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Climate and management factors influence saffron yield in different environments

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Abstract

The economic yield of saffron (*Crocus sativus* L.) has a wide range in different parts of the world, and it is not clear why this considerable difference exists. In this research saffron yield and yield components of 13 fields with varied geographic and climatic conditions were studied to determine which factor(s) are more important. Among the studied factors, temperature, field age, soil texture, bulk density, soil and water pH, irrigation events, and growth period had the greatest effect on saffron yield. The highest dry stigma weight, as economic yield, was obtained in three regions of Birjand (27 kg ha^{-1}), Sarayan (24 kg ha^{-1}), and Golshan (23.5 kg ha^{-1}), followed by Neyshabur (18 kg ha^{-1}) and Kashmar (17.5 kg ha^{-1}), which had lower temperatures, coarse soil, balanced soil, and water pH, and longer growth periods. The average yields were increased until the sixth or seventh year (20.8 kg ha^{-1}) and then decreased, however, it seems to be economic before the 10th year. Lower temperatures in early fall were important to stimulate flowering and increase yield in that year, and warm and sunny days in the spring are important for next year yields. We

Abbreviations: ECe, electrical conductivity of soil; ECiw, electrical conductivity of irrigation water; EWP, economic water productivity; SY, stigma yield; WP, water productivity.

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found that the optimal temperature for the first irrigation is ~16°C and for flowering is ~5°C–10°C. High-yield fields did not have higher irrigation water volumes but more irrigation events (6.3), resulting in less water volume per irrigation. No direct relationship was observed between manure consumption and yield; however, processed manure increases yield by improving the soil structure and moisture retention ability. Fields with a complete chemical fertilizer composition had higher yields. It was concluded higher yields are achieved in saffron fields where regions are higher in altitude (at least 1300 m) and lower temperature in early autumn with complete fertilizer composition (especially sulfur and iron). There was no evidence of high salinity sensitivity of saffron.

1 | INTRODUCTION

Saffron (*Crocus sativus* L.) from the Iridaceae family is one of the most valuable plants in the world that produces the most expensive spices (Koocheki & Khajeh-Hosseini, 2020). A special characteristic of saffron is having a biological cycle with a long pause in summer and active growth in autumn, which lasts until early spring. The corms are dormant (without leaves) in summer, although flower differentiation occurs at this time (de Juan et al., 2009).

Since saffron flowers are sterile and do not produce seeds, it is propagated asexually and through corms; therefore, breeding methods are not very effective. In this situation, efforts to improve the saffron yield have shifted to climate factors and field management including sowing time and method, fertilization, irrigation, soil situations, and so forth (Turhan et al., 2007). Proper farming practices along with the use of high-quality plant material help farmers to increase yield and consequently increase their profit (de Juan et al., 2009). The results of a study documented that most traits have little variation and therefore selection has no effect on improving traits; therefore, the best way to increase saffron yield is to improve farm management (Bayat et al., 2016).

Appropriate field management including proper planting date, selection of high-yielding ecotypes, suitable density, and larger and higher quality corms have undeniable roles in improving the yield, yield components, and quality of saffron products (Bayat et al., 2016). Climatic conditions are one of the most important factors determining the yield of saffron, which limits the development of its cultivation in different parts of the world (Bayat et al., 2016). Amirnia et al. (2013) and Siracusa et al. (2010) indicated that the environmental situations and corm origin have considerable influence on the saffron stigma yield (SY) and yield components. Furthermore, Gresta et al. (2009) and Maggi et al. (2011) showed quality and quantity of saffron were affected by climatic and environmental conditions such as air temperature and soil moisture content. Gresta et al. (2009) stated that the flowering start of saffron is affected by the interaction of air temperature and soil moisture, however, the timing of flowering is independent of the origin of the corm, environment, and planting density. They also concluded that colder environments lead to higher flower production, but lower quality stigmas.

Saffron is typically grown in arid and semiarid regions in early fall and completes the cycle by mid-spring (Pirasteh-Anosheh & Kamgar-Haghighi, 2019). Even though most of the life span for saffron occurs in autumn and winter, it should be irrigated with supplementary irrigation because most of the saffron fields are located in arid and semiarid regions. As rainfall is usually delayed in the autumn, it requires 100 mm of irrigation before flowering (Sepaskhah & Kamgar-Haghighi, 2009). Due to the scarcity of freshwater resources, especially in arid and semiarid regions, using brackish water for saffron farming is inevitable. In this situation, water management with saline water should be carefully observed because of the salinity sensitivity of saffron (Pirasteh-Anosheh & Kamgar-Haghighi, 2019).

The most important soil characteristics of saffron fields for successful production are good nutrient content, good bulk density, well-developed flexible structure, well-drained, and sufficient water-holding capacity (Shahandeh, 2020). Saffron is harvested at the beginning of the season; so does plant nutrition after harvest affect the yield? Adequate nutrition of mother plants leads to the production of more and larger daughter corms, which will increase next year's yield. Furthermore, with increasing temperatures and decreasing soil moisture in late winter and early spring, the mother corm nutrients are fully transferred to daughter corms (Rashed-Mohassel, 2020).

Despite all these interpretations, several agroecological factors play a role in determining the yield of saffron, of which the importance and the prioritization of many of them are still unknown. For example, it is generally believed that saffron is one of the most sensitive plants to salinity, therefore, prioritization can be challenging based on some research and experimental observations. The prioritization and importance

of factors have been investigated in the present study; so, the general purpose of this study is to investigate the effect of different factors, such as climatic conditions, field properties, fertilization, irrigation, and soil factors on the yield of saffron.

Core Ideas

- High temperatures are the main factor limiting development of saffron in new regions.
- Soil texture, bulk density, and soil and water pH influence the saffron yield.
- Saffron yield is affected by the irrigation frequency rather than irrigation volume.
- The saffron field yield increases until the sixth to seventh years and then decreases.
- A practical pattern was drowned for optimum air temperature during growing cycle.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

This study was conducted to investigate agroecological factors affecting saffron yield. This study examined the different characteristics of the saffron fields in different regions of Iran during the 2020–2021 growing season, and their characteristics are presented in Table 1. These 13 regions included Jiroft, Marvdasht, Ashkezar, Meybod, Golshan, Sarayan, Birjand, Bakharz, Kashmar, Neyshabur, Esfarayen, Shoqan, and Zanjan. Attempts were made to select fields from all saffron cultivation areas of Iran as the major saffron-producing country (90%−95% of the world's production) to cover all climatic conditions (i.e., weather, soil and water conditions, altitude, latitude, and longitude).

2.2 | Sampling and data collection

The necessary information was collected in six groups in early to mid-autumn during visits to the fields. The first group consisted of geographical information, age, and size of fields determined by satellite maps and farmers' information. Climate characteristics considered of temperature, precipitations, and relative air humidity were the second group. The climatic data were obtained from the synoptic meteorological stations of each region using the database of the Iran Meteorological Organization. The third group was related to plant nutrition, which was obtained through a questionnaire including manure, nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and other fertilizers. The soil characteristics of the fields were in the fourth group, which included taxonomy class, temperature regime, moisture regime, texture, bulk density, electrical conductivity (EC_e), and pH. The taxonomy class, temperature regime, and moisture regime were determined based on the USDA soil taxonomy methods (Anonim, 2014). Furthermore, the calculation of the texture and bulk density as well as the measurement of EC_e and pH of the soil were performed according to Klute (Klute, 1986). The ECe and pH were measured using an EC-meter (WTW, Terminal Le3 InoLab) and a pH-meter (Metrohm, 827 pH lab) in the soil-saturated extract. Due to the depth of activity of underground organs, soil sampling was done at a depth of 0–30 cm.

TABLE 1 Characteristics of the saffron fields in the surveyed regions.

Province	Region	Longitude (E)	Latitude (N)	Height (m ASL)	Field age (year)	Field size (m^2)
Kerman	Jiroft	57.146	28.709	1722	2	1000
Fars	Marvdasht	52.880	29.913	1612	3	1000
Yazd	Ashkezar	54.231	32.055	1133	3	1000
	Meybod	54.098	32.074	1138	2	2000
Isfahan	Golshan	51.742	31.935	1961	7	5000
South Khorasan	Sarayan	58.270	33.494	1365	4	15,000
	Birjand	59.349	33.328	1775	5	2000
Razavi Khorasan	Bakharz	60.312	34.996	1283	5	10,000
	Kashmar	58.175	35.22	1100	8	4000
	Neyshabur	58.796	36.211	1198	4	250,000
North Khorasan	Esfarayen	57.525	37.058	1248	4	5000
	Shoqan	56.881	37.342	1515	3	4000
Zanjan	Zanjan	48.450	36.683	1620	2	500

The fifth data set was related to field irrigation. This information included the electrical conductivity of irrigation water (EC_{iw}) and pH of irrigation water, irrigation number, total used water volume, and irrigation times. Yield and yield components of saffron in the sixth group of data were collected. To measure the yield and yield components, three randomly 10 m^2 samples were used in each field and consisted of flower number per area, average of single flower weight, flower weight per area, and stigma weight per area.

2.3 | Data analysis

Water productivity was obtained based on the ratio of yield to water consumption and through the following formula:

$$WP = \frac{SY}{TUW},$$

where WP, SY, and TUW are water productivity (g m^{-3}), stigma yield (g ha^{-1}), and total used water (m^3 ha^{-1}), respectively. Although in most crops, WP is calculated in kg m^{-3}, given that the economic yield of saffron is much lower in weight than other plants, WP was calculated in g m^{-3}.

The economic productivity of water was obtained by considering the economic value of water in the production of the product and using the following formula:

$$EWP = \frac{SY}{TUW},$$

where EWP, EY, and TUW are economic water productivity ($ m^{-3}), economic yield ($ ha^{-1}), and total used water (m^3 ha^{-1}), respectively. The price of saffron stigma is very variable in different parts of the world, however, 3.0 USD g^{-1} was considered for the price calculation as an average global price. The yield and yield components as well as WP and EWP were compared with standard error (±SE) with three replications. The statistical analyses were performed by SAS ver 9.2 software. The relationships between the traits were obtained using regression and correlation analyses performed by Microsoft Excel 2019 and SAS ver 9.2 software.

3 | RESULTS

3.1 | Geography and climate

The surveyed saffron fields were studied in all latitudes, however, they were mainly located in the eastern half of the country (Table 1). These fields were all in relatively high altitudes, ranging in height from 1100 to 1961 m above sea level (ASL) as shown in Table 1.

The year also had an important effect on the saffron yield, and with a limited increase in field life, the yield was also increased (Figure 1a). Age field had also a positive significant correlation (+0.672*) with the saffron yield (Table 2). The surveyed fields ranged in age from 2 to 8 years (Table 1), which covers almost all real fields of producers. However, the most yields were obtained from fields 4–5 years and older (i.e., Birjand, Sarayan, and Golshan). However, the yield also declined on old fields (e.g. Kashmar). According to the estimates, the yield of saffron increases until the sixth year, and then decreases, it is predicted that the yield in the 10th year will fall to a maximum of half the highest yield in the sixth year (Figure 1a).

Based on Köppen's climate classification, 13 saffron fields have three climate systems. Jiroft, Ashkezar, and Meybod have hot desert climate (BWh), Golshan and Bakharz have cold desert climate (BWk), Marvdasht, Sarayan, Birjand, Kashmar, Neyshabur, Esfarayen, Shoqan, and Zanjan have cold semiarid climate (BSk).

Three factors, air temperature, precipitations, and relative air humidity in the surveyed saffron fields were examined (Table 3). The air temperature was relatively well correlated with the yield of saffron fields so that lower air temperature was associated with a higher yield. In the four high-yielding Bakharz, Golshan, Sarayan, and Birjand fields, the average annual temperatures were 14.0˚C, 14.6˚C, 15.8˚C, and 17.0˚C, respectively, which were almost lower than in other areas (Table 3). The temperatures of the first 2 months of the saffron growing season, that is, October and November, were also lower in these four fields than in other fields (Table 3). Of course, this relationship was not absolute in the case of very low temperatures, because in Zanjan, where the air temperature was lower than all fields, no high yield was observed.

Monthly distribution and total annual precipitations were also approximately correlated with yield (Table 3). High-yield fields such as Sarayan, Bakharz, Kashmar, and Neyshabur had relatively good annual rainfall. Of course, fields such as Zanjan, Marvdasht, and Jiroft did not have much yield with relatively high rainfall. Except for Ashkezar and Meybod, in other fields, the rainfall distribution was such that there was rainfall in all months of the saffron growing season. There was no significant relationship between relative humidity and yield, and high-yield fields had almost moderate humidity (Table 3).

3.2 | Soil, fertilization, and irrigation

Soil classification of the saffron fields had little variation (Table 4). All examined saffron fields are located in Inceptisol and Aridisol taxonomy class, Mesic soil temperature regime,

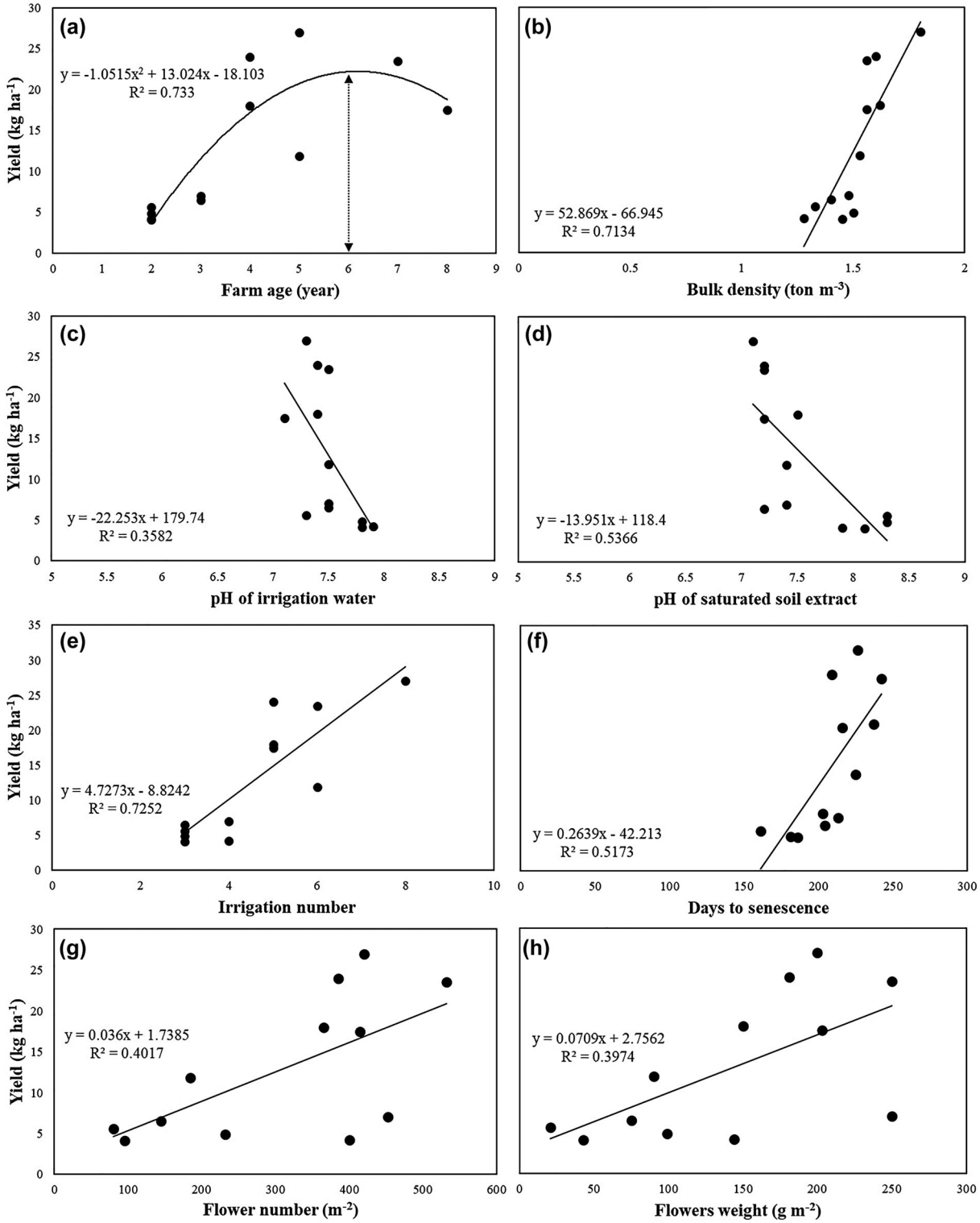

FIGURE 1 The relationship between different factors (a: farm age, b: soil bulk density, c: pH of water, d: pH of soil, e: irrigation number, f: senescence, g: flower number, and h: flower weight) with stigma yield in saffron. In (a), the dotted line is the estimated time to reach the maximum yield, after which the yield decreases.

and Xeric and Aridic soil moisture regime. The soil texture of the saffron fields was mostly on the lower left of the soil texture triangle, where the soil is usually not heavy. About 39% of the soil texture was sandy loam, and about 15% were loam. As most soils had coarse texture, their average bulk density was 1.49 ton m^{-3} ranging from 1.28 to 1.80 ton m^{-3} (Table 4). A close relationship was observed between the bulk density and yield (Figure 1b), as the higher yields were obtained in

TABLE 2 Correlation between the measured traits with yield (stigma dry weight).

Long	Lati	ASL	Age	Area	Manure	N
0.403 ns	0.148 ns	0.255 ns	0.672*	0.218 ns	0.230 ns	−0.368 ns
P	K	S	Bd	EC_e	pH_e	EC_{iw}
0.099 ns	0.195 ns	−0.144 ns	0.845**	0.138 ns	−0.733**	0.458 ns
pH_{iw}	IrrN	TUW	FN	SFFW	TFFW	
−0.609*	0.852**	−0.133 ns	0.634*	0.282 ns	0.63*	

Abbreviations: ASL, height above sea level; Bd, bulk density; EC_e, electrical conductivity of saturated soil extract; EC_{iw}, electrical conductivity of irrigation water; FN, flower number; IrrN, irrigation number, K, potassium; Lon, longitude; Lat, Latitude; N, nitrogen; ns, nonsignificant; P, phosphorus; pH_e, acidity of saturated soil extract; pH_{iw}, acidity of irrigation water; S, sulfur; SFFW, single flower fresh weight; TFFW, total flower fresh weight; TUW, total used water.
* and ** represent significance at 5% and 1% probability levels, respectively.

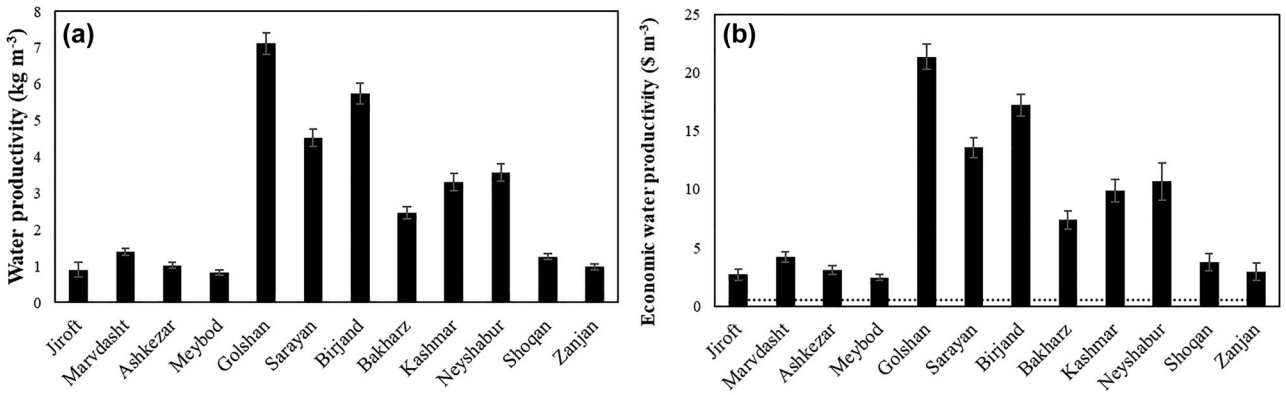

FIGURE 2 Water productivity (a) and economic water productivity (b) for saffron fields in different regions. In (b), the dotted line represents the economic water productivity of wheat as an indicator crop.

fields with higher bulk density (e.g., in Birjand, Neyshabur, and Sarayan).

In the studied saffron fields, an average of 42 ton ha^{-1} of manure was used (Table 5), most of which also used cattle manure. The minimum and maximum manure used were in Esfarayen and Kashmar by 15 and 100 ton ha^{-1}, respectively. There is no clear-cut trend in chemical fertilization between the fields (Table 5). All fields used manure, however, 85%, 70%, 70%, and 62% of fields used N, P, K, and sulfur S, respectively, but only 31% of fields (four out of 13) applied iron fertilizer as foliar application. Foliar spraying of humic acid and algae was also recorded in some of the fields. In Neyshabur, the farmer used a kind of enriched manure namely Eliuo. Eliuo is claimed to be an enriched manure (cow) that is continuously injected with moisture and aeration for a year. Then different types of plant residues including fruit pomace and plant waste are added, which is finally ready to be consumed in the form of a fully decomposed processed manure. In this field, 40 ton Eliuo per hectare was applied without any other manure or chemical fertilizers, however, it still achieved a high yield (18 kg ha^{-1}) on a large scale (25 ha).

The pH of soil-saturated extract (pH_e) and irrigation water (pH_{iw}) both affected the yield of saffron, as shown in both the correlation (Table 2) and the regression analyses (Figures 1c and 2d). The mean pH_e of the studied saffron fields was 7.6 ranging from 7.1 to 8.3 (Table 4), and the mean pH_{iw} was 7.5 ranging from 7.1 to 7.9 (Table 6). The correlations of pH_e (−0.733**) and pH_{iw} (−0.609*) with yield were significantly negative (Table 2). The highest pH_e was in Jiroft and Zanjan with low yields, whereas Ashkezar and Meybod regions also had the lowest yield and the high pH_e. The highest pH_{iw} was also in Meybod, Ashkezar, and Jiroft, all three regions with the lowest yields. Areas such as Birjand and Kashmar had high yields with low pH_e and pH_{iw}. In general, a negative inverse relationship was observed between pH_{iw} (Figure 1c) and pH_e (Figure 1d) with saffron yield.

The soil salinity (EC_e) varied from 0.9 to 5.8 dS m^{-1} (Table 4) and irrigation water salinity (EC_{iw}) varied from 0.40 to 4.10 dS m^{-1} (Table 6). No clear relationship was found between the soil and water salinity of the fields with the growth and yield of saffron.

The surveyed saffron fields were irrigated on average 4.5 times with 5030 m^3 ha^{-1} of total used water, however, the number and volume of irrigation water varied between three and eight times and 3650 and 5780 m^3 ha^{-1}, respectively (Table 6). Interestingly, the total used water was not related to

TABLE 3 The long-term average of weather characteristics of the surveyed regions.

Region	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
	Average temperature (°C)												
Jiroft	12	14	19	25	30	34	35	34	31	25	18	14	24
Marvdasht	5	7	11	16	22	27	30	29	25	19	11	7	17
Ashekzar	6	9	13	18	24	28	30	29	25	17	11	7	18
Meybod	7	9	15	18	25	29	33	31	26	19	12	9	19
Golshan	1	3	9	14	20	25	28	26	22	16	7	3	15
Sarayan	3	5	11	17	22	26	27	25	22	17	9	5	16
Birjand	4	6	12	18	23	28	29	27	23	18	11	6	17
Bakharz	1	3	9	15	20	24	26	24	20	15	8	3	14
Kashmar	3	6	10	15	21	26	28	27	23	17	10	5	16
Neyshabur	2	4	10	16	21	26	27	26	22	15	9	4	15
Shoqan	2	4	10	15	21	25	28	27	22	16	8	3	15
Esfarayen	0	2	7	13	19	23	16	25	21	14	7	2	13
Zanjan	−3	−1	5	11	16	22	25	24	20	14	7	1	12
Precipitation (mm)													
Jiroft	56	65	46	11	1	0	2	2	0	1	7	27	218
Marvdasht	66	54	56	26	6	0	0	0	0	2	24	49	283
Ashekzar	7	2	12.2	22.2	0.8	2.2	0	0	3.2	0	2.2	0	50.8
Meybod	6	1	11.5	22	0.9	2.3	0	0	2	0	1.5	0	47.2
Golshan	30	21	21	17	10	3	0	0	0	5	18	22	147
Sarayan	37	41	41	18	6	1	0	0	0	2	10	22	178
Birjand	31.3	32.4	35.1	31.6	7.1	0.3	0.1	0.2	0	2.6	8.4	19.7	168.8
Bakharz	44	68	71	52	25	4	0	0	0	6	18	31	319
Kashmar	29	24	31	37	17	2	0	0	0	6	13	19	178
Neyshabur	35	49	63	49	39	13	5	2	3	10	20	25	313
Esfarayen	27	32	43	29	20	7	4	2	2	8	16	17	207
Shoqan	21	24	36	23	12	5	3	1	2	7	13	13	160
Zanjan	33.5	30	45.7	56.5	46.2	7.3	4.6	3.4	4.2	26	28.8	29.2	315.4
Relative humidity (%)													
Jiroft	52	51	36	24	16	15	18	17	19	22	35	40	29
Marvdasht	57	55	46	40	25	17	17	17	19	26	44	54	35
Ashekzar	52	45	35	30	24	16	15	17	18	25	35	45	30
Meybod	50	43	33	28	25	15	15	16	16	22	30	44	28
Golshan	53	47	37	32	22	14	15	15	16	27	46	55	32
Sarayan	54	53	40	30	22	18	19	19	19	27	42	48	33
Birjand	57	55	46	38	27	21	21	22	22	28	39	52	36
Bakharz	64	65	57	48	34	25	25	23	26	35	54	58	43
Kashmar	55	53	44	41	33	23	23	24	23	30	37	50	36
Neyshabur	60	59	53	46	37	27	26	24	26	36	50	56	42
Esfarayen	67	67	59	54	47	35	32	28	33	43	57	65	49
Shoqan	61	59	51	46	40	32	32	29	36	43	57	63	46
Zanjan	72	69	61	54	49	40	38	39	38	49	59	68	53

TABLE 4 Soil properties of the saffron fields in the surveyed regions.

Region	Taxonomy class	Temperature regime	Moisture regime	Texture	Bulk density (ton m^{-3})	EC_e (dS m^{-1})	pH_e
Jiroft	Inceptisol	Mesic	Xeric	Sandy loam	1.50	2.5	8.3
Marvdasht	Inceptisol	Mesic	Xeric	Sandy loam	1.48	5.3	7.4
Ashkzar	Aridisol	Thermic	Aridic	Silty loam	1.45	5.5	8.1
Meybod	Aridisol	Thermic	Aridic	Silty clay loam	1.28	1.6	7.9
Golshan	Inceptisol	Mesic	Xeric	Sandy clay loam	1.56	1.2	7.2
Sarayan	Aridisol	Mesic	Aridic	Sandy loam	1.60	4.0	7.2
Birjand	Inceptisol	Mesic	Xeric	Loamy sand	1.80	5.8	7.1
Bakharz	Aridisol	Mesic	Aridic	Loam	1.53	3.2	7.4
Kashmar	Aridisol	Mesic	Aridic	Sandy loam	1.56	0.9	7.2
Neyshabur	Inceptisol	Mesic	Xeric	Sandy clay	1.62	5.5	7.5
Esfarayen	Inceptisol	Mesic	Xeric	Silty clay	1.44	2.3	7.6
Shoqan	Inceptisol	Mesic	Xeric	Loam	1.40	1.4	7.2
Zanjan	Inceptisol	Mesic	Xeric	Clay loam	1.33	2.5	8.3

Abbreviations: EC_e, electrical conductivity of saturated soil extract; pH_e, acidity of saturated soil extract.

TABLE 5 Fertilizations of the saffron fields in the surveyed regions.

Region	Manure (ton ha^{-1})	Nitrogen (N) (kg ha^{-1})	Phosphorus (P) (kg ha^{-1})	Potassium (K) (kg ha^{-1})	Sulfur (S) (kg ha^{-1})	Others
Jiroft	50	100	2	2	0	*[a]
Marvdasth	40	50	40	20	30	*[b]
Ashkzar	40	35	25	0	15	–
Meybod	40	50	0	0	0	–
Golshan	50	30	5	4	10	*[c]
Sarayan	40	50	50	15	20	*[d]
Birjand	40	35	50	25	30	*[e]
Bakharz	25	85	50	75	50	*[f]
Kashmar	100	0	0	50	0	–
Neyshabur	40[g]	0	0	0	0	–
Esfarayen	15	50	0	25	0	*[h]
Shoqan	20	45	20	20	50	*[i]
Zanjan	50	100	50	50	50	–

[a]Twice foliar application (NPK 20-20-20).
[b]Twice foliar application (Fe).
[c]Twice foliar application (NPK 20-20-20).
[d]Foliar application (NPK, humic acid, Fe, and algae).
[e]Twice foliar application (humic acid).
[f]One foliar application of NPK (20-20-20) and twice foliar application of P and K.
[g]Eliuo.
[h]Fe fertilization.
[i]Foliar application (NPK, humic acid, Fe, and algae).

the yield of saffron, while the irrigation number was closely associated with the yield. So, the correlation between the irrigation number and the yield was positive and significant (+0.852**) (Table 2), this relationship was also illustrated in the regression analysis (Figure 1e).

The most applied irrigation water was in Jiroft and Zanjan regions, followed by Sarayan and Kashmar (Table 6). The WP is a range of crop water efficiency in each region, which varied from 0.76 g m^{-3} in Meybod to 6.4 g m^{-3} in the Golshan region (Figure 2a). On the other hand, the highest EWP was in the Golshan area with 19.32$ m^{-3} and the lowest EWP was in Meybod with 2.29$ m^{-3} (Figure 2b). The first irrigation is the most sensitive irrigation for saffron, however, no relationship was found between the time of the first

TABLE 6 Irrigation characteristics of the saffron fields in the surveyed regions.

Region	EC_{iw} (dS m^{-1})	pH_{iw}	Irrigation number	Used water (m^3 ha^{-1})
Jiroft	0.95	7.8	3	5400
Marvdasht	3.70	7.5	4	5200
Ashkzar	2.91	7.8	3	3700
Meybod	0.75	7.9	4	5500
Golshan	0.75	7.5	6	3650
Sarayan	3.05	7.4	5	5750
Birjand	4.10	7.4	8	4800
Bakharz	0.45	7.3	6	4800
Kashmar	0.40	7.5	5	5780
Neyshabur	3.41	7.1	5	5250
Esfarayen	1.42	7.4	3	4360
Shoqan	0.60	7.5	3	5500
Zanjan	1.10	7.3	3	5700

Abbreviations: EC_{iw}, electrical conductivity of irrigation water; pH_{iw}, acidity of irrigation water.

irrigation and yield. The date of the first irrigation in 13 studied areas was 51 days, in other words, the interval between the earliest and the latest first irrigation was 51 days. The first irrigation in all fields occurred in September, October, and November, although about 85% of them were done in October, whereas the longer growing season resulted in greater stigma yield (Figure 1f).

3.3 | Yield and yield component

The three studied components of saffron yield in our study were flower number, single flower weight, and total flower weight (Table 7). Mean flower number and total flower weight were 314 and 143 g m^{-2}, respectively, which had a positive and significant relationship (+0.634* and +0.630*, respectively) with yield (Table 2). In general, higher flower numbers and total flower weight led to higher SY (Figure 1g,h). The highest flower number and total flower weight were obtained in Golshan and the lowest in Zanjan. Golshan, Birjand, and Kashmar, which had more flower numbers and total flower weight, also had higher SYs, whereas Ashkzar and Zanjan with lower flower numbers and total flower weight had the lowest SY (Table 7). The average single flower weight in the studied fields was 451 mg and had no significant relationship with yield (Table 2). The range of changes in the single flower weight was not very wide and ranged from 362 to 550 mg (Table 7).

Since we tried to select contrasting fields, the yields were very different among these fields, from 410 mg m^{-2} in Ashkzar to 2700 mg m^{-2} in Birjand (Table 7). The average yield of the studied fields was 1221 mg m^{-2} and 54% of the fields had a yield of more than 700 mg m^{-2}.

4 | DISCUSSION

The geographically selected areas were consistent with the geographical distribution of saffron cultivation in the country, and most of them were in the eastern half. However, in the same eastern half, they were present from the south to the north of the country. Since the fields were selected from the main areas of saffron cultivation, they can be considered representative of saffron cultivation areas. Therefore, it can be concluded that saffron is not cultivated in lowland areas, and it is mainly farmed in areas higher than 1000 m ASL. For example, in the city of Jiroft, which has a low altitude (690 m), the saffron fields were found in an area where it is considered one of the highest lands in that region. Therefore, it can be said that altitude is one of the important factors in choosing a saffron cultivation area. Kothari et al. (2021) identified saffron-prone environments in the Western Himalayas, where the height of selected sites ranged from 1472 to 2591 m ASL. In another statement, the most important saffron cultivation area in India is Kashmir, which is at an altitude of 1585–1677 m ASL with a temperate climate (Ganaie & Singh, 2019). In the research of Kothari et al. (2021), it was shown that flower number and fresh flower yield were significantly greater at a location with a higher altitude (2195 m), which could be attributed to the favorable environmental conditions, such as average temperature, total rainfall, and relative humidity. The importance of altitude in successful saffron cultivation has been shown in different regions (Ganaie & Singh, 2019; Kothari et al., 2021; Mykhailenko et al., 2020; Panwar et al., 1995); which is due to better weather situations.

A good relationship (+0.672*) was observed between field age and yield. This relationship is also an accepted principle among the producers, that yield is low in the first year but increases over time. Mykhailenko et al. (2020) indicated that better-quality corms were produced in the second year, which resulted in more flowers and greater yields. Kothari et al. (2021) also reported the flower number, fresh flower weight, and SY were significantly higher in the second year, and the interaction effect of year and geographical locations was significant on the growth and yield of saffron. The main increase is due to the increase in plant density per unit area, which is obtained from the reproduction of corms and the production of daughter corms every year. Each mother corm produces about five daughter corms per year if nutrition is well. Daughter corms are formed on the mother corms after flowering, and as a result, the density of the plant increases in each growing season compared to the previous year (Koocheki & Seyyedi, 2020). In a study, the number of corms in 1- to 8-year-old

TABLE 7 Yield and yield components of saffron in the surveyed field.

Region	Flower number (m^{-2})	Single flower weight (mg)	Flowers weight (g m^{-2})	Dry stigma weight (mg m^{-2})
Jiroft	232 ± 17.7	427 ± 37.3	99 ± 9.0	486 ± 21.1
Marvdasht	440 ± 36.2	550 ± 44.9	250 ± 20.4	700 ± 40.3
Ashkzar	95 ± 8.5	450 ± 34.9	43 ± 4.1	410 ± 14.2
Meybod	400 ± 31.4	360 ± 30.4	144 ± 12.6	420 ± 15.1
Golshan	532 ± 43.7	470 ± 41.2	250 ± 21.4	2350 ± 158.2
Sarayan	385 ± 33.6	470 ± 40.4	181 ± 14.7	2400 ± 185.2
Birjand	420 ± 35.6	475 ± 40.1	200 ± 14.3	2700 ± 197.8
Bakharz	184 ± 13.5	490 ± 40.4	90 ± 9.6	1165 ± 85.1
Kashmar	415 ± 33.2	490 ± 40.4	203 ± 14.7	1750 ± 140.8
Neyshabur	365 ± 31.3	410 ± 34.5	150 ± 12.3	1800 ± 135.2
Esfarayen	390 ± 33.2	385 ± 32.8	151 ± 11.6	460 ± 18.9
Shoqan	145 ± 10.7	515 ± 44.7	75 ± 6.4	650 ± 37.0
Zanjan	80 ± 5.8	262 ± 21.1	21 ± 3.0	560 ± 28.9

Note: Means in each column were separated using standard error (±SE).

fields was 55, 65, 71, 128, 151, 152, 184, and 248 m^{-2}, respectively (Mollafilabi et al., 2015), indicating an increase in the corms number as the field age increased to the eighth year. The performance of saffron fields over the years is highly related to the first-year corms density and quality. A field established by higher density and good quality corms will get to economical yields earlier. Although there is a belief that saffron yield is closely related to the size of the field, our findings did not provide any relationship to support this theory.

We estimated the highest yield is obtained in the sixth year, however, Koocheki and Seyyedi (2020) believe that the saffron SY increases with increasing field age until the fourth to fifth year, and then decreases. It was theorized that the yield of saffron decreases in terms of economic efficiency after the sixth year, but it is economically viable before the ninth to 10th year. The reason for the decrease in yield from the fourth to the fifth year (Koocheki & Seyyedi, 2020) or the sixth year (our finding) is that with the formation of high corm in the soil, soil firmness and compaction increase and soil fertility decreases (Koocheki & Seyyedi, 2020). During the growing years, due to the presence of saffron corms in the soil, it is not possible to order enough soil to improve soil conditions.

About 62% of surveyed saffron fields have a cold desert climate (BWk), and yield in this climate was greater than others. On the other side, three saffron fields with a hot desert climate (BWh) had the lowest yield. Saffron is planted in many different warm and cold climates, however, greater yield is obtained in cold climates (Koocheki & Khajeh-Hosseini, 2020). Negbi (2006) stated that the mild subtropical climate is the most suitable climate for saffron cultivation. Saffron production seems to be sensitive to climate change, as saffron yield has been reduced in recent years due to climate change (Duan, 2020).

Our results showed a good correlation between air temperature and precipitations with yield, in which temperature had a greater effect than precipitations. Lower temperatures, especially in the days before flowering, were associated with higher yields. In other words, fields with higher yields had lower temperatures. Air temperature reduction leads to the dormant corms waking up for a new growing season (Rashed-Mohassel, 2020). The central corm buds are induced by the lower temperatures, and root primordia appear at the base of corms (Negbi, 2006). Higher temperature postpones flowering (Rashed-Mohassel, 2020), decreases flower number, and reduces yield (Koocheki & Khajeh-Hosseini, 2020; Negbi, 2006; Pirasteh-Anosheh et al., 2022). In addition to greater yield, lower temperature also leads to better quality. A saffron crop is obtained under conditions with 13°C–19°C temperatures and 60%–65% relative humidity (Rashed-Mohassel, 2020). Although still in need of further study, the relatively high temperature (not hot) on sunny spring days, which coincides with the peak of leaf photosynthesis, could lead to more yields next year. So, it can be assumed that autumn temperature is important for determining the yield of the current year and spring temperature is important for determining the yield of the next year.

In general, the average annual rainfall of saffron fields (without Ashkzar and Meybod) was about 230 mm, and higher-yield fields had more rainfall. Precipitations during the early growing season and before flowering are very effective for increasing yield, whereas under drought conditions small flowers with small stigmas are expected (Negbi, 2006). Importantly, the high-yield monthly rainfall of the Golshan, Sarayan, Birjand, Bakharz, and Kashmar fields was zero (or close to zero) during the summer from July to September.

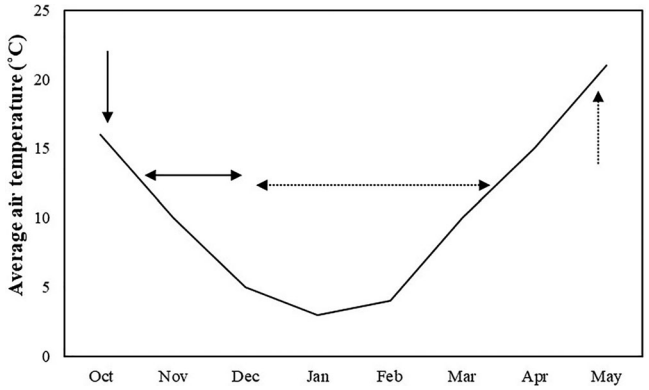

FIGURE 3 Optimal air temperature distribution during the saffron growing season for maximum yield. Black arrow, first irrigation; black double-arrow, flowering period; dashed double-arrow, daughter corms formation; dashed arrow, plant senescence.

Despite the high rainfall in Zanjan, the yield was lower. Perhaps one of the reasons is that there is not any month with zero rainfall in this region, even during the summer. Heavy rainfall in summer can damage saffron corms and therefore is considered as a harmful factor. Growth and yield are greater in subtropical regions with relatively cold winters and dry summers without rainfall in summer (Bazoobandi et al., 2020). Rainfall was less important in determining yield than the air temperature, perhaps because the lack of rainfall is compensated by irrigation.

By examining field management and the saffron growth and yield, we plotted the appropriate temperature distribution for maximum yield in Figure 3. It seems that the optimal temperature for the first irrigation and flowering period is around 16˚C and 5˚C–10˚C, respectively. Flowering occurs when air temperatures reach around 12˚C (Koocheki & Khajeh-Hosseini, 2020). Although saffron is known as a hysteranthous plant (Negbi, 2006), however, it can also act as a synanthous plant depending on temperature (Rashed-Mohassel, 2020). The flower appears before the leaves in the hysteranthous plant and after the leaves in the synanthous plant. The first watering is the critical stage of the irrigation in saffron, however, no clear-cut trend was observed between the date of first irrigation and SY. As saffron is a hysteranthous plant, so the first irrigation should be done according to the temperature of the environment (Hashemi et al., 2023). The time of the first irrigation is an important determinant for the saffron yield because the vegetative growth dominates (like a synanthous) and the flower emergence occurs less if the first irrigation takes place earlier, as a result, the yield reduces (Pirasteh-Anosheh et al., 2022). Even if early irrigation coincides with inappropriate air temperature, there is a possibility of zero (or close to zero) yield.

The findings of current research showed that saffron is cultivated in soils with Xeric or Aridic soil moisture regimes, which could provide plant corms with a dry environment in warm seasons. This fact is very important to land evaluation for planting new fields because the propagation of saffron corms is very vulnerable to fungi disease and other infections when its surrounding environment is warm and moist (Bazoobandi et al., 2020; Rezvani-Moghaddam, 2020). Also, keeping the soil dry and free of soil moisture in the summer during corm dormancy is very important for keeping the corms healthy and consequently the yield of the upcoming cropping year. Otherwise, the corms will rot in the wet (or damp) soil during the warm season. Saffron demands cold winters and dry summers for better propagation and economically efficient production (Ghorbani & Koocheki, 2017). The saffron fields were located in areas with Mesic and Thermic soil temperature regimes, to meet those demands.

Most saffron fields had light soil, which was either inherently coarse or improved using additives. This finding was also reflected in the bulk densities of the surveyed saffron fields, as all of them had a bulk density equal to or greater than 1.3 tons m^{-3}. Soil swelling and shrinking properties mostly appear in heavy soils, which have a high amount of expandable clays (Jones et al., 2020). These bad properties postpone and reduce well sprouting of saffron plants (Saeidirad, 2020). Choosing lands with coarse texture soils and the application of high amounts of organic manure is an important part of Iranian ethnic knowledge of saffron cultivation. In our surveyed saffron regions, the fields with light soil (quantified by bulk density) had greater yields.

Although no significant correlation was found between the amount of chemical fertilizers and the yield of saffron, interestingly, the fields that all used N, P, K, and S fertilizers had higher yields. It was estimated that 0.3%−2.0% organic materials were added by manure fertilization. Although the use of manure or large amounts did not necessarily lead to increased yields, high-yield fields used sufficient manure (40–100 ton ha^{-1} as shown in Table 5). The manure enriches the fields and provides the saffron plant with plenty of nutrients, including N, P, K, and microelements (Kononova, 2013). Organic matter also reduces the soil swelling and shrinking properties, in addition, improves the soil physical properties such as moisture capacity and mechanical resistance (Hanks, 2012). It seems that only processed manure could be beneficial in yield increasing, as we observed in Neyshabur by Eliuo. Based on the results of this study and the authors' empirical observations, we offer a comprehensive practical fertilization recommendation: (1) 50 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, 100 kg of potassium sulfate per hectare, 6 L ha^{-1} of humic acid (12%) with the first water, (2) 10–15 kg of potassium sulfate per hectare and 50 kg N ha^{-1} after harvesting flowers, and (3) complete fertilizer (NPK 20-20-20) along with micronutrients (e.g., iron and zinc) as foliar application in late January to early March. From the middle of February onwards, the roots of the mother corms are drying up and they are not

very active in absorbing nutrients. While forming daughter corms do not have roots to absorb, but need high nutrients for growth. Therefore, foliar application of a complete combination of micro- and macro-fertilizers is necessary at this time.

Among these conditions, soil nutrient content has received the most attention since it can be changed more readily than the others after corms are planted. However, soil texture among all soil properties evaluated has been suggested to be the most significant factor for saffron production in Iran. This is because other soil characteristics, such as bulk density, aeration, infiltration, and drainage are harder to change, are related to soil texture, and can influence all these properties (Shahandeh, 2020).

Saffron growing fields mostly were coarse soils, which can provide a better environment and have low mechanical resistance for the corms sprouting at the first growing season and propagation in the late growing cycle. Otherwise, farmers inevitably use plenty of organic manure each year. In Iran, most saffron fields are located at the foot of the mountains or near the mountains and these local lands mostly originated from sediments and debris of the mountains. Most of these evaluated lands have coarse soils and Xeric/Aridic soil moisture regimes which endure enough cold winters. Regarding the low water holding capacity of coarse texture soils (Hanks, 2012), as our data showed, using high amount of manures might be due to balancing soil conditions for both water holding capacity and reduction of soil mechanical resistance.

Birjand, Kashmar, Sarayan, and Golshan, the fields with a higher yield, had less pH_e (Figure 1d) and pH_{iw}. In general, the inverse relationship between pH_e and pH_{iw} with the yield of the studied fields was well demonstrated. Soil pH strongly affects soil functions and the availability of water and nutrients for plants (Khalil et al., 2015). McGimpsey et al. (1997) examined 19 saffron fields around the world and reported soil pH of 16 fields ranging from 6.0 to 7.8, and soil pH of three saffron fields in New Zealand ranging from 5.2 to 5.6. However, some researchers (Dhar, 2000; Gresta et al., 2008) indicated that the optimum pH is neutral to slightly alkaline (6.8 to 7.8). In general, highly acidic and alkaline soils seem to be not suitable for saffron cultivation.

Soil and water salinity of the saffron fields were maximum of 5.8 and 4.1 dS m^{-1}, respectively; which is not really considered very saline water and good enough to grow saffron well (Pirasteh-Anosheh et al., 2022). Although various studies have shown the sensitivity of saffron to salinity (Sepaskhah & Kamgar-Haghighi, 2009; Yarami & Sepaskhah, 2015), our findings showed economic production of saffron is achievable even in relatively saline conditions. It seems that literature, often based on controlled experiments in a field or greenhouse, has overstated the salinity sensitivity of saffron. For example, Yarami and Sepaskhah (2015) evaluated the varied fertilization rates and different irrigation systems and reported the threshold EC_e for saffron yield between 0.52 and 1.12 dS m^{-1} in 2011–2012 and between 0.56 and 1.14 dS m^{-1} in 2012–2013. These values are far from the realities of agriculture. Of course, saffron is not a tolerant plant to salt stress. Either way, due to Iran struggling with the land salinization phenomena situation (Pirasteh-Anosheh et al., 2021), the cultivation of saffron may be in danger of salt stress.

We could not find a clear relationship between irrigation water volume and yield, as regions such as Zanjan, Jiroft, and Shoqan, although consuming high volumes of water, did not have higher yields than other regions. However, the number of irrigations had a good relationship with yield, in Birjand, Golshan, and Kashmar fields, which had more irrigation numbers, higher yields were obtained. Considering enough winter precipitations, the water availability in 12-day intervals in spring up to the leaf senescence has an increasing effect on daughter corms size and flowering in the next year (Behdani & Fallahi, 2015). Sepaskhah and Kamgar-Haghighi (2009) reported less flowering period and delayed flowering initiation in rain-fed conditions compared with normal irrigation. Based on their estimation, irrigation with 15- and 24-day intervals is needed in the region with 200- and 400-mm rainfall. Referring to the need for 300 mm of rainfall for the successful production of saffron, Coskun et al. (2017) believed that Karabuk in the Black Sea region of Turkey with 440 mm annual rainfall can be a good region for saffron cultivation.

There was a great deal of variation in WP in different fields, which was due to both differences in yields and the volume of consumed water. The reasons for low WP in Meybod can be several factors, including soil and water quality, climatic conditions, type of water source and irrigation system, land ownership and area, and the amount and type of agricultural operations and inputs. In a study (Sepaskhah & Kamgar-Haghighi, 2009) by examining saffron fields with varied ages and different irrigation systems and schedules, yield-based WP was reported between 11 and 464 g m^{-3}. Pirasteh-Anosheh et al., 2022 also reported biomass-based WP ranging from 0.221 to 0.295 kg m^{-3} in the first year, 0.315 to 0.539 kg m^{-3} in the second year, and 0.661 to 0.891 kg m^{-3} in the third year.

Despite the very low WP of saffron compared to other crops such as wheat, due to the much higher economic WP (Figure 2b), saffron cultivation is economically viable. The economic water efficiency of saffron was about 16 times that of wheat on average. Due to this issue and the potential of areas such as Golshan, Sarayan, and Nishabour, saffron cultivation can lead to more efficient use of limited water resources compared to the development of crops such as wheat and corn with higher water requirements. This recommendation does not mean the elimination of other crops from the cultivation program of these regions, and appropriate cultivation patterns should be considered based on the climatic, economic, and social situation of the regions.

It should also be noted that this amount of economic water efficiency of saffron is obtained only for the stigma, while in addition to the stigma, the other organs can also be used. Saffron petals can be used as food coloring because the petals have anthocyanin dye. In conditions of limited resources for agricultural development, shoots and petals can be used to feed livestock; as research has shown saffron petals have intermediate forage quality and digestibility in comparison with good-quality forage plants such as alfalfa. Feeding of saffron shoots by local livestock such as sheep and goats has been reported in Khorasan (Koocheki & Khajeh-Hosseini, 2020). Saffron shoots can be used to feed livestock and tiny corms that are not suitable for stigma production can also be used in the starch industry. Based on a report (Pirasteh-Anosheh et al., 2022), the shoot biomass in well-managed saffron was enough to be considered as a new forage source in semi-saline conditions. As a result, by considering other parts of saffron in calculating the WP, the obtained values will be high.

The weight of a single flower was an almost unchanging trait that did not have much variance between the studied fields. If the two lowest fields (Meybod and Zanjan) were excluded, the weight of each flower was about 0.5 g. However, the other two components of yield, flower number per unit area and total flower weight with high variance had a positive effect on yield. In similar findings, it was reported that the saffron flower number is positively correlated with the SY, however, the correlation of flower number with single flower weight was negatively significant (Gresta et al., 2009). Saffron flower and corm yield is determined by the influence of several factors consisting of climatic, edaphic, agronomic, and to some extent physiographic factors (Rezvani-Moghaddam, 2020). Birjand, Sarayan, and Golshan fields had more SY with more flower number and flower weight. Of course, the number of flowers depends on the age of the field, if the passage of time and the daughter corms production increases the number of corms and flowers per unit area. This was the reason why saffron yield had a significant relationship with field age in our study. The growth rate of daughter corms mainly depends on the leaf photosynthesis of the mother plant; hence, proper leaves development (number and area) has a considerable influence on producing larger daughter corm and consequently increase the yield of the next year (Rezvani-Moghaddam, 2020). The saffron SY each year generally depends on the stored corm nutrients from last year's growth and not directly on the soil and fertilization of the current year (Shahandeh, 2020).

5 | CONCLUSIONS

Saffron yield is affected by various climatic, soil, irrigation, and fertilization factors as well as field management. The results of our research showed that there is no limit in terms of latitude and longitude for saffron cultivation, however, the altitude should be above 1000 m ASL. The yield of saffron increased until the sixth year and then decreased, however, it seems to be still economic before the 10th year. The application of fertilizers composition was well associated with increased yield, and manure is an integral part of saffron cultivation, which is most likely due to the effect on soil texture. Coarse soil texture with higher bulk density, lower EC, and pH, along with lower EC and pH of water was directly related to higher saffron yield. The irrigation number had a greater effect on yield rather than the irrigation volume. The growing cycle of saffron was about 7 months, and higher yielding fields had longer growing periods. In general, climate, field age, soil texture, soil and water pH, irrigation number, growth period length, and flower number are the most important factors determining saffron yield that can lead to more yield with proper management.

AUTHOR CONTRIBUTIONS

Hadi Pirasteh-Anosheh: Conceptualization; data curation; formal analysis; project administration; writing original draft; writing—review and editing. **Mohammad Javad Babaie-Zarch and Mohammadebrahim Nasrabadi**: Data curation; investigation; writing—original draft. **Amir Parnian**: Data curation; formal analysis; writing—original draft. **Seid Mohammad Alavi-Siney and Seyed Elahe Hashemi**: Data curation; writing—original draft. **Hossein Beyrami**: conceptualization; formal analysis; writing—original draft. **Hamed Kaveh and Marco Race**: conceptualization; writing—review and editing. **Urs Durrer and Karl McDonald**: Formal analysis; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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