2020, January 2021, and February 2022.

Growth indicators

Mature flowers were handpicked, and the total flower count was recorded. The stigmas were carefully extracted and dried in a forced-air oven at 30 °C for 24 hours. Two months after fertilization, leaf length was measured, and at the end of the experiment, corms were removed from the soil. Their number and weight were recorded.

To analyze chlorophyll content, 1 gram of leaves was immersed in 30 ml of methanol and refrigerated at 4°C for one week. The leaves turned whitish, indicating complete chlorophyll extraction. Chlorophyll content was then measured using a spectrophotometer at 663 nm, 645 nm, and 460 nm, with the total chlorophyll concentration calculated using the formula: Total Chlorophyll = (A652 × V) / 34.5.

Statistical analysis

Data analysis for the second and third years was conducted using IBM SPSS Statistics 20 software. A one-way ANOVA followed by Duncan's Multiple Range Test (DMRT) was employed to evaluate statistical differences, with results expressed as mean ± standard error (SE), and a p-value ≤ 0.05 considered statistically significant. Additionally, Pearson's correlation analysis was used to investigate the relationships between morphological and production traits in saffron under various densities and fertilization regimens.

Results

During the second year, plant density emerged as the predominant factor influencing flower production, with a statistically significant impact ($p < 0.01$), leading to a doubling in flower numbers in denser cultivations. In contrast, the effects of KNO_3 and VOM were negligible, regardless of the dose or combination used. However, in the third year, VOM and KNO_3 significantly influenced flower production ($p = 0.041$), while plant density did not have a notable effect, as treatments across densities overlapped. The highest number of flowers, 1222.5, was recorded in treatment T7' (Figure 1).

Figure 2 highlights the development of the flower number factor over two consecutive years. In the second year, the variation was minimal, but a slight yet significant increase ($p = 0.04$) was observed in response to different doses and combinations of KNO_3 and VOM, while the effect of density was negligible. Interestingly, that the best results were recorded in the control treatments for both densities (T5: 149; T'5: 167). In the third year, the variation between treatments became more pronounced, with slightly higher values observed in denser cultivations. However, the most significant impact on this parameter was from KNO_3 and VOM ($p = 0.032$). Treatments with only KNO_3 showed

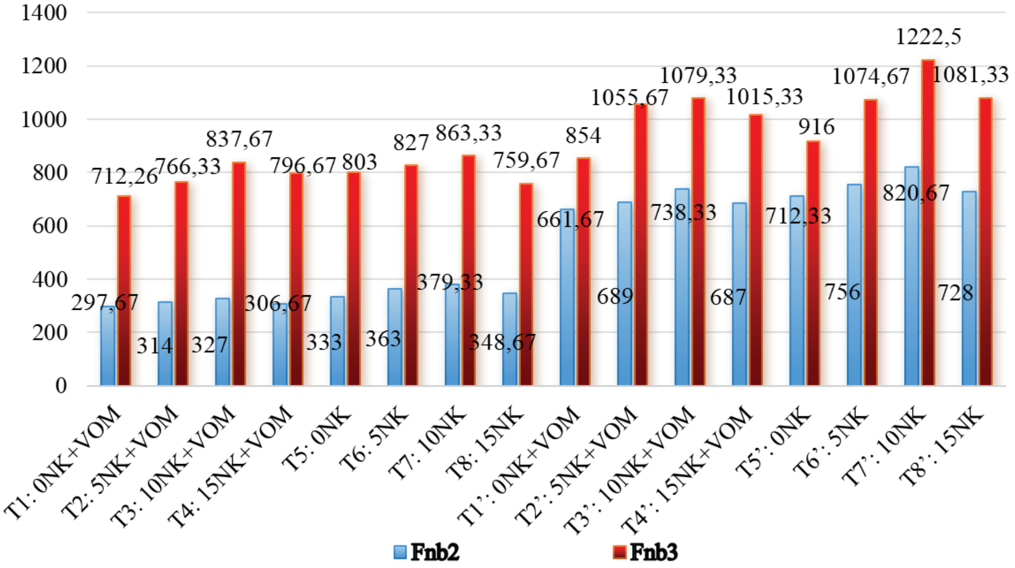

Fig. 1. Variation of flower number during two consecutive years as affected by treatments
Fnb: Flowers number; 2: second year; 3 third year.
Source: Authors' own elaboration

higher results compared to the combined KNO_3 and VOM treatments, similar to the second year, with the control treatments again achieving the highest values (T5: 159.33; T'5: 195).

Figure 3 illustrates the variation in leaf length over two consecutive years. In the second year, KNO_3, VOM, and density all had a significant impact on leaf length, with some overlap observed ($p < 0.01$). The best results were achieved in both densities with combined KNO_3 and VOM treatments, where leaf length increased with increased KNO_3 doses, reaching a maximum of 52.8 cm in T4 and 60 cm in T'4. In the third year, leaf length increased beyond the levels observed in the second year; however, the variation was not significantly influenced by the factors studied, with leaf lengths ranging from 55.33 cm to 64.33 cm.

Interestingly, the chlorophyll content (p: 0.586) remained unaffected by any of the applied factors, fluctuating between 1.09–1.38 mg/g MF.

The final number of corms was significantly influenced by the treatments involving VOM, KNO_3, and density ($p < 0.01$), revealing an interesting trend. Higher corm numbers were observed in treatments with increased density, particularly notable in the case of KNO_3 alone (T8': 1044) and combined with VOM (T7': 924; T4': 915; T3': 912; T2': 910). The most substantial increase in number occurred in cultures with lower initial density (30), as indicated by the Corm multiplication factor. Although this factor wasn't statistically significant (p: 0.22), it was higher in low-density conditions, particularly in treatments with KNO_3 alone (T8: 23.6; T7: 23.7; T6: 21.9), control (T5: 21.9), and VOM alone (T1: 20.6). Notably, individual corm weight was significantly affected by all factors (p: 0.022), with heavier corms

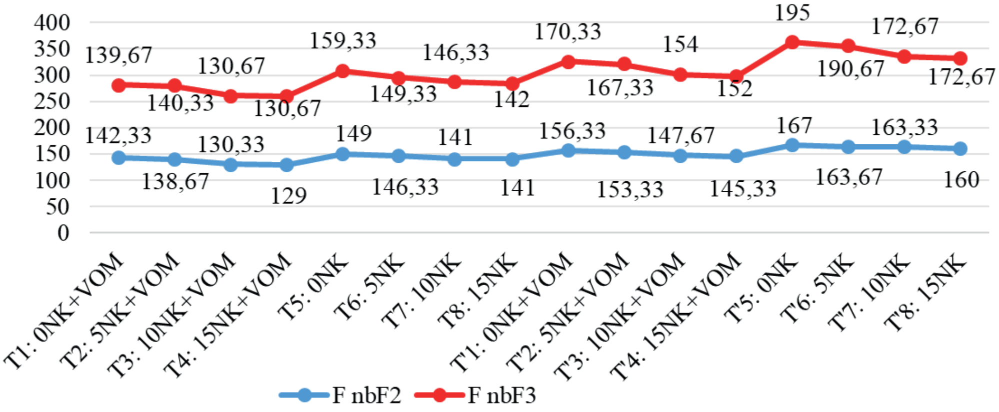

Fig. 2. Variation in the factor of flower's number over two consecutive years as influenced by treatments F nbF: factor of flower's number. 2: Second year; 3: Third year.

Source: Authors' own elaboration

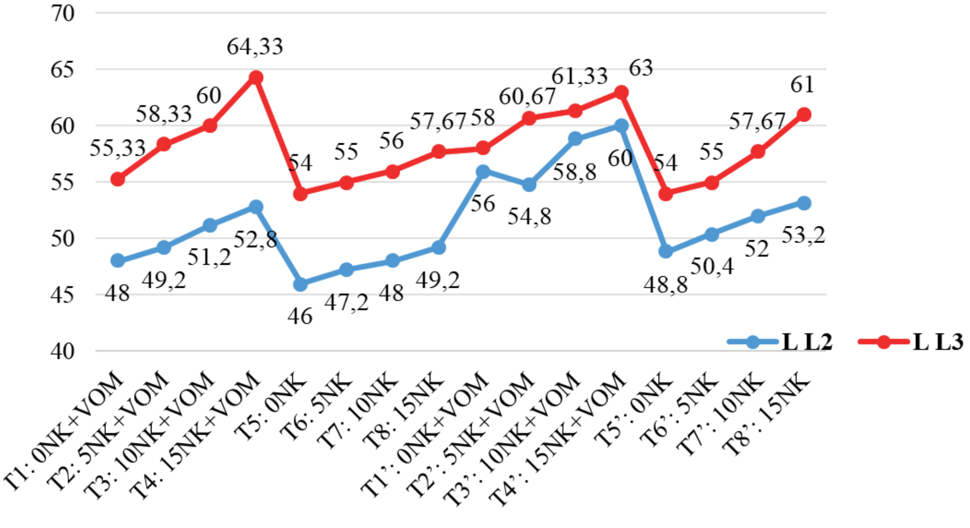

Fig. 3. Variation of leaf length during two consecutive years as affected by treatments L L: Leaf length; 2: second year; 3 third year.

Source: Authors' own elaboration

obtained under lower density conditions, especially in treatments combining VOM and KNO_3 (T3: 9.2g; T2: 9.1g; T4: 8.3g) (Figure. 4).

Figure 5 shows that saffron weight was influenced by different factors in each year. In the second year, KNO_3 and VOM had no significant impact on saffron weight; however, the weight doubled in denser cultivation, indicating a strong influence of density ($p<0.01$). In the third year, the situation shifted, with KNO_3 and VOM significantly impacting saffron weight (p: 0.03), while the effect of density became less pronounced. In lower-density cultivation, the best results were achieved with treatments T3 (6.233g) and T4 (6g). In denser cultivation, in addition to T'3 (7.233g) and T'4 (6.967g), treatments T'7 (7.3g) and T'8 (6.833g) also showed high results.

Table 1 presents the correlations between various morphological and production traits in saffron. The final number of corms was strongly and positively correlated with

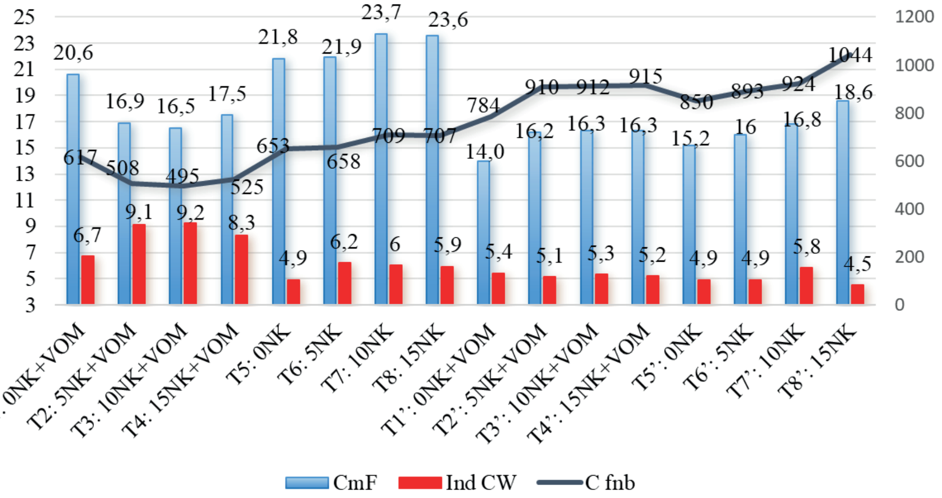

Fig. 4. Variation of corm parameters as affected by treatments
CmF: Corm multiplication factor; Ind CW: individual corm weight; C fnb: Corm final number
Source: Authors' own elaboration

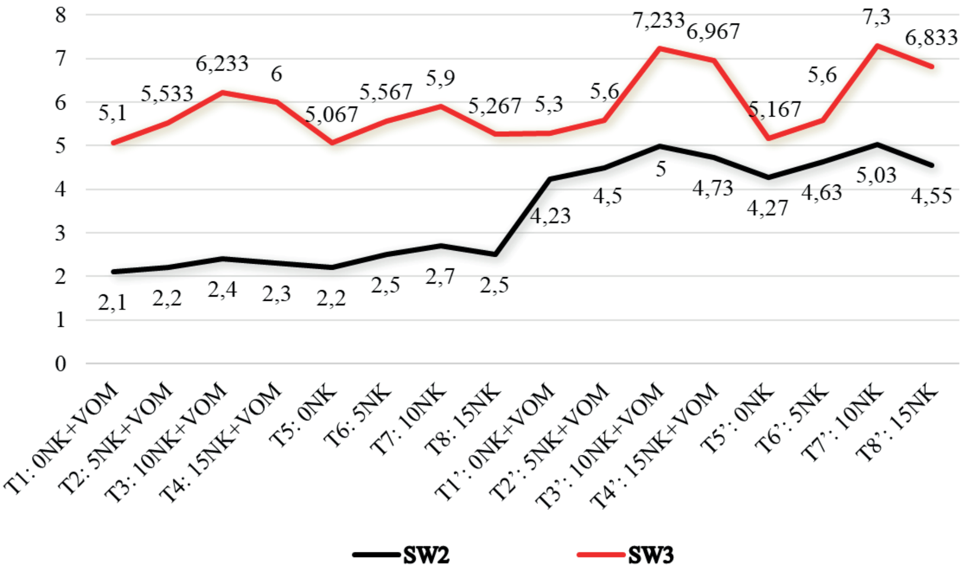

Fig. 5. Variation in saffron weight over two consecutive years as influenced by treatments
SW: Saffron weight;
2: Second year;
3: Third year.
Source: Authors' own elaboration

both the number of flowers (R = 0.8) and saffron weight (R = 0.8) in the second year, with high significance. Conversely, it showed a strong, highly significant negative correlation with individual final corm weight (R = -0.7). Additionally, the final number of corms had a moderate positive correlation, also with high significance, with the factor of flower number in both the second year (R = 0.64) and the third year (R = 0.59), as well as with the number of flowers (R = 0.65) and corm weight (R = 0.58) in the third year.

The flower number in the third year exhibited a strong positive correlation, with high significance, with the flower number (R = 0.75), saffron weight (R = 0.73), and the factor of flower number (R = 0.68) from the second year. It also showed a positive correlation with the factor of flower number (R = 0.7) and saffron weight (R = 0.65) in the third year. A weak but highly significant positive correlation was observed with the final corm weight (R = 0.46), while a negative correlation was found with individual corm weight (R = -0.43).

Remarkably, leaf length in the second year showed a moderate, highly significant positive correlation with the flower number (R = 0.56) and saffron weight (R = 0.64) of the same year. It was also positively correlated with both the leaf length (R = 0.53) and saffron weight (R = 0.48) in the third year. On the other hand, individual corm weight exhibited a moderate, highly significant negative correlation with the flower number (R = -0.62) and saffron weight (R = -0.61) in the second year, as well as with the factor of flower number in the third year (R = -0.54). A strong, highly significant negative correlation was also observed with the factor of flower number in the second year (R = -0.69).

Discussion

Saffron growth and yield are significantly influenced by various environmental and management factors, including plant density, maternal corm characteristics, and nutrition (Temperini et al., 2009). Ghanbari and Khajoei-Nejad (2022) highlighted that a balanced and timely fertilizer supply is crucial for achieving saffron's optimal yield and quality. However, some researchers argue that fertilization may be unnecessary in fertile soils due to the significant nutrient storage capacity of saffron corms. This perspective is further supported by the relatively low nutrient absorption observed in saffron (Shahandeh, 2020).

In the climatic conditions of Lebanon's central Bekaa Valley (arid and semi-arid region), the study demonstrated that, starting with uniformly sized and weighted mother corms, the effects of planting density and fertilizer regimes – whether KNO_3 alone or in combination with VOM at varying doses – varied across different growth and yield parameters.

Our findings indicate that the impact of fertilizers is cumulative, with fertilization directly enhancing nutrient accumulation in subsequent corms. This nutrient boost positively affects both vegetative growth and productive parameters. These statements align with the study conducted by El Hajj et al. (2024), which reported that the triple-dose treatment produced the most effective results in terms of saffron yield parameters. Moreover, consistent with our observations, previous studies have established that achieving a minimum corm size and weight is critical for successful flower production (Douglas et al., 2014). Likewise, Soheilivand et al. (2007) previously reported differences in flower production between heavy and light corms, emphasizing that heavier

Table 1. Pearson Correlation Matrix for Agro-Morphological and Production Traits in Saffron

	F nb2											
SW2	.99**	SW2										
F nbF2	.76**	.68**	F nbF2									
F W3	0.17	0.18	0.14	F W3								
L L3	0.23	0.28	0.09	-0.1	L L3							
F nb C	.80**	.8**	.64**	-0.02	0.16	F nb C						
F nbF3	.66**	.6**	.79**	0.13	0.03	.59**	F nbF3					
SW3	.47**	.5**	0.26	-0.16	.37**	.37**	0.08	SW3				
F nb3	.75**	.73**	.68**	-0.08	.32*	.65**	.70**	.65**	F nb3			
L L2	.56**	.64**	0.11	0.21	.53**	.36*	0.04	.48**	.37**	L L2		
CW3	.41**	.42**	0.17	-0.09	0.10	.58**	0.24	.36*	.46**	0.26	CW3	
Ind CW	-.62**	-.61**	-.69**	-0.08	-0.09	-.70**	-.54**	-0.15	-.43**	-0.17	0.07	Ind CW
C multF	-0.21	-0.21	0.06	-.31*	0.02	.3*	0.06	-0.04	0.03	-.4**	0.16	-.33*

[**] Correlation is significant at the 0.01 level (2-tailed).

[*] Correlation is significant at the 0.05 level (2-tailed).

Source: Authors' own elaboration

mother corms produce more flowers than lighter ones. In our current study, the number of flowers and saffron weight were significantly influenced by the type and dosage of fertilization during the third year, even surpassing the impact of crop density, which would typically have a greater effect. Notably, the increase in factor of flower numbers suggests that, under the correct fertilization regimen, the corms store sufficient nutrients to boost production in the following season, achieving results comparable to those of more densely cultivated plots. Furthermore, Seliem et al. (2024) found that saffron flowering is particularly responsive to potassium fertilization, with the effect varying based on the type and dose of potassium fertilizer used. Esmaeilian et al. (2022a) observed that manure, various bio- and chemical fertilizers, and their interactions significantly influenced the number of flowers and dry stigma yield over three consecutive years, with each year showing consistent improvement. Similarly, Daneshmandi et al. (2024) reported that organic amendments increased flower number and stigma weight in arid and semi-arid regions. These findings align with our results, highlighting that, under Lebanese conditions (arid and semi-arid region), the fertilization regime plays a pivotal role in enhancing flower production and, consequently, stigma yield.

However, there are contrasting data regarding the effect of fertilization type and dosage on leaf length. Our study showed a significant impact on leaf length during the second year with various doses and combinations, but no significant impact in the following year, despite higher averages compared to the previous year. These outcomes align with earlier research indicating that the use of NPK fertilizer enhances plant growth, including the total number of leaves and leaf length (Jahan and Jahani, 2006; Abbas and Ali, 2011; Bashir et al., 2019; Hourani, 2022). Omidi et al. (2009) also noted significant effects of different chemical and bio-fertilizer sources of nitrogen on leaf length. However, Ünal and Çavuşoğlu (2005) previously reported no significant differences among different nitrogen fertilizer treatments regarding leaf length.

Corm productivity and its characteristics are critical aspects of saffron production. Several studies have established that these parameters are closely affected by the nutrient content of the growing media and the application of amendments (Hourani, 2022; Dewir et al., 2022a, 2022b; Esmaeilian et al., 2022b; El-Mahrouk et al., 2023). Ghanbari et al. (2019) reported improvements in saffron flower and corm traits over the first to third years of their experiment, noting that the condition of corms directly influences vegetative and reproductive growth. The number of corms per unit area, and consequently corm yield, typically increases during the growth periods of this perennial plant due to the production of daughter corms on mother corms. This trend usually continues until the fourth to sixth year, after which the yield decreases due to the increased number of corms and other environmental factors affecting plant growth (Khazaei et al., 2013; Koocheki and Khajeh-Hosseini, 2020). The findings of the research conducted by Midya et al. (2021) indicate that the various nutritional approaches for saffron, which enhance soil properties and nutrient availability, mobility, and dynamics, have overall improved the plant's growth environment. These favorable conditions optimize the plant's physiological processes, ultimately boosting both vegetative and reproductive growth. Various studies indicate that the combined use of manure and chemical fertilizers can mitigate the limitations and shortcomings of using individual fertilizers, making it an effective agronomic method to improve soil fertility and quality, leading to higher yields (Cui et al., 2018). Some studies also show that the combined use of manure and chemical fertilizers has a greater effect than their individual application on different traits of saffron (Turhan et al., 2007; Amiri, 2008).

Our findings align with previous research, showing that after three years, the final number of corms was significantly influenced by treatments involving vermicompost (VOM) and potassium nitrate (KNO_3). The most notable increase in corm numbers was observed in lower-density cultures, as indicated by the corm multiplication factor, although it did not reach statistical significance (Cui et al., 2018). This factor tended to be higher in low-density conditions, particularly with KNO_3 treatments. Additionally, individual corm weight was significantly affected by the type and dosage of fertilizer and cultural density, with heavier corms observed under lower density, especially when VOM and KNO_3 were combined, suggesting improved nutrient availability for corm development in terms of both number and weight.

Ebrahimi et al. (2021) reported significant increases in flower number, style-stigma dry weight, and the number and weight of daughter corms when large-sized corms were planted. Similarly, planting heavier maternal corms (>12 g) led to earlier and prolonged flowering periods, significantly boosting flower and stigma yields, as well as corm yield (Alie et al., 2023). In our study we achieved similar results starting from smaller corms and relying on fertilization combinations.

This study highlights the complex relationship between corm development, vegetative growth, and saffron production. The strong correlations between corm number, flower production, and saffron yield underscore the need for careful management of corm density and fertilization practices to optimize output. However, the inverse relationships involving individual corm weight suggest further research is needed to refine fertilization strategies and cultural practices to enhance both corm and flower productivity.

Conclusion

This study emphasizes the importance of optimizing both plant density and fertilization strategies for saffron cultivation. For corm production, lower plant density combined with appropriate fertilization is more effective, while higher plant density with the right type and dosage of fertilization enhances dried saffron yield. The findings suggest that while plant density significantly impacts flower production, using KNO_3 and VOM can greatly improve flower numbers and saffron weight. Future research should focus on balancing corm multiplication with individual corm quality to maximize overall saffron production.

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