Effects of Methanol and Nitrogen Fertilizer on Growth and Quantitative and Qualitative Yield of Saffron (Crocus sativus. L) under Rainfed and Irrigated Cultivation

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Abstract

This study used a two-way randomized complete block design with three replications to investigate the effects of methanol spray and nitrogen fertilizer on the growth and quantitative and qualitative yield of saffron (*Crocus sativus* L) in rainfed and irrigated cultivation in northern Iran in 2020 and 2021. The cultivated saffrons were exposed to rainfed and irrigated conditions, and four levels of ammonium sulfate fertilizer (0, 30, 60, and 90 kg/ha) and three levels of methanol spray (0%, 5%, and 10%) were investigated. The results showed that the studied traits were better in the first year than in the second year. Irrigation and nitrogen fertilizer increased the number of buds, bloomed flowers, flower weight, number and area of leaves, and dry weight of stigma and stigma. Methanol spray and nitrogen fertilizer application in irrigated lands increased the number of buds and leaves, but had no effect in rainfed lands. The highest number of flowers bloomed in the first (101.6) and second (106) years was observed in irrigated fields with 90 kg of nitrogen fertilizer and without methanol spray. Irrigation and nitrogen fertilizer positively affected the dry weight of stigma and stigma. Also, irrigation with different levels of nitrogen fertilizer and methanol spray in irrigated fields increased the number and weight of successor buds. The findings indicate that saffron cultivation in northern Iran requires effective agricultural management and irrigation in September, October and November along with 90 kg of nitrogen fertilizer per hectare is recommended to achieve optimal yield.

Introduction

Saffron, belonging to the Iridaceae family, is recognized as the most expensive spice globally. The dried stigmas of the saffron plant hold significant value in the pharmaceutical, cosmetic, perfumery, and textile dye sectors. Additionally, recent studies highlighting the medicinal properties of this plant have further enhanced its global significance (Gohari et al., 2013). Phytochemical analyses indicate that saffron contains several essential carotenoids, particularly crocin and its glycosidic derivatives, including picrocrocin and safranal, which contribute to the yellow color, bitter flavor, and fragrance of saffron, respectively (Caballero-Ortega et al., 2007). Saffron is cultivated in several countries such as Iran, Greece, Spain, Morocco, India, Switzerland, Italy, Argentina, Azerbaijan, and Turkey. Iran is the largest producer of saffron in the world, as it accounts for about 90% of global saffron production and about 60% of the world's area under saffron cultivation (Koocheki, 2004). The average temperature and rainfall are critical factors influencing saffron production. Identifying optimal regions for saffron cultivation through the analysis of meteorological parameters can significantly enhance the advancement of saffron farming (Kumar et al., 2022).

Although saffron cultivation in Iran has a long history, it primarily occurs on marginal lands and depends heavily on local knowledge, resulting in a low yield per unit area (Koocheki, 2004). Saffron is classified as a perennial plant, necessitating the maintenance of long-term soil fertility to ensure optimal production and profitability per unit area (Ghanbari et al., 2019). Soils designated for saffron cultivation necessitate the application of mineral fertilizers and the incorporation of organic matter to enhance fertility and achieve optimal yield. Nitrogen is essential for the structural integrity and metabolic processes of plants (Moshki et al., 2024). It is also necessary for the growth and flowering processes of numerous plant species (Matinizadeh et al., 2025). Nitrogen plays a crucial role in crop development by influencing growth processes, leaf expansion, reproduction, and biomass production (Rousta et al., 2023). Nitrogen serves as the primary component of proteins and protoplasm within cells, facilitates vitamin production, and is crucial for enhancing biomass and plant reproduction (Delijani et al., 2022). This element is essential for chlorophyll synthesis and enhances the efficiency of the photosynthetic process (Nouri et al., 2020). Studies indicate that nitrogen deficiency in saffron results in reduced leaf chlorophyll content and hastened senescence (Elahi Gharabaghlou et al., 2024; Nouri et al., 2020). Emam et al. (2012) investigated the effects of three nitrogen fertilizer levels on saffron growth and yield. Their findings indicated that nitrogen fertilizer significantly influenced the number of flowers, as well as the wet and dry weights of stigmas. Moreover, the application of 75 kg/ha of nitrogen fertilizer resulted in the highest saffron yield. A study examining the effects of four nitrogen fertilizers (ammonium nitrate, ammonium sulfate, urea, and calcium ammonium nitrate) on saffron yield in Turkey revealed that urea treatment resulted in the highest number of flower as well as the greatest wet and dry saffron yields (Unal and Cavusoglu, 2005).

One way to reduce the effects of excessive use of chemical fertilizers is foliar fertilization. Foliar spraying with methanol has been previously reported to increase the yield of chickpea (Hossinzadeh et al., 2012), rapeseed (Ahmadi et al., 2018), and thyme (Mousavi et al., 2021). Methanol spraying increases CO_2 uptake, minimizes plant photorespiration, and increases photosynthetic efficiency. Foliar spraying with 35% methanol in lentils (*Lens culinaris* Medik) has been shown to enhance various growth parameters, including plant height, pod count, dry weight of leaves, roots, and shoots, chlorophyll content, photosystem II quantum yield, intracellular CO2 concentration, photosynthetic efficiency, and water use efficiency, both under stress and non-stress conditions. The use of 20% methanol aqueous extract in cotton cultivation increased intracellular CO_2 concentration (266.6 to 295.1 ppm), rubisco activity, photosynthesis rate, and crop yield in cotton cultivation (Badron et al., 2004). Methanol decreased the activity of antioxidant enzymes and increased the quantum yield, proline and chlorophyll content, and yield of chickpea compared to the control (no methanol spraying) (Seyed Sharifi and Seyed Sharifi, 2020). The foliar spraying of 20% methanol aqueous extract in sugar beet led to an increase in sugar yield, root yield, and chlorophyll content (Khalilvand Behrouzyar and Yarnia, 2017). Three cycles of foliar spraying with methanol aqueous solutions (0, 6, 12, 18, and 24%) at two-week intervals did not influence the growth or yield of the Shiroodi rice cultivar and was deemed ineffective as a growth promoter (Abbasian et al., 2016).

Previous studies have reported contradictory results regarding the effectiveness of methanol in improving crop yield. In addition, the literature review showed that a few studies have addressed the effect of methanol foliar spraying on saffron growth and yield. Although saffron is considered an important medicinal plant in the pharmaceutical industry and also plays a major nutritional role as a spice and food supplement, few studies have comprehensively addressed this plant in the climatic conditions of Deylaman. Therefore, this study aims to investigate the effect of nitrogen fertilizer and methanol foliar spraying on the growth and quantitative and qualitative characteristics of saffron under rainfed and irrigated conditions in the Deylaman region of Gilan Province in northern Iran.

Materials and methods

This study was conducted in Niavol, Deylaman, Gilan Province, in 2022 and 2023. This region lies at 36°54'24"N 49°58'29"E and is 1400–1600 meters above sea level. The study area was located in a region with a semi-arid summer and an average annual rainfall of 396 mm. The meteorological data related to the study period are presented in Table 1. Soil samples were collected from various locations within the study area at a depth of 0–30 cm for the analysis of soil properties before the experiment. A composite sample was prepared and subsequently sent to a laboratory for analysis. Table 2 lists the soil properties analyzed in this study.

Table 1
Write the table title here Meteorological data related to the study area in 2022–2023

	Rainfall (mm)		Average minimum temperature (°C)		Average maximum temperature (°C)		Mean humidity		Maximum wind speed	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
March-April	22.9	80	7.3	1.6	19.7	10.6	46	67	12	17
April-May	10.2	22	8.7	7.6	21.4	18.3	57	66	12	16
May-June	18.4	31.4	11.2	10.7	21.7	20.8	66	70	12	12
June-July	15.3	1.2	13.7	14.1	20.9	24.1	77	66	11	9
July-August	3.2	6.7	15.2	14.2	24.4	20.9	69	77	9	10
August-September	23.6	44.3	14.5	12.7	25.7	20.6	65	75	13	10
September-October	20	7.7	11.2	9.7	20.9	19.5	69	66	11	11
October-November	91.6	88.7	3.3	5.5	9.4	15.6	80	65	10	14
November-December	99.2	43.8	-0.4	0.4	7.4	7.7	65	65	12	12
December-January	21.2	10.9	-2.4	3.1	6.2	11.6	61	57	21	18
January-February	59.7	30.1	1.3	0.3	8.6	7.8	63	62	17	13
February-March	11.4	36.4	2.4	4.4	12.7	12.3	52	61	17	21
Annual	396.7	403.6	7.2	7.0	16.6	15.8	64	67	21	21

Table 2
Physical and chemical properties of soil in the study area (depth: 0–30 cm)

Soil texture	Sand (%)	Silt (%)	Clay (%)	Chlorine (me/l)	Available Sodium (mg/Kg)	Absorbable potassium (mg/Kg)	Absorbable phosphorus (mg/Kg)	Total nitrogen (%)	Organic carbon	EC (dS/m)	Total saturated acidity (pH)
Sandy Clay Loam	53	15	32	21.3	1	485	7.7	3.76	1.2	0.587	7.5

This study employed a split-plot experimental design in completely randomized blocks with three replicates. The experimental treatments were as follows: rainfed and irrigated cultivation (the primary factor), four levels of ammonium sulfate-based fertilizer: 0 kg/ha (as the control), 30 kg/ha, 60 kg/ha, and 90 kg/ha (the first secondary factor), and three levels of methanol spraying: 0% (as the control), 5% volume percentage, and 10% volume percentage (the second secondary factor). The area of each experimental plot was 3 m^2, with a distance of 0.5 meters between plots and an additional 0.5 meters between blocks. The weight of the saffron replacement corms ranged from 6 to 9 grams. Following the acaridae and fungicide treatments, which involved immersing the bulbs in chlorine and sodium hypochlorite (10 grams per liter) three times, the bulbs were subsequently spread, dried, and disinfected. They were then planted at a depth of 15 cm in the last week of August, spaced 15 cm apart in four rows of eight per m^2, resulting in approximately 100 bulbs per three-square-meter plot, measuring 2.85 meters in length and 1.20 meters in width, while considering the river margins and patrol. According to the experimental treatments, half of the nitrogen fertilizer, specifically ammonium sulfate (with a minimum ammonia nitrogen content of 20.5, a minimum water-soluble sulfate content of 23, a maximum moisture content of 0.5, and a maximum free acidity of sulfuric acid of 0.03), was incorporated into the soil before planting following tillage and plowing. The remaining portion was applied post-germination of the corms. The corms were planted in the last week of August in both years. In saffron cultivation, planting typically occurs in July. During this period, hormonal changes in the bulb lead to the initial appearance of flowers, followed by the emergence of leaves. In this study, the objective was to examine the effects of methanol foliar spraying; consequently, planting was conducted in late August, resulting in the initial occurrence of leafing (leaves were observed to emerge on November 7, 2022, and irrigation was done three times a day during the leafing period). The initial flowers emerged on October 25, 2022, and the flowering period extended until November 6, 2022 (irrigation was done twice a day during the flowering period). Foliar spraying treatments were conducted five times: three times during the leafing period and twice during the flowering period. Foliar spraying was performed between 4 pm and 7 pm, during which atmospheric conditions were most stable, characterized by minimal wind and the absence of direct light, in order to ensure complete wetting of all leaves. Methanol with a purity of 98% was initially employed for foliar spraying, mixed with 5% glycine amino acid and combined with water in specified volume percentages. The resulting solution was then manually sprayed on the leaves using a sprayer.

Weed control involved only manual weeding, and no chemical pesticides or herbicides were used for this purpose. In the irrigation and rainfed treatments, the land was completely irrigated once during the land preparation stage to meet the necessary water requirements through flooding. Additionally, during the leafing and growth stages in October and November, superficial irrigation was applied to the plots designated for irrigated cultivation. The required water for irrigation was sourced from the Chakroud River. Table … presents an analysis of the characteristics of the water utilized.

The saffron flowers were harvested daily over two weeks from 8 to 11 am until November 6. The ropes delineating the plots were removed, and access roads were established. Data were precisely recorded daily for each plot. Following morphometric measurements using a caliper and appropriate standard instruments, along with manual enumeration and verification, the flowers were manually segregated and their stigma and style were precisely weighed twice using a digital scale. After the drying process, they were precisely weighed once again, and the stamens from each plot were placed in appropriately sealed containers and sent to a specialized laboratory for biochemical analysis.

Commencing in November, daily flower harvesting was conducted from three square meters of each plot, thereby eliminating the marginal effect. Following harvesting, the flowers from each plot were promptly placed in nylon bags and transported to the laboratory for subsequent measurements. The stigmas and styles were detached from the flowers, subsequently weighed, dried in the shade, and, finally, their dry weight was recorded.

The main secondary metabolites crocin (color factor), picrocrocin (flavor factor), and safranal (fragrance factor) were measured using a spectrophotometer at 440, 257, and 330 nm, respectively, according to the Iranian National Standard No. 259-2 (Omidi et al., 2009). Sampling of corms during the first and second measurements occurred randomly on June 5, 2023, and June 1, 2024, respectively, from an area of 30 cm^2 in each plot. The number and weight of replacement corms per unit area were subsequently calculated.

Before the combined analysis of the data, the Bartlett Test of Sphericity was employed to verify the homogeneity of the experimental error variance. Variance analysis and statistical tests were performed in SAS-9.1, and the means of the examined traits were compared via Tukey's test at a significance level of 5%. The normality test was also performed in SAS to assess the normal distribution of data.

Table 3

Combined analysis of variance of the effect of irrigation, nitrogen fertilizer, and methanol spraying on the studied tra

Source of changes	df	Mean squares										
		Number of buds	Number of leaves	Leaf surface canopy	Number of flowering plants	Whole flower weight	Style length	Dry weight of style per hectare	Stigma length	Dry weight of stigma per hectare	Crocin content	Picrocrocin content
Year (Y)	1	1647**	13**	0.04**	680.3**	2.2**	1.5**	0.02**	1.98**	0.001 ns	1540.5**	4.3**
Replicates (year)	4	8.7	0.2	0.00006	0.72	0.004	0.004	0.00001	0.05	0.006	1.3	2.5
Irrigation (I)	1	257302.5**	147**	0.44**	68775**	174.5**	1**	27.3**	0.75**	0.6**	10557. 5**	6.2**
Y×I	1	105**	0.04 ns	0.0001*	22.5**	0.0003 ns	*0.1	0.0006**	0.04**	0.0003 ns	1.1 ns	8.5**
Main plot error (Error a(	4	10.2	0.05	0.0001	0.7	0.005	0.0003	0.000008	0.04	0.006	1.2	1.6
Nitrogen (N)	3	9197.7**	46.7**	0.15**	3735.4**	45.7**	8**	2.5**	7.6**	0.06**	19708**	2101.7**
Y× N	3	140.5**	0.77**	0.002**	9.8**	0.001 ns	0.11**	0.0004**	0.14**	0.01*	83.2**	3.6**
I× N	3	5145**	4.4**	0.01**	184.3**	9.2**	1.8**	0.8**	1.8**	0.009*	165.7**	689**
Y×I× N	3	135.2**	0.3**	0.0005**	6.3**	0.05**	0.03**	0.001**	0.05**	0.01*	23.4**	6.4**
Subplot error (Error b(	24	5.4	0.06	0.00007	0.67	0.001	0.001	0.00001	0.03	0.002	1.8	0.55
Methanol (M)	2	536.7**	16.2**	0.0005**	1608.5**	35.8**	0.98**	1.4**	2.5**	0.007 ns	8*	86.2**
Y× M	2	170.7**	0.02**	0.0002**	10.7**	0.04**	0.03**	0.0001**	0.03**	0.003 ns	3.8 ns	63.7**
I× M	2	820.2**	45.6**	0.0006**	940.3**	35**	0.22**	1**	0.21**	0.04**	20**	83**
N × M	6	256.3**	9.8**	0.001**	29.5**	10.3**	0.16**	0.17**	0.16**	0.01*	35.7**	16.3**
Y×I× M	2	142.5**	0.09 ns	0.001**	14**	0.13**	0.001 ns	0.0006**	0.001ns	0.003 ns	2 ns	50.2**
Y× M × N	6	101.2**	0.5**	0.0002**	14.8**	0.15**	0.01**	0.001**	0.01**	0.01*	10**	8.3**
I× M × N	6	332.47**	5.4**	0.0004**	174.8**	0.11**	0.03**	0.2**	0.03**	0.007*	11.8**	11.5**
Y×I× M × N	6	197**	0.25**	0.0002**	15.8**	0.01**	0.001 ns	0.0007**	0.001ns	0.009*	9.7**	6.6**
Test error	64	3.5	0.03	0.0005	0.66	0.001	0.001	0.00001	0.001	0.003	2.3	0.99
Coefficient of variation (percentage(	-	1.4	6.4	0.46	1.4	1.6	1.7	0.4	1.4	0.07	0.61	1

Results and discussion

Number of buds

The interaction of year, irrigation, nitrogen fertilizer, and methanol foliar spraying significantly affected the number of buds at the 1% probability level (Table 3). The findings indicated that the number of buds in the second year exceeded that of the first year. This increase is likely attributable to higher rainfall during that year, which may have facilitated greater bud production. Additionally, irrigation demonstrated a more positive effect on this trait compared to rainfed cultivation at all nitrogen and methanol levels. In both years of the study, an increase in nitrogen fertilizer levels corresponded with a rise in the number of buds (Table 4). The application of 10% methanol via foliar spraying influenced the number of buds per corm under irrigation conditions, particularly when 60 and 90 kg/ha of ammonium sulfate fertilizer was used, resulting in an increased number of buds. Conversely, in rainfed plots, neither fertilization nor methanol spraying affected the number of buds per corm (Table 4). The highest number of buds (230.3) was obtained in the second year of the study under irrigated cultivation when 90 kg/h of ammonium sulfate and 10% methanol spraying were applied, while the number of buds under the same treatment in the first year was 216. Rezvani Moghaddam et al. (2014) have also reported comparable findings regarding the effect of nitrogen-containing fertilizers on the number of buds in saffron corms and clones. The highest number of buds per corm in these two studies (6.5 buds) was observed when the saffron farms were treated with 100 kg/ha of urea fertilizer. Saffron has apical and lateral buds on the corm epidermis, which may be either active or dormant throughout the growing season (Molina et al., 2004). According to (Koocheki et al., 2019), the size of the mother corm significantly influences the number and mechanism of budding in saffron. Additionally, the performance of dry stigmas is enhanced with the increasing number of lateral buds. However, some studies have attributed the stimulation of dormant buds to genetic mechanisms and agronomic management (Kumar et al., 2008).

Leaf count and area

The interaction of year, irrigation, nitrogen fertilizer, and methanol foliar spraying significantly affected leaf count and canopy leaf area at the 1% probability level (Table 3). The results showed that the number of leaves increased under the irrigation × nitrogen fertilizer. The highest number of leaves (30.6) was obtained under irrigation cultivation with the application of 90 kg/ha of ammonium sulfate and 10% methanol spraying (Table 3). The data on leaf area also indicated that the leaf area was greater in the second year than in the first year of the study. This can be attributed to the higher rainfall in October and November in the second year of the study.

Rainfed cultivation significantly reduced the leaf area compared to irrigation treatments. Various plants have shown a reduction in leaf count and growth when subjected to rainfed cultivation. A 60% reduction in water consumption in tomatoes resulted in a 9%, 36%, and 37% decrease in leaf number, width, and length, respectively, when compared to the control (Medyouni et al., 2021). Irrigation in maize at 60% and 80% of plant evapotranspiration (ETc), relative to the control at 100% ETc, resulted in significant reductions in leaf area index, leaf nitrogen content, net photosynthetic rate, transpiration rate, chlorophyll fluorescence, chlorophyll synthesis, and yield (Guo et al., 2022). A study on saffron comparing three irrigation treatments (100%ETo as the control, 60%ETo, and 40%ETo) indicated that leaf number, leaf length, and leaf area exhibited an inverse relationship with stress intensity; the lowest values of these traits were recorded at the 40% ET0 treatment (Mzabri et al., 2017). The initial plant response to water deficit includes a reduction in leaf area, which is accompanied by decreased cell division and elongation (Feng et al., 2016; Zhou et al., 2015). Key physiological processes, including photosynthesis and respiration, exhibit sensitivity to water deficit. Drought stress diminishes plant growth and yield by impairing leaf photosynthesis and elevating dark respiration (Feller, 2016; Zhao et al., 2020).

The total number and area of leaves were significantly increased by the use of ammonium sulfate fertilizer in both years of the study, as well as irrigation and rainfed treatments (Table 4). The application of 30, 60, and 90 kg/ha of the fertilizer in the irrigation treatments during the first year resulted in a leaf area increase from 9.9 in the control group to 23.56, 26.56, and 2.29, respectively. These figures in the irrigation treatments in the second year were 2.24, 2.8, and 30.4. Nitrogen is a crucial element that significantly influences plant growth and development. The use of no ammonium sulfate fertilizer under both irrigated and rainfed cultivation methods in both years of the study generally caused a decrease in the number and area of leaves. Nitrogen deficiency impacts leaf area, leaf lifespan, and plant yield through a reduction in the rate of photosynthesis. It also decreases stomatal conductance in mesophyll and vascular sheath cells (Mu and Chen, 2021). This study found that nitrogen fertilizer had a minimal effect on leaf growth and the expansion of saffron canopy area in rainfed cultivation. The application of nitrogen fertilizer in this cultivation method demonstrated a minimal impact on the leaf area increase. Moreover, the use of methanol spraying under rainfed cultivation negatively affected leaf area. Foliar spraying with 10% methanol significantly reduced leaf area compared to the control under rainfed cultivation in both years, while foliar spraying with 5% and 10% methanol in the irrigation × nitrogen fertilizer treatments significantly increased the leaf area of saffron plants (Table 4). Previous studies have reported the impact of water deficit on the availability of minerals, including soil nitrogen. The transpiration flux significantly influences nitrogen availability in the rhizosphere. The flux of mineral nitrogen into the xylem is typically diminished under water deficit, with nitrogen uptake exhibiting even greater sensitivity to such deficits (Gonzalez-Dugo et al., 2010). This study demonstrated that methanol foliar spraying significantly influenced both the number and area of leaves in the irrigation × fertilizer treatments. Specifically, foliar spraying with 5% and 10% methanol increased both leaf count and area when compared to the control group.

Number of flowering plants

The interaction of year, irrigation, nitrogen fertilizer, and methanol foliar spraying significantly influenced the number of flowering plants at the 1% probability level (Table 3). This study observed that flower emergence followed leaf emergence, whereas, in Khorasan, leaf emergence occurs subsequent to flower emergence in September and October. The varying climatic conditions in the Deylaman region, in northern Iran, seem to account for the differing phenology of the saffron plant observed in this study. Koocheki and Seyyedi (2015) stated that flowers may appear before, concurrently with, or after the leaves emerging from the stem sheath, depending on the cultivated area and climatic conditions. The number of flowering plants in this study was higher in the second year, because the rainfall in September and October in the second year of the study was higher than in the first year. The maximum temperature in the flowering months was also lower in the first year (Table 1). Flowering stimulation in saffron takes place at higher temperatures, whereas its flowers appear at lower temperatures (Molina et al., 2004).The flowering and yield of saffron are directly influenced by ambient temperature, and deviations from optimal temperatures may hinder flowering stimulation (Molina et al., 2005). This study revealed the positive effects of irrigation on the flowering of plants in both years of the study. A study of irrigation intervals in saffron cultivation demonstrated that four-week irrigation intervals were effective in increasing the number of flowers (Shajari et al., 2022). According to Dastranj and Sepaskhah (2019) and Renau-Morata et al. (2012), drought stress is associated with a decrease in saffron yield and photosynthesis rate.

The highest number of flowering plants in this study was observed in the irrigation × 90 kg/ha of ammonium sulfate fertilizer × no methanol spraying treatment, yielding 101.6 plants per unit area in the first year and 106 plants per unit area in the second year. The application of nitrogen-containing fertilizers in both irrigation and rainfed systems increased the number of flowers (Table 4). Previous studies have reported the beneficial impact of nitrogen fertilizer on flower yield in saffron. A study examining the effects of urea, ammonium sulfate, and animal manure on saffron yield in Turkey indicated that the urea fertilizer treatment resulted in the highest number of flowers (Unal and Cavusoglu, 2005). Emam et al. (2012) examined the effects of nitrogen and phosphorus fertilizers on the number of flowers, as well as the wet and dry weight of flowers and stigmas. Their findings indicated that nitrogen fertilizer significantly influenced the number of flowers, and the application of 100 kg/ha of nitrogen resulted in the highest number of flowers. As a macronutrient essential for growth, nitrogen significantly influences flowering time. The internal regulation of flowering time in plants involves a complex network of nitrogen-dependent environmental signaling and photoperiod (Zhang et al., 2022). Nitrogen deficiency in Arabidopsis is associated with a reduction in total yield, whereas optimal nitrogen levels promote early flowering, with a significant response observed in the expression of photoperiod-related genes linked to nitrogen-dependent flowering (Weber and Burow, 2018). The results demonstrate the need for a detailed plan for irrigation in saffron cultivation in the Deylaman region to attain optimal yield.

This study found that methanol spraying enhanced corm germination and increased the number of buds on corms; however, this treatment resulted in a decrease in the number of flowering plants. The reduction was more pronounced in the treatments containing higher levels of nitrogen fertilizer (Table 4). Studies have shown that methanol foliar spraying positively influences the growth and yield of various C3 plants (Khoshkharam et al., 2021; Sadeghi-Shoae et al., 2012; Vojodi Mehrabani, 2019). However, this treatment is ineffective or even detrimental in some plant species (Abbasian et al., 2016; Mitchell et al., 1994). The application of methanol results in toxic damage to plants in some cases, potentially due to unknown factors influencing methanol metabolism, which have been less extensively studied in plant systems compared to microbial systems (Madhaiyan et al., 2006).

Flower weight

The interaction of year, irrigation, nitrogen fertilizer, and methanol foliar spraying significantly affected flower weight at the 1% probability level (Table 3). The mean flower weight was higher in the second year of the study, which can be attributed to the higher rainfall and lower maximum temperature in September and October of this year (Table 1). Differentiation of buds in the mother corm necessitates high temperatures for flowering, whereas the saffron flowers appear at low temperatures (Molina et al., 2004). Integrating environmental temperature signals with internal plant signals is crucial for facilitating the transition from vegetative growth to flowering and for regulating the number of flowers through temperature control (Chen et al., 2021).

The irrigation and nitrogen fertilizer treatments increased flower weight in both years of the study, while methanol spraying failed to effectively change this trait. These treatments were also effective in increasing the number of buds, leaf growth, and leaf area. The highest mean flower weight in the first year (0.48 g) and the second year (0.5 g) of the study was observed in the irrigation × 90 kg/h of ammonium sulfate treatment. These figures indicate a 50% increase compared to the rainfed cultivation × no nitrogen fertilizer (Table 5). Bayat et al. (2016) concluded that saffron yield exhibits the strongest phenotypic and genotypic correlation with the wet and dry flower weight, suggesting that saffron yield can be increased by improving these traits. Nitrogen is recognized as a significant factor in enhancing saffron flower yield. The application of nitrogen-containing fertilizers to saffron farms enhances nitrogen concentrations in the leaves, promoting the synthesis of chlorophyll molecules and elevating photosynthetic activity, which subsequently boosts vegetative growth and plant biomass. As a result, increased growth may result in the development of larger flowers (Hourani, 2023). These findings are consistent with the findings of this study regarding irrigation plots and the use of ammonium sulfate fertilizer. Khorramdel et al. (2015) also reported that fertilization positively influences flower weight in saffron. Optimal quantitative and qualitative performance in saffron cultivation necessitates effective nutrient management and careful consideration of climate, soil type, irrigation and drainage practices, planting time, corm quantity and size, planting density, weed control, and post-harvest operations (Kumar et al., 2008).

Table 4
Interactive effects of year, irrigation, nitrogen fertilizer, and methanol spraying on the saffron plant traits

Study year	Irrigation	Nitrogen	Methanol	Number of buds	Leaf surface canopy	Number of flowering plants	Flower weight (g)	Dry style weight per ha (kg)	Dry stigma weight per ha (kg)	Replacement corm weight (g)
First year	Rainfed	Level 1	Level 1	83m	5 k	25 k	0.24 d	0.25hi	1.24 o	0.0001 h
			Level 2	81.6 n	5.1 h	23.3 k	0.24 d	0.24 h	1.2 o	0.0001 h
			Level 3	79.3 n	3 l	17 l	0.18 e	0.17 i	1.02 pq	0.0001 h
		Level 2	Level 1	86.6 m	6 i	33.6 j	0.26 d	0.36 gh	1.74 n	0.0001 h
			Level 2	84 m	5.82 i	33 j	0.27 cd	0.36 gh	1.78 mn	0.0001 h
			Level3	83.3 m	5.51 j	32.3 j	0.27 cd	0.36 gh	1.71 n	1.2 b
		Level 3	Level 1	90.6 lm	6.3 h	35 ij	0.28 cd	0.42 g	1.92 l	0.0001 h
			Level 2	90 lm	6.31 h	34.3 ij	0.29 c	0.42 g	1.92 l	0.0001 h
			Level 3	89 lm	6 i	35.3 ij	0.28 cd	0.38 gh	1.88 lm	0.0001 h
		Level 4	Level 1	90.6 lm	7.421 fg	43.6 jh	0.32 c	0.51 g	2.45 j	0.0001 h
			Level 2	90.6 lm	7.41 fg	42.3 h	0.32 c	0.51 g	2.44 j	0.0001 h
			Level 3	89 lm	6.8 gh	42.6 h	0.32 c	0.46 gh	2.31 jk	0.00001 h
	Irrigation	Level 1	Level 1	141 ij	10.5 e	70 d	0.27 cd	0.77 f	3.92 h	0.0001 h
			Level 2	136.6 j	9.8 e	67.3 de	0.27 cd	0.81 ef	3.8 h	0.0001 h
			Level 3	137 j	9.4 e	60.6 f	0.72 cd	0.72 f	3.35 i	1.5 a
		Level 2	Level 1	h160	22.11 d	79.6 c	0.34 cd	cd1.260	6.24 f	0.91 cd
			Level 2	158.6 h	22.46 d	74.6 cd	0.38 c	1.25 cd	6.06 f	0.92 cd
			Level 3	169.8 j	26.11 c	60.6 f	0.37 c	0.79 f	3.84 h	1.4 ab
		Level 3	Level 1	e6/180	23.48 cd	86.6 b	0.41 b	1.65 c	8 c	0.73 e
			Level 2	174 f	42.2 c	71.6 d	0.42 b	1.42 cd	6.31 ef	0.69 ef
			Level 3	179.6 e	31.81 ab	62.6 e	0.42 b	0.99 e	4.52 g	0.96 c
		Level 4	Level 1	196.6 bc	26.22 bc	101.6 ab	0.46 ab	2.24 a	10.5 a	0.6 f
			Level 2	181 e	28.4 b	96.6 ab	0.48 ab	2.01 b	9.79 b	0.62 f
			Level 3	216 b	33 ab	79.6 c	0.48 ab	1.02 e	6.47 d	0.85 d
Second year	Rainfed	Level 1	Level 1	91.6 l	5 k	33 j	0.24 d	0.29 h	1.25 o	0.0001 h
			Level 2	83.3 m	5 k	24.6 k	0.24 d	0.24 hi	1.2 o	0.0001 h
			Level 3	83.6 m	4 l	19 l	0.21 de	0.17 i	0.85 q	0.0001 h
		Level 2	Level 1	89.3 lm	7.02 gh	35.6 ij	0.31 c	0.39 g	1.8 m	0.0001 h
			Level 2	91 l	6.7 gh	34.3 ij	0.32 c	0.39 g	1.81 m	0.0001 h
			Level 3	91.03 l	6.41 h	35 ij	0.32 c	0.37 gh	781 mn	1.4 ab
		Level 3	Level 1	94.6 kl	7.01 gh	38.6 i	0.32 c	0.45 gh	1.99 l	0.0001 h
			Level 2	95 kl	7.01 gh	37.03 i	0.32 c	0.45 gh	1.99 l	0.0001 h
			Level 3	93.6 l	6.7 gh	38 i	0.33 c	0.42 gh	1.99 l	0.0001 h
		Level 4	Level 1	94 kl	7.7 f	47.3 g	0.34 cd	0.55 g	2.53 j	0.0001 h
			Level 2	95.6 kl	7.73 f	47.6 g	0.35 cd	0.55 g	2.53 j	0.0001 h
			Level 3	95.3 kl	7.72 g	49.6 g	0.34 cd	0.5 g	2.39 jk	0.0001 h
	Irrigation	Level 1	Level 1	83m	5 k	25 k	0.24 d	0.25hi	1.24 o	0.0001 h
			Level 2	81.6 n	5.1 h	23.3 k	0.24 d	0.24 h	1.2 o	0.0001 h
			Level 3	79.3 n	3 l	17 l	0.18 e	0.17 i	1.02 pq	0.0001 h
		Level 2	Level 1	86.6 m	6 i	33.6 j	0.26 d	0.36 gh	1.74 n	0.0001 h

Study year	Irrigation	Nitrogen	Methanol	Number of buds	Leaf surface canopy	Number of flowering plants	Flower weight (g)	Dry style weight per ha (kg)	Dry stigma weight per ha (kg)	Replacement corm weight (g)
			Level 2	84 m	5.82 i	33 j	0.27 cd	0.36 gh	1.78 mn	0.0001 h
			Level 3	83.3 m	5.51 j	32.3 j	0.27 cd	0.36 gh	1.71 n	1.2 b
		Level 3	Level 1	90.6 lm	6.3 h	35 ij	0.28 cd	0.42 g	1.92 l	0.0001 h
			Level 2	90 lm	6.31 h	34.3 ij	0.29 c	0.42 g	1.92 l	0.0001 h
			Level 3	89 lm	6 i	35.3 ij	0.28 cd	0.38 gh	1.88 lm	0.0001 h
		Level 4	Level 1	90.6 lm	7.421 fg	43.6 jh	0.32 c	0.51 g	2.45 j	0.0001 h
			Level 2	90.6 lm	7.41 fg	42.3 h	0.32 c	0.51 g	2.44 j	0.0001 h
			Level 3	89 lm	6.8 gh	42.6 h	0.32 c	0.46 gh	2.31 jk	0.00001 h

Table 5
Interactive effects of irrigation, nitrogen fertilizer, and methanol spraying on the saffron plant traits

Irrigation	Nitrogen	Methanol	Style length (cm)	Stigma length (cm)	Number of replacement corms
Irrigation 1	Level 1	Level 1	0.5g	2.49de	0.0001h
		Level 2	0.51g	2.34ef	0.0001h
		Level 3	0.51g	2.35e	0.0001h
	Level 2	Level 1	0.55f	2.87cd	0.0001h
		Level 2	0.54f	2.9cd	0.0001h
		Level 3	0.54f	2.8d	0.0001h
	Level 3	Level 1	0.58ef	3.03c	0.0001h
		Level 2	0.58ef	3.07c	0.0001h
		Level 3	0.56ef	2.93cd	0.0001h
	Level 4	Level 1	0.62e	3.31ab	0.0001h
		Level 2	0.62e	3.32ab	0.0001h
		Level 3	0.61e	3.02c	0.0001h
Irrigation 2	Level 1	Level 1	1.14c	2.67d	0.0001h
		Level 2	1.07d	2.65d	1g
		Level 3	1.06d	2.62d	1.3f
	Level 2	Level 1	1.21b	2.52de	2.16e
		Level 2	1.21b	2.52de	2.33c
		Level 3	1.03d	2.22f	4b
	Level 3	Level 1	1.13c	3.34b	2.33c
		Level 2	1.24b	3.31b	2.33c
		Level 3	1.1cd	2.9cd	4.16b
	Level 4	Level 1	1.38a	1.4a	2.66d
		Level 2	1.38a	4.1a	2.16e
		Level 3	1.12c	3.41b	5.33a

Data with different letters in the same column are significantly different at 0.05 level

Length and dry weight of stigma and style

The interaction effect of irrigation, nitrogen fertilizer, and methanol spraying on the length of the style and stigma was significant at the one percent probability level. Additionally, the interaction effect of year, irrigation, nitrogen fertilizer, and methanol spraying on the dry weight of the style and stigma was significant at the five percent probability level (Table 3). The findings indicated that irrigation and nitrogen fertilizer application significantly influenced the length and dry weight of the style and stigma. The highest style length (1.8 cm) was recorded in two treatments: irrigation × 90 kg/ha of nitrogen fertilizer × no methanol spraying and irrigation × 90 kg/ha of nitrogen fertilizer × 5% methanol spraying. These treatments increased the style length by 63.8% compared to the control treatments (rainfed cultivation × no fertilizer × no methanol spraying) (Table 5). The highest dry weight of the style (1.24 kg/ha) was related to the irrigation × 90 kg/ha of nitrogen fertilizer × no methanol spraying treatment (Table 5). Behnia et al. (1999) also reported the positive effect of nitrogen fertilizer on the weight of flowers, styles, and stigmas. Nutrient management is critical in saffron cultivation for achieving optimal yield. The quantity, type, composition, and timing of nutrient application are essential for attaining optimal yield and high-quality potential in saffron (Hourani, 2023).

The highest stigma length was observed in irrigated treatments compared to rainfed ones. However, this increase was not statistically significant in some treatments (Table 5). Similar to the style length, the highest stigma length (4.1 cm) was observed in treatments irrigation × 90 kg/ha of nitrogen fertilizer × no methanol spraying and irrigation × 90 kg/ha of nitrogen fertilizer × 5% methanol spraying. These treatments increased the stigma length by 39.3% compared to the control treatments (rainfed cultivation × no fertilizer × no methanol spraying) (Table 5). The study demonstrated that irrigation in both years positively influenced stigma dry weight and enhanced the quantitative yield of saffron in northern Iran. Previous studies have also documented the beneficial effects of irrigation on the quantitative yield of saffron (Askary et al., 2024; Eslami et al., 2024). The irrigation treatments in this study influenced both the number and weight of flowers. The flowering process in saffron involves a pathway associated with the reactive oxygen species-antioxidant system and the conversion of starch to sugar, regulated by a complex and sensitive molecular network influenced by environmental factors such as humidity, temperature, and photoperiod (Chen et al., 2021). Saffron cultivation is basically for its colored stigma, suggesting that increasing the number of flowers may serve as an effective method for increasing saffron production (Agayev et al., 2009). The application of nitrogen fertilizer positively influenced stigma dry weight under both rainfed and irrigated conditions. The highest stigma dry weight in the first year (10.5 kg/ha) and the second year (10.6 kg/h) of the study was related to the irrigation × 90 kg/ha of nitrogen fertilizer × and no methanol spraying. These figures show an 89.6% increase in the stigma dry weight compared to the control treatments (rainfed cultivation × no fertilizer × no methanol spraying) (Table 4). Fertilization with ammonium sulfate fertilizer, similar to irrigation, positively affected the stimulation of buds and increased the number and area of leaves, the number of flowering plants, flower weight, and length and weight of the style. The application of fertilizer in the irrigated cultivation of saffron in the Deylaman region enhanced the quantitative yield of saffron by promoting growth and stimulating flower bud development. Various studies have reported the substantial impact of fertilizer treatments on both the quantitative and qualitative characteristics of saffron. Ghanbari et al. (2019) investigated the effect of biological and chemical fertilizers on saffron growth and yield and concluded that fertilization positively influenced the number of flowers and stigma yield by enhancing plant growth and replacement corms.

Table 6
Interactive effects of year, irrigation, nitrogen fertilizer, and methanol spraying on the crocin, picrocrocin, and safranal content and the weight of replacement corms

Study year	Irrigation	Nitrogen	Methanol	Crocin content	picrocrocin content	Safranal content	Weight of replacement corms
First year	Rainfed	Level 1	Level 1	206h	95.3b	26d	25k
			Level 2	205.6h	94.6b	26d	23.3k
			Level 3	208g	94.6b	26.3d	17l
		Level 2	Level 1	232e	95.3b	27.8d	33.6j
			Level 2	233.3e	95b	27.8d	33j
			Level3	228ef	93.6bc	27.4d	232.2j
		Level 3	Level 1	245.3d	89.6c	29.4cd	35ij
			Level 2	246d	91.3bc	29.4cd	34.3ij
			Level 3	245.6d	90.3c	29.4cd	35.3ij
		Level 4	Level 1	257.3c	84.3d	30.7c	43.6jh
			Level 2	256.3cd	85.3cd	31.4c	42.3h
			Level 3	254.3cd	85cd	31.6c	42.6h
	Irrigation	Level 1	Level 1	218.6fg	112a	33bc	70d
			Level 2	219.3fg	113a	33bc	67.3de
			Level 3	217fg	111a	32.7c	60.6f
		Level 2	Level 1	257.3c	92.2bc	37.2b	79.6c
			Level 2	259 c	92 bc	37.8 b	74.6 cd
			Level 3	252.9 cd	94.7 b	36.7 b	60.6 f
		Level 3	Level 1	260.3 c	89.8 c	39.8 ab	86.6 b
			Level 2	263.6 bc	88.9 c	38.7 ab	71.6 d
			Level 3	bc265	91.3 bc	37.5 b	62.6 e
		Level 4	Level 1	268 b	84.1 d	39.9 ab	101.6 ab
			Level 2	270.6 b	84 d	40.3 a	96.6 ab
			Level 3	273.6 b	85 cd	39.1 ab	79.6 c
Second year	Rainfed	Level 1	Level 1	210.3 g	95 b	27 d	33 j
			Level 2	205 h	94.6 b	26 d	24.6 k
			Level 3	209.3 h	94.6 b	26 d	19 l
		Level 2	Level 1	244.3 d	95.3 b	28.2 cd	35.6 ij
			Level 2	244 d	94.3 b	28.7 cd	34.3 ij
			Level 3	238.6 de	94.6 b b	27.9 cd	35 ij
		Level 3	Level 1	255 cd	89.6 c	30.1 c	38.6 i
			Level 2	254.3 cd	91.3 bc	31.3 c	37.3 i
			Level 3	253.6 cd	90 c	30.1 c	38 i
		Level 4	Level 1	260.6 c	83.3 d	31.8 c	47.3 g
			Level 2	260.6 c	84.6 d	31.6 c	47.6 g
			Level 3	263 bc	85.3 cd	32.2 c	49.6 g
	Irrigation	Level 1	Level 1	206h	95.3b	26d	25k
			Level 2	205.6h	94.6b	26d	23.3k
			Level 3	208g	94.6b	26.3d	17l
		Level 2	Level 1	232e	95.3b	27.8d	33.6j
			Level 2	233.3e	95b	27.8d	33j

Study year	Irrigation	Nitrogen	Methanol	Crocin content	picrocrocin content	Safranal content	Weight of replacement corms
			Level 3	228ef	93.6bc	27.4d	232.2j
		Level 3	Level 1	245.3d	89.6c	29.4cd	35ij
			Level 2	246d	91.3bc	29.4cd	34.3ij
			Level 3	245.6d	90.3c	29.4cd	35.3ij
		Level 4	Level 1	257.3c	84.3d	30.7c	43.6jh
			Level 2	256.3cd	85.3cd	31.4c	42.3h
			Level 3	254.3cd	85cd	31.6c	42.6h

The study results indicated that the application of 90 kg/ha of ammonium sulfate fertilizer caused better effects than other levels of nitrogen fertilizer; accordingly, this level of nitrogen fertilizer increased the stigma dry weight under all irrigation levels in both years of the study. Kirmani et al. (2014) examined the effects of nitrogen management on saffron yield, corm production, nutrient concentration, crocin content, and soil health in Kashmir, India, and found that the application of 90 kg/ha of nitrogen fertilizer resulted in a 57.57% increase in stigma yield, rising from 2.3 kg/ha in the control treatment to 3.64 kg/ha in the fertilizer treatment. In another study, Omidi et al. (2009) investigated the synergistic effect of chemical and biological fertilizers on saffron yield and reported that the highest stigma yield was observed when 150 kg/ha of urea fertilizer or a combination of 2.5 kg/ha of nitrogen fertilizer and 75 kg/ha of urea fertilizer was used. The integration of vermicompost with 50 kg/ha of urea fertilizer resulted in a 42.6% increase in stigma yield (stigma dry weight) relative to the control group. The complete application of vermicompost alongside half the recommended dosage of urea fertilizer enhances yield and soil properties in saffron cultivation (Feli et al., 2018). Nitrogen enhances the growth rate of plants, resulting in the development of larger flowers and heavier stigmas, which is consistent with the findings of this study.

Methanol foliar spraying did not affect the style length in rainfed treatments; in fact, there was no significant difference between the 0%, 5%, and 10% levels of methanol solution spraying at all nitrogen fertilizer levels. By contrast, methanol foliar spraying significantly reduced the style length in irrigation treatments (Table 5). Methanol spraying also showed no positive effect on the style dry weight (Table 5). Methanol spraying in rainfed cultivation caused no positive change in the stigma yield, and even 10% methanol spraying significantly reduced the stigma dry weight. These results were consistent across both years of the study. Methanol foliar spraying also caused a reduction in stigma weight in irrigation treatments. Nevertheless, the enhanced yield and expedited flowering resulting from methanol foliar spraying in C3 plants have been attributed to elevated intracellular CO_2 concentrations (Nadali et al., 2010). In a study about the effects of methanol foliar spraying on rice yield, Abbasian *et al.* (2016) concluded that the ineffectiveness of this treatment in improving rice yield can be attributed to the low levels of methanol applied compared to canopy-fixed CO_2 during the growing season. Furthermore, the rainy weather during the saffron cultivation period in the study area may have hindered the positive effects of methanol on saffron yield. Most reports of the successful application of methanol in saffron cultivation are related to the studies conducted under water deficit and other climatic tensions (Khalilvand Behrouzyar and Yarnia, 2017).

Crocin, picrocrocin, and safranal content of stigma

The composite variance analysis demonstrated the significant interactive effect of year, irrigation, nitrogen fertilizer, and methanol spraying on the crocin, picrocrocin, and safranal content of the stigma (Table 3). The findings indicated that the concentrations of these three substances were greater in the second year of the study compared to the first year (Table 6). The results can be attributed to the varying temperatures recorded in the two years of the study. Moreover, irrigation positively influenced the content of crocin, picrocrocin, and safranal in the stigma. In both years of the study, irrigated treatments exhibited higher levels of these compounds compared to rainfed treatments (Table 6).

The application of nitrogen fertilizer positively influenced the content of crocin and safranal, with higher levels of fertilizer resulting in a significant increase in both compounds. In contrast, methanol foliar spraying failed to change the levels of these substances (Table 6). The highest content of crocin (280.6 μg/g) was observed in the second year of the study under the irrigation × 90 kg/h of ammonium sulfate fertilizer × 10% methanol spraying. The analysis of data from both years of the study and both irrigation methods indicated that an increase in ammonium sulfate fertilizer resulted in a decrease in picrocrocin content, whereas methanol spraying did not affect its levels, similar to the crocin or safranal content. In fact, at all treatments of irrigation and nitrogen fertilizer, there was no significant difference between the 0%, 5%, and 10% methanol spraying in this regard (Table 5). Kianimanesh et al. (2022) demonstrated that chemical fertilizer positively influences the levels of crocin and picrocrocin. In another study, Askary et al. (2024) investigated the effect of organic and chemical fertilizers on the yield of saffron and found significant increases in the levels of crocin, picrocrocin, and safranal when compared to the control group. Heydari et al. (2016) reported that applying 25 kg/ha of nitrogen fertilizer enhanced the levels of crocin, picrocrocin, and safranal. In contrast, the application of 50 kg/ha of nitrogen, while increasing the weight of flowers and stigmas, resulted in a reduction in the crocin, picrocrocin, and safranal content. The contradictory results regarding the content of these active ingredients can be attributed to the effects of various external factors, including climatic conditions, on the biochemical pathways involved in the synthesis of the respective compounds. This study demonstrated that nutritional status significantly influences the quality of saffron by affecting plant growth.

Number and weight of replacement corms

Saffron yield depends on the growth of replacement corms in the previous season. This study demonstrated the significant interactive effects of irrigation, nitrogen fertilizer, and methanol spraying on the number of replacement corms at the 1% probability level. Additionally, the interactive effect of year, irrigation, nitrogen fertilizer, and methanol spraying on the weight of replacement corms was also significant at the 1% probability level (Table 5). The findings indicated that both the number and weight of replacement corms were lower in the rainfed treatments compared to the irrigated treatments. In rainfed treatments, nitrogen fertilizer and methanol spraying failed to change these traits, as the lowest number of replacement corms were recorded in the rainfed plots. In the irrigated plots, higher levels of nitrogen fertilizer and methanol application resulted in an increased number of replacement corms. Across all nitrogen fertilizer levels, the application of 10% methanol spraying resulted in the highest number of replacement corms. The highest number of replacement corms (3.5 per m^2) was obtained in the irrigation × 90 kg/ha of ammonium sulfate × 10% methanol spraying treatment (Table 5). Balanced nutrient uptake is crucial for the formation of replacement corms and the yield of saffron flowers (Koocheki and Seyyedi, 2015). In another study, Azizi et al. (2023) emphasized the significance of management factors, including irrigation and nutrition, in the production of high-quality saffron corms. Insufficient irrigation results in reduced growth of replacement corms and diminished flower yield (Koocheki et al., 2014). In addition to the number of replacement corms, their weight also showed a significant increase in the irrigation treatments in both years of the study (Table 4). A study by Koocheki et al. (2016) has reported the positive effect of irrigation on the weight of replacement corms. Ensuring optimal water availability for saffron, particularly during low rainfall periods and early spring when significant weight gain in replacement corms occurs, can enhance the production of heavier corms.

In irrigation treatments, increasing the level of ammonium sulfate fertilizer reduced the weight of corms, while methanol spraying showed a positive effect on this trait (Table 4). The heaviest replacement corm (1.5 g) was obtained from the irrigation × no nitrogen fertilizer × 10% methanol spraying in both years of the study. Koocheki and Seyyedi (2020) reported that the application of chemical fertilizers resulted in the lowest number and weight of medium- and large-sized replacement corms. Chaji et al. (2013) investigated the effect of urea fertilizer on the number and weight of replacement corms in saffron and showed that the application of 100 kg/ha of nitrogen fertilizer resulted in a 36.5% increase in the number of replacement corms, whereas it led to a 17.4% decrease in their weight. The application of nitrogen-containing fertilizer significantly stimulated bud formation on the mother corm, resulting in an increased production of replacement corms. The competition among corms also resulted in a reduced weight of the replacement corms, which is consistent with the findings of this study. Koocheki et al. (2019) reported that certain intensive agricultural practices, including over-irrigation and excessive use of chemical fertilizers, can activate dormant buds and heighten competition among them for nutrients from the mother corm reserves and soil solution. This results in the production of numerous small corms, which diminishes the quantitative yield of saffron in the subsequent year. The primary economic value of saffron is associated with the three-branched stigma of the flowers; however, the cultivation of saffron corms can also serve as a source of income for farmers. Consequently, both the quality of the stigmas and the weight of the saffron corms significantly influence the economic performance of this crop (Azizi et al., 2023). The primary economic value of saffron is associated with the three-branched stigma of the flowers; however, the cultivation of saffron corms can also serve as a source of income for farmers. Consequently, both the quality of the stigmas and the weight of the corms significantly influence the economic performance of saffron (Azizi et al., 2023). Considering the effects of weather conditions, soil's physical and chemical properties, corm density, planting depth, and nutrient availability on the size of saffron replacement corms (Azari et al., 2023), it is crucial to follow effective management practices for the production of larger corms. The findings of this study also confirm the significance of irrigation and nutrients for saffron growth and quality.

Conclusion

The potential for multiple years of yield from a single planting, minimal water needs, irrigation during non-critical periods, along with its economic significance and access to international markets, contribute to the value of saffron as a crop. This study investigated the growth and quantitative and qualitative yield of saffron in the Deylaman region, northern Iran. This study aimed to assess the feasibility of cultivating this crop in the above-mentioned region and the effect of irrigation and fertilization on its quantitative and qualitative yield. For this purpose, two cultivation methods (rainfed and irrigated), four nitrogen fertilizer levels (0, 30, 60, and 90 kg/ha of ammonium sulfate), and foliar spraying with 0%, 5%, and 10% methanol were considered. The parameters evaluated included the number of buds, leaf count and area, flower weight, number of flowering plants, style and stigma length, dry weight of style and stigma, and the number and weight of replacement corms. The study findings indicated that irrigation and nitrogen fertilizer positively influence both the quantitative and qualitative growth of saffron. Methanol foliar spraying enhanced leaf growth and the number of buds and replacement corms under irrigation and nitrogen fertilizer treatments; however, it not only did not improve the quantitative yield of saffron but also exhibited a negative effect on saffron yield in rainfed plots and nitrogen fertilizer treatments. This study generally suggests that saffron cultivation in irrigated plots with the application of 90 kg/ha of ammonium sulfate fertilizer effectively enhances both the quantitative and qualitative yield of saffron in the studied region.

Declarations

Conflicts of interest:

The authors of this article declare that they have no conflict of interest.

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mazyar Farokhroz, Majid Ashouri, Naser Mohammadian Roshan and review and editing were done by, Ebrahim Amiri and Seyyed Mostafa Sadeghi. The first draft of the manuscript was written by Mazyar Farokhroz and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated and analyzed during the current study were available from the corresponding author on reasonable request.

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