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Research Paper

Application of a superabsorbent hydrogel for improving water productivity and quality of saffron (*Crocus sativus* L.) under water deficit conditions

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ABSTRACT

Water deficit regimes and techniques using moisture-absorbent materials are the main approaches to achieving the goals of sustainable agriculture and water resources conservation in arid and semi-arid areas. A field experiment as a split-plot based on randomized complete blocks design with three replications at the research farm of the Saffron Institute of the University of Torbat Heydarieh during three consecutive crop years (2015–16, 2016–17, and 2017–18). The main plots consisted of three irrigation regimes 20 (W1), 35 (W2), and 50-day irrigation interval (W3), and the sob-plots included without application (H0) and application of superabsorbent hydrogel (H1). The research findings showed that the highest values of the plant leaf number (19.3, 21.3, and 33.5, respectively) and the dry leaf yield (2291.9, 3837, 4979.5 kg ha^{-1}, respectively) during the experiment years were achieved from the application of hydrogel under full irrigation condition (W1H1). The improvement in these crop parameters was significantly higher when the hydrogel was used under water deficit compared to well-watered conditions. Based on the three-year means, the highest increase in the leaf number (18.1 %) as a result of the hydrogel application was observed in the W3 treatment, while the highest increase in the dry leaf yield (24.8 %) was observed in the W2 treatment. The fresh flower yield also peaked in the W1H1 treatment (776.5, 1421.1, and 2074.8 kg ha^{-1}, respectively). Similarly, dry stigma yield reached its highest values (6.3, 11.2, and 17.0 kg ha^{-1}, respectively) in the W1H1 treatment. While the highest increase in the two mentioned traits due to hydrogel application in the experiment years (25.3 and 32.9 %, respectively) was obtained when the saffron plants were subjected to a 35-day irrigation interval. While the W1H1 treatment displayed the highest corm number (122.8, 252.8, and 341.4) and corm yield (19.8, 31.7, and 45.1 t ha^{-1}), the effect of hydrogel in improving these parameters was greater under prolonged irrigation intervals, so that the highest increase in the corm number (19.6 %) was obtained under 35-day irrigation interval and in the corm yield (21.9 %) was observed under 50-day irrigation interval. The flower-to-stigma conversion factor and water productivity achieved their peak values in the W2H1 treatment (0.98, 1.1, and 1.0 %, and 0.0018, 0.0020, and 0.0043 kg m^{-3}, respectively). Furthermore, the W2H1 treatment exhibited the highest concentrations of crocin (11.9 and 12.2 %), picrocrocin (6.7 and 5.8 %), and safranal (2.6 and 2.4 %) in the last two years of the experiment. This underscores the potential of hydrogel application in enhancing not only yield-related parameters but also the quality attributes of saffron.

In summary, the findings highlight the positive influence of superabsorbent hydrogel in mitigating the impact of water deficit on saffron cultivation, offering a promising avenue for sustainable and efficient water management in arid agricultural regions.

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1. Introduction

Climate change is considered the main global challenge in the 21st century. It has irreparable and irreversible impacts on the sustainability of natural agroecosystems (Wang et al., 2021). Climate change and global warming have the greatest effects on agriculture and food security, with stronger negative impacts in arid and semi-arid regions. The challenge of access to fresh water worldwide is becoming crucial. This is even more acute in dry areas, facing severe water shortages directly affecting human societies. Moreover, population growth and increasing water demand are the main obstacles to sustainable development (Gorjian and Ghobadian, 2015).

The average global water consumption in agriculture is about 70 %, while this amount in Iran is higher than 90 % (Samian et al., 2015). In addition to the much higher consumption of water for irrigation, the efficiency of irrigation systems in Iran is very low with an average of about 35 % (Madani, 2014), well below the range of 70 to 90 % in most developed countries (FAO, 2016). Thus, irrigation management strategies aiming to reduce water consumption and increase water use efficiency are vital to achieving water security and sustainability in this region.

Due to limited access to water in Iran, residents from different regions have, for many years, used innovative strategies to adapt to climatic conditions, trying to maximize water use efficiency under water shortage conditions. These strategies have been used in agriculture throughout history and adapted to produce different crops. Some of the most essential techniques include selecting drought-resistant plant species, type of cropping system, water catchment, and harvesting systems, and establishing appropriate irrigation practices (Mirzaei et al., 2024). In this sense, the cultivation of saffron (*Crocus sativus* L.) in the east and northeast of Iran has a very long history, so the employment and livelihood of many households depend on this valuable crop.

Although Iran is ranked first among saffron-producing countries in terms of cultivated area and annual production, its average yield is low compared to the global average yield of this crop (Kumar et al., 2009). Climate change and global warming, and most importantly frequent droughts, and lack of freshwater resources, are the primary reasons for this decline in yield. Saffron is cultivated in most of Iran's saffron cultivating areas by traditional methods, and the lands under saffron cultivation are typically managed in smallholder farms. One of the common operations in saffron cultivation in Iran is the irrigation method, which mainly performed as basin irrigation (furrow irrigation). Moreover, the water source for most saffron fields is qanat (underground channel). For this reason, one of the main challenges in saffron cultivation in these areas is the supply and management of irrigation water. Due to limited water resources and the extent of saffron fields, even if irrigation water is available, this water may be provided by going through a very long irrigation cycle and with a long delay. Thus, irrigation management and increasing water use efficiency in saffron cultivation should be among the main priorities of researchers, planners, farmers, and policymakers in the Iranian agricultural sector.

Researchers have recently made great efforts to improve crop water productivity. In doing so, they have considered water deficit and irrigation frequency approaches, the use of water-absorbing compounds, and the prevention of water loss as the main strategies (Islam et al., 2011). In irrigation management, the water deficit method aims to prevent the adverse effects of severe stress on plant growth with special techniques while reducing the use of irrigation water and increasing water productivity (Sabbaghpour, 2003; Piri et al., 2011; Rodrigo-Comino et al., 2022; Al-Shammary et al., 2023).

Superabsorbent hydrogels (SAH) are solid polymer networks made of hydrocarbons with a three-dimensional cross-linked structure (Singh et al., 2021). They can absorb water from rainfall or irrigation and store it, preventing water losses through drainage and evaporation. Moisture absorbed in SAH can be used during plant growth (Zhong et al., 2013; Moradi-Ghahderijani et al., 2017; Saha et al., 2020). Additionally, SAH can improve the availability of nutrients through their gradual release (Noppakundilograt et al., 2015; Rizwan et al., 2021). Applying SAH in soils is known as a water deficit technique and water conservation strategy used in arid and semi-arid regions (Wu et al., 2008; Rafieian et al., 2019; Tianjiao et al., 2022). Safari Zarch et al. (2020) conducted a study evaluating the impact of different levels of superabsorbent polymer on saffron. Their findings suggested that this soil amendment could serve as a viable option for enhancing saffron traits, particularly in regions facing drought stress.

Saffron holds significant importance in the arid and semi-arid regions of northeastern Iran, contributing substantially to farmer livelihoods, industrial development, and non-oil exports. However, the scarcity of water resources poses a significant challenge to the expansion of cultivated areas and the production of this valuable crop. Limited research has explored the interaction between moisture absorbents, soil conditioners, and irrigation regimes on saffron plants, with a particular focus on qualitative aspects.

Against this backdrop, this study aimed to achieve two primary objectives: (1) investigate the effects of water deficit on saffron yield and quality indices; and (2) assess the effect of superabsorbent hydrogel (SAH) application on yield, quality and water productivity of saffron under full irrigation and water deficit conditions in an arid climate.

2. Materials and methods

2.1. Experimental site

The experiment was performed at the research farm of the Saffron Institute of the University of Torbat Heydarieh in Zaveh, Khorasan Razavi province, Iran (35° 21' N, 59° 36' E, and 1484 m a.s.l.). Fig. 1 shows the experimental site location. The average annual temperature of the area is 14.3 °C, while the minimum and maximum temperatures are −4.3 and 33.5 °C in February and August, respectively. The average annual rainfall is 274.8 mm, with precipitation mainly occurring between January and April. The average annual relative humidity is 46 %, with a minimum of 33 % and a maximum of 64 % during August and February respectively. Based on the Köppen-Geiger classification, the area's climate belongs to the dry climate category. Fig. 2 presents the climatic monthly averages of the study area during the experiment years.

2.2. Experimental design, soil, and irrigation water characteristics

The experiment was performed as a split-plot based on a randomized complete blocks design with three replicates from 2015 to 2018. The first factor included three irrigation regimes of 20 (W1), 35 (W2), and 50-day intervals (W3), and the second factor involved no application (H0) or application of a SAH at a rate of 250 kg ha^{-1} (H1). The SAH is commercially available as SUPERAB A200 (price: 2.57$ per kg) from Khorasan Petrochemical Company (Bojnurd, Iran). The main characteristics of the SAH are given in Table 1.

Before implementing the design, soil samples were collected at the experimental site from the top 30 cm for soil characterization (Table 2). The soil texture was measured by decantation method based and characterized according to the USDA soil texture classification (Gee and Bauder, 1986), pH in a 1:1 water-to-soil suspension (Mclean, 1982), soil electrical conductivity (EC) in a 1:1 water-to-soil solution (Jones, 2001), organic carbon by wet oxidation (Walkley and Black, 1934), and N, P, and K were determined using the Kjeldahl, colourimetric, and spectrophotometric methods, respectively (Yang et al. 2008). The irrigation water was sampled and analyzed using the methodologies provided by APHA, AWWA, and WEF (2005). Na was measured by flame emission spectrometry; carbonate, bicarbonate, Ca, Mg, and Cl by the titration method; and sulphate by spectrophotometry (Table 3). The sodium adsorption ratio (SAR) calculated according to Suárez et al. (2006):

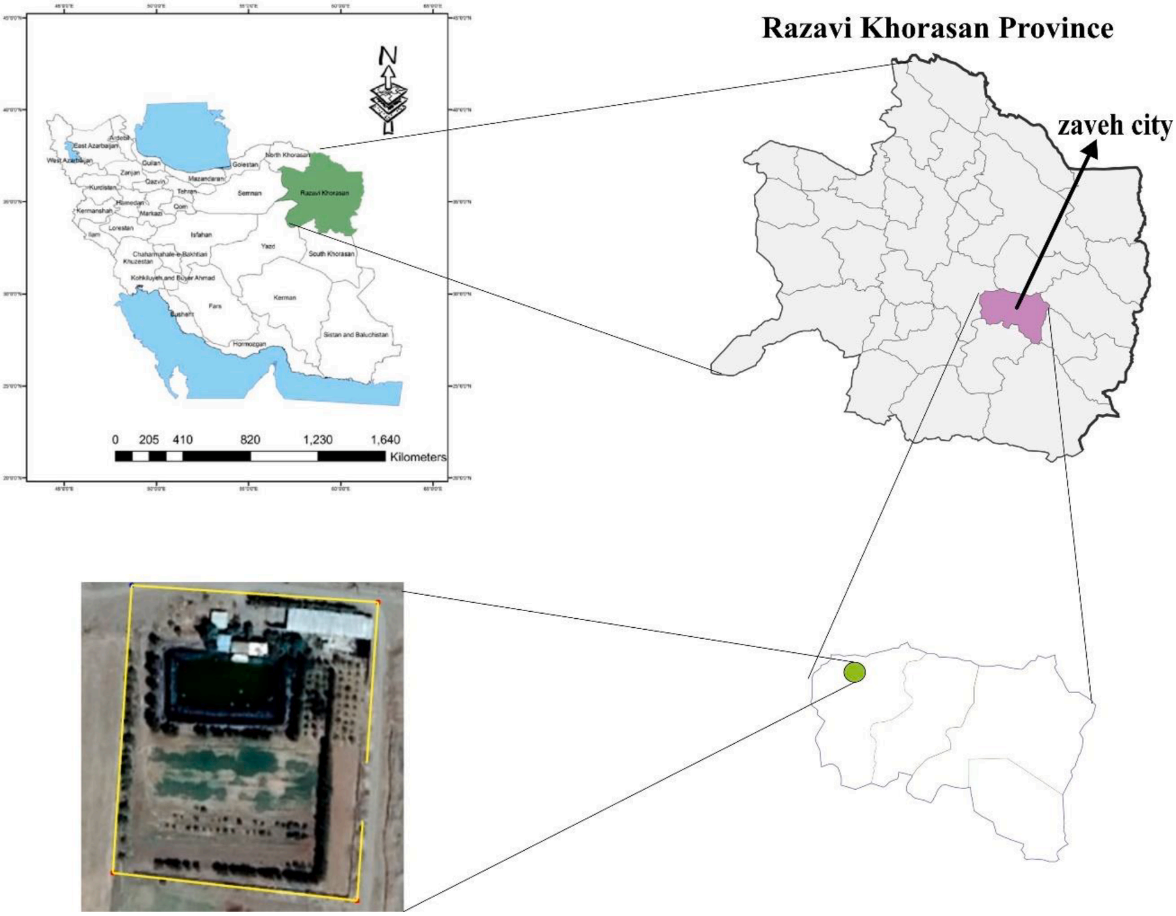

Fig. 1. Experimental site location.

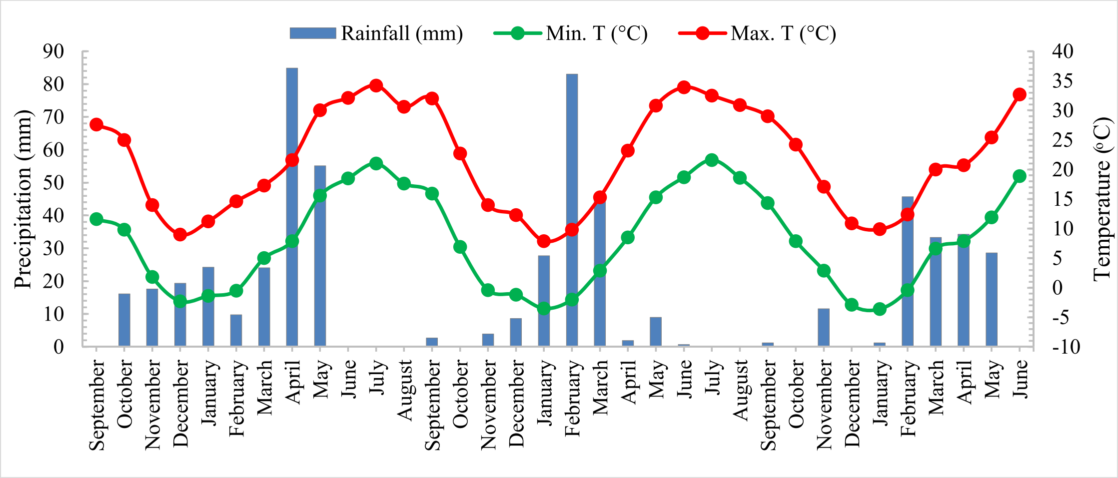

Fig. 2. Climatic monthly averages of the study area during the experiment years (2015–2018).

Table 1
Main characteristics of the super absorbent hydrogel applied.

Appearance	Particle size (μm)	Density (g cm^{-3})	Maximum Stability (year)	Moisture (%)	Water absorbing capacity (g^{-1})	Solubility	pH
White granular	1.3	1.4–1.5	7	5–7	220	Insoluble	6–7

Table 2
Summary of soil physicochemical properties at the experimental site.

Soil texture	EC (dS m^{-1})	pH	Total N (%)	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Organic carbon (%)
Sandy loam	1.3	7.9	0.083	14.8	253	0.881

Table 3
Chemical analysis of irrigation water applied.

SAR	Cations (meq L^{-1})		Anions (meq L^{-1})			
	$Mg^{++}+Ca^{++}$	Na^{+}	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}
8	1.7	0.053	0.5	3.0	0.75	0.14

$$SAR = \frac{Na^{+}}{\frac{1}{2}(Ca^{++} + Mg^{++})}$$

where Na^{+}, Ca^{++}, and Mg^{++} are the ion concentrations expressed in meq L^{-1}.

Table 4
Amount of irrigation water applied during the growing season of saffron.

Irrigation interval Year	20-days	35-day	50-day
	Irrigation water amount (mm)		
2015–2016	488	258	217
2016–2017	524	310	259
2017–2018	490	264	234

2.3. Implementation of the experimental design and crop management

After plowing and crushing the clods, the experimental site was levelled. Then, experimental plots of 4 × 2 m (8 m^2) were created manually, with a 2 and 1 m distance between blocks and plots, respectively, to eliminate the effects of treatments on each other. Before planting, in plots treated with the SAH, furrows at a depth of 15 cm were made in the rows of cultivation, and the SAH (100 kg ha^{-1}) was poured into the furrows at the corresponding rate. Planting of the corms (September 25, 2014) was done at 15 cm soil depth with a density of 50 corms m^{-2} (20 cm distance between the rows and 10 cm distance between the corms in the row, Fig. 3a). The weight of the planted corms was between 8 and 10 g.

The first irrigation (as pre-flowering irrigation) in each plot was performed as a basin irrigation method on October 12, 6, and 8 from the first to the third year of the experiment. The second irrigation (as post-flowering irrigation) was applied on December 9, 12, and 7 for each of the experiment years, respectively. Additional irrigation was performed based on the established irrigation intervals of 20, 35, and 50 days from the end of flowering to the end of plant growth in mid-spring for each year. Table 4 presents the amount of irrigation used for each treatment during each year of the study period. The difference between the amounts of irrigation water used for each of the irrigation regimes is primarily related to the saffron field age and secondly to changes in climate, especially the amount and distribution of rainfall during the years of the experiment. To improve the soil surface condition and facilitate the emergence of flowers, crust-breaking operations were carried out after the first irrigation every year. To control weeds, two stages of manual weeding were done in December and January every year. No specific pests or diseases were observed in the field during the study period.

2.4. Sampling and measurements

Considering that the growth characteristics and yield of saffron during the initial growing season can be influenced by corm characteristics, particularly its nutritive reserves, this might impact the accuracy of experimental evaluations. Hence, the data from the second and fourth flowering seasons (autumn of 2015, 2016, and 2017, corresponding to field ages of 2, 3, and 4 years, respectively) were exclusively considered. Notably, the experimental treatments, particularly those related to irrigation, did not have an impact on the first flowering season since the irrigation intervals were implemented after the initial flowering season. The saffron flowers were harvested every day from each plot in November of each flowering season (Fig. 3b). Immediately after harvesting, the flowers were placed in a plastic bag and weighed using a precision digital scale (±0.0001 g), and then the fresh flower yield was calculated in kg ha^{-1}. Afterwards, the saffron stigmas were separated from the flowers, and each sample was dried for 72 h at room temperature. Then, the stigmas were weighed and calculated in kg ha^{-1}.

To measure the number of leaves, five plants from each plot were randomly selected. Dry leaf yield was measured in March 2016, 2017, and 2018 by randomly harvesting plant leaves in 0.5 m^2 from each plot, drying the samples at room temperature for six days, and then weighing

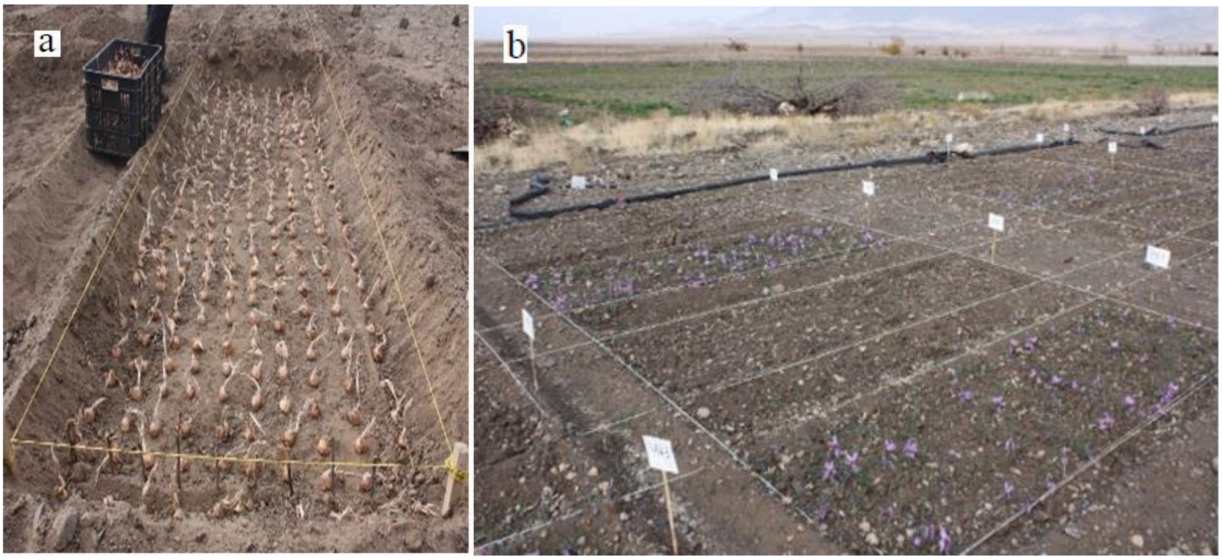

Fig. 3. Experiment layout. (a) the saffron corm planting and (b) the saffron flowering stage.

Table 5

The mean squares of ANOVA for growth, yield, and qualitative traits of saffron in variance analysis of 2015–2018 data.

	DF	LA	DLY	FFY	DSY	CN	CY	FSC	WP	C	P	S
Y	2	483.94**	16,125,989**	3,916,106**	273.93**	169,990**	1782**	0.0068	17.56**	0.029	0.231*	0.035*
YE	4	0.04ns	1691.04ns	387.8ns	0.04ns	10.14ns	0.178ns	0.0018ns	0.003ns	0.0021ns	0.0002ns	0.00001ns
R	2	1.76	38,944.59	5797.9	0.453	148.9	3.67	0.0024	0.0096	0.173	0.0318	0.0116
DI	2	319.18**	5,721,736**	850,912**	67.84**	16,367**	777.7**	0.1790**	1.362**	3.096**	1.642**	0.5405**
Y×DI	4	20.6**	264,176**	58,384**	4.06**	1109**	48.2**	0.0002ns	0.027ns	0.492*	0.220**	0.0355**
DIE	4	7.19	169,301	25,083	1.72	818	12.3	0.0157	0.1051	2.385	0.676	0.1105
SAH	1	97.06**	3,063,442**	470,866**	67.78**	8322**	238.9**	0.1157**	4.278**	0.097ns	1.889**	0.3112**
DI×SAH	2	0.11ns	162,838**	25,155**	2.51**	601**	3.98ns	0.0057ns	0.074*	0.822*	0.491**	0.0624**
Y×SAH	2	2.15*	423,134**	77,778**	8.27**	410*	11.6**	0.0012ns	0.5696**	0.891*	0.305**	0.0179ns
Y×DI×SAH	4	3.25**	42665ns	6979ns	0.61*	47.37ns	1.12ns	0.0012ns	0.0256ns	0.498*	0.316**	0.0191ns
SAHE	26	0.66	16,772.8	2741.5	0.21	95.8	1.50	0.0024	0.014	0.187	0.051	0.008
CV (%)	–	4.1	3.4	4.6	5.0	4.8	8.4	6.1	5.1	3.9	4.0	2.4

ns, *, and ** indicated no significant, significant at 5 %, and 1 % level of probability, respectively.

DF: Degree of freedom; LA: Leaf number; DLY: Dry leaf yield; FFY: Fresh flower yield; DSY: Dry stigma yield; CN: Corm number; CY: Corm yield; FSC: Flower-to-stigma conversion factor; WP: Water productivity; C: Crocin; P: Picrocrocin; S: Safranal.

Y: Year; YE: Year error; R: Replication; DI: Deficit irrigation; DIE: Deficit irrigation error; SAH: superabsorbent hydrogel; SAHE: superabsorbent hydrogel error; CV: Coefficient of variations.

them. To measure the number of corms and yield, the corms in 0.1 m^2 (25×40 cm) of each plot were harvested in June 2016, 2017, and 2018, and after counting the corms, they were dried at room temperature for seven days. The corms' weight was measured to estimate corm yield. The flower-to-stigma conversion factor (FSC) was calculated as follows:

$$\text{FSC} = \frac{\text{Dry stigma weight}}{\text{Fresh flower weight}} \times 100$$

Water productivity (WP) was calculated by dividing dry stigma yield by the amount of irrigation used during saffron growth periods (Yarami and Sepaskhah, 2018). To determine the percentage of the main compounds of saffron stigma essential oil, ultraviolet-visible spectrophotometry was used according to the ISO/TS 3632 standard. About 500 mg of saffron stigma was weighed from each treatment and poured into Erlenmeyer with a volume of 1000 ml. The balloons were completely covered with aluminium foil to prevent light from reaching the samples. Then, about 900 ml of distilled water was added to the balloons, and the samples were placed on a magnetic mixer for one hours. The volumetric balloon was increased to the target line with distilled water and shaken again to obtain a uniform solution. Then, using a pipette, 20 ml of the solution was transferred to a 200 ml volumetric balloon to increase the volume. The solution was remixed to obtain a uniform solution, and filtered with an air vacuum pump and silicate filter paper. The soluble light absorption was measured using a spectrophotometer (WPA model, S2000 UV/Vis Spectrophotometer) at 257, 330, and 440 nm for picrocrocin, safranal, and crocin, respectively. The results were expressed based on the maximum absorption of 1 % aqueous solution at the mentioned wavelengths based on minimum dry matter, according to the following equation (Esmaeilian et al., 2022):

$$E_{1cm}^{1\%} = \frac{D \times 10,000}{m \times (100 - H)}$$

where $E_{1cm}^{1\%}$ is the absorbance of aqueous saffron extract, D is the spectrophotometer reading, m is the weight of the saffron stigmas in g, and H is the water content of the sample, which was considered 6.45 %.

Absorbance values converted to concentrations as follows:

$$\text{Crocin}\left(\text{mg g}^{-1}\right) = \frac{\text{C, roc, in , abs, orb, anc, e v, alu, } e \times 9, 76., 96\times, 100, 0}{8, 900, 0 \times 0, .5}$$

$$\text{Picrocrocin}\left(\text{mg g}^{-1}\right) = \frac{\text{Picrocrocin absorbance value} \times 150.21 \times 1000}{7500 \times 0.5}$$

$$\text{Safranal}\left(\text{mg g}^{-1}\right) = \frac{\text{,Saf,ran,al ,abs,orb,anc,e v,alu,} e \times 3,30.,37\times,100,0}{1,010,0 \times 0,.5}$$

2.5. Statistical analysis

Analysis of variance (ANOVA) and comparison of means using Duncan's multiple range tests at a 5 % probability level was performed with SAS software version 9.1 (SAS, Cary, NC, USA).

3. Results and discussion

3.1. Leaf number and leaf dry yield

ANOVA results for leaf number (LN) and leaf dry yield (LDY) showed significant differences under the influence of irrigation interval, SAH application, and the interaction of these two factors (Table 5). Fig. 4a shows that by increasing the age of the saffron field during the experiment years, LN increased for all treatments. As Fig. 4a indicates, reducing irrigation by increasing days of irrigation intervals caused a decrease in LN during the three years of the experiment (2015–16, 2016–17, and 2017–18). This decrease was more evident in the third year compared to other years of the experiment (a reduction of 19.2 and 39.3 %, compared to W1 for W2 and W3, respectively). Similar results were reported by Maleki et al. (2011). The decrease in rainfall in the third experiment year compared to the previous two years (Fig. 2) increased the severity of the effect of drought stress caused by the decrease in water availability, which ultimately led to a reduction in plant LN. This result reveals that drought, in addition to the direct effect on photosynthesis, caused a reduction in plant growth and production of leaves by limiting nutrient uptake from roots and their transfer to the plant shoots (López-Marín et al., 2017). Our results also indicated that applying SAH under normal and water deficit conditions increased LN in saffron plants. Results also suggest the favourable effects on LN when using SAH under low water supply where, except for the second year in which there was no significant increase in LN, the improvement was about 9 to 10 % for the second and third years, respectively.

Similar to LN, LDY showed an increasing trend throughout the years of the experiment (Fig. 4b). Dastranj and Sepaskhah (2019) also reported a 59.6 % increase in LDY for the second year compared to the first year of their experiment. The decrease in the days of irrigation interval caused an increase in LDY. The increase in the first level of the irrigation regimes (W1) compared to the third level (W3) across the first to the third year of the experiment was about 42, 51, and 48 %, respectively (Fig. 4b). The use of SAH in all the irrigation water regimes improved the LDY. The highest increase (29 %) was observed in the W2 treatment, and

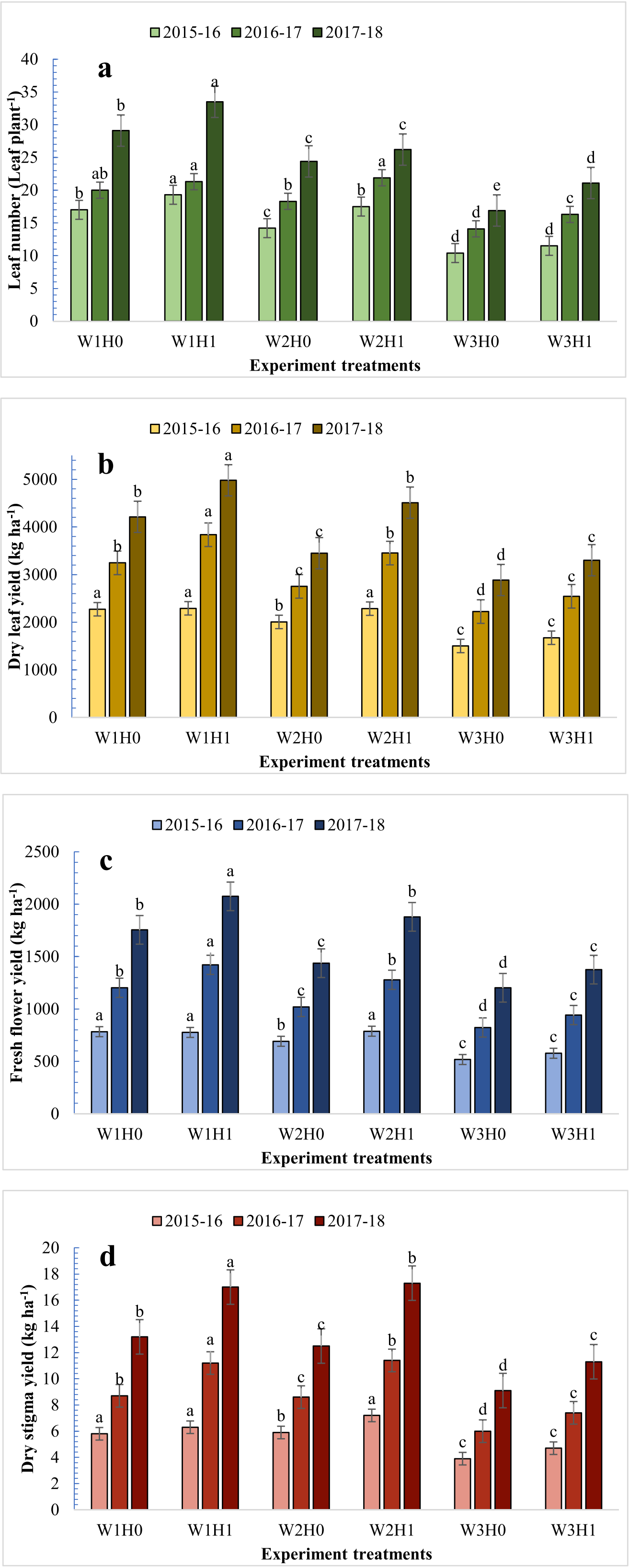

Fig. 4. Interaction effects of SAH × irrigation interval on leaf number (a), dry leaf yield (b), fresh flower yield (c), and dry stigma yield (d) of saffron. W1, W2, and W3 will be used for 20, 35, and 50 days interval, respectively; H0, and H1: No super absorbent hydrogel (SAH), and SAH application, respectively.

the SAH increased equivalently (14 %) the LDY under other irrigation intervals (Fig. 4b). Martin et al. (1993) reported that the micro pores in hydrogels allow micro and macro elements to spread among the polymer particles and, depending on the rate of decomposition, nutrient type, and polymer diffusion properties, the nutrients are gradually released from it into the soil. Also, it has been reported that SAH can reduce nitrogen leaching by 45 % (Mikkelsen et al., 1993), which can play an essential role in improving nitrogen availability and efficiency.

In the comparison of mean interactions between experimental factors (Fig. 4b), it was evident that saffron plants subjected to optimal irrigation and treated with SAH (W1H1 treatment) consistently displayed the highest values of LDY throughout the experiment years (2291.9, 3837.0, and 4979.5 kg ha^{-1}, respectively). Conversely, plants exposed to severe water deficit and not treated with SAH (W3H0 treatment) exhibited the lowest values (1501.2, 2223.6, and 2885.7, respectively). Notably, the application of SAH significantly mitigated the adverse impact of severe water deficit on this trait, resulting in a 16.3 % lower reduction in LDY compared to scenarios without SAH application.

3.2. *Fresh flower yield and dry stigma yield*

Significant variations in the fresh flower yield (FFY) and dry stigma yield (DSY) of saffron under the different treatments and their interactions were also found from the ANOVA (Table 5). As shown in Fig. 4c, FFY shows a gradual increase during the three years of the study period. There was an increase of 425 and 506 kg ha^{-1} for the second and third years, respectively, in comparison to the first year.

For the irrigation regimes, the highest amounts of FFY (780, 1310, and 1915 kg ha^{-1} for the first to the third year, respectively) were always obtained with W1. Decreasing the amount of irrigation water applied by increasing days of irrigation intervals gradually decreased FFY. It has been reported that there is a high correlation between flower production and water availability in saffron cultivation (Esmaeilian et al., 2022). In other words, to achieve higher FFY in saffron, it is necessary to reduce the frequency of irrigation (Behdani et al., 2008). The interaction effect between irrigation intervals and SAH shows that FFY was higher for plants with shorter irrigation intervals and application of SAH (Fig. 4c). Moreover, plots with SAH showed higher FFY increase than those without SAH under the W2 treatment (14, 26, and 31 % increase from the first to the third year of the study period, respectively). Yu et al. (2017) stated that because most soils in arid and semi-arid regions have low levels of clay and organic matter, they have low water retention and productivity, and thus, drought stress leads to yield loss and reduced crop productivity in these areas. Therefore, using SAH can improve water availability and reduce the negative impacts of drought on crops.

Changes in DSY in response to the experimental treatments showed similar trends to those in FFY. DSY increased by 3.25 and 4.50 kg ha^{-1} in the second and third year, respectively, compared to the first year during the study period. The reduction in irrigation interval from W1 to W2 led to a 40 %, 49 %, and 48 % decrease in DSY over the three years of the experiment, respectively (Fig. 4d). These findings align with Dastranj and Sepaskhah (2019), who reported a 21 % and 37 % decrease in saffron stigma yield when irrigation water supply was reduced by 75 % and 50 %.

The interaction effects of the experimental factors highlighted a positive and significant response of DSY to increased irrigation regimes and the application of SAH. As depicted in Fig. 4d, the W1H1 treatment consistently resulted in the highest values over the three years of the study period (6.3, 11.2, and 17.0 kg ha^{-1}, respectively), while the W1H0 treatment led to the lowest values (3.9, 6.0, and 0.91 kg ha^{-1}, respectively). The beneficial impact of SAH on increasing DSY under full irrigation was evident, with a 29 % increase observed in the second and third years compared to scenarios without SAH application. Given that saffron irrigation employed the basin method, which may lead to water and nutrient losses through drainage, the use of SAH could potentially mitigate these losses, thereby enhancing DSY (Dehkordi, 2017).

3.3. Corm number and corm yield

There was a significant difference in the corm number of saffron under the influence of experiment treatments and their interactions from the ANOVA results (Table 5). Corm characteristics of saffron can determine the growth and yield of flowers and stigmas in the following year. Based on the results, the CN during the study period had a significant increasing trend, such that at the end of the study period (third year of the experiment), CN increased by 190 % as compared to first year of the experiment (Fig. 5a). Aghhavani Shajari et al. (2020) reported a 41 % increase in the number of saffron corms in the second year compared to the first year of their experiment. There was a decreasing trend in CN values during the experiment years, so increasing days of irrigation intervals decreased CN values. Fig. 5a clearly shows that saffron plants grown under W1 treatment had the highest CN values during the experiment years (116, 245, and 329 corms m^{-2}, respectively), while the lowest values (83, 186, and 245 corms m^{-2}, respectively) corresponded with the W3 treatment. Similar to our results, Koocheki et al. (2016) reported that increasing water availability in saffron cultivation through supplying better conditions for the daughter corm formation and improving the photosynthetic capacity of the plant led to improvement of corm traits such as the number of daughter corms. The interaction effect of the experiment factors on the CN was significant (Table 5). Based on the results, the positive impacts of SAH application on the improvement of CN under water deficit conditions was significantly higher than the no water deficiency condition. This increase was more evident in the second irrigation regime (W2H1), with a 25.3, 17.1, and 19.6 % increase compared to no SAH application, respectively, during the experiment years (Fig. 5a). Due to saffron's adaptability to the arid and semi-arid climates of east and north-east Iran and less water requirement compared to other crops, this crop is a very suitable option for implementing sustainable strategies in agriculture in these regions. In this regard, SAH can produce standard corms by retaining water for growing saffron (Fallahi et al., 2016).

The effect of the experiment treatments and their interaction on the corm yield (CY) was significant (Table 5). Fig. 5b indicates that this index also showed an increasing trend during the first to third year of the experiment (16, 25, and 36 t ha^{-1} for the first to third year, respectively). An increase in the CN and CY of saffron as a result of the increase in the saffron field age has also been reported by other researchers (Aghhavani Shajari et al., 2020). In general, drought stress caused by low water supply had more effects in reducing CY compared to CN. The W3 treatment led to a 35.5, 43.3, and 40.0 % decrease during the first to third year, respectively, compared to the W1 treatment. Other researchers also reported that the best irrigation interval for saffron cultivation was 24 days and stated that increasing days of irrigation intervals decreased CY (Azizi Zohan et al., 2008). Additionally, De Juan et al. (2009) highlighted that optimal saffron irrigation enhances flower yield by improving corm attributes, such as corm size. The mean comparison of treatment interactions underscored the positive and significant impact of SAH application on enhancing CY and mitigating the

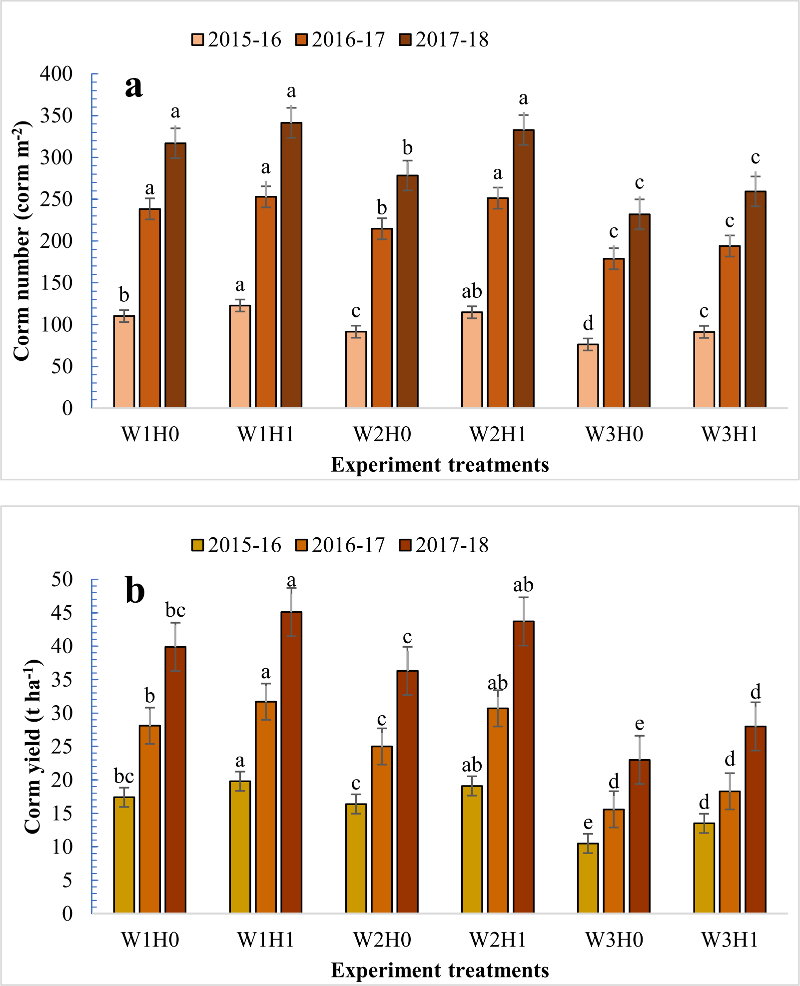

Fig. 5. Interaction effects of SAH × irrigation interval on corm number (a), and corm yield (b) of saffron.

adverse effects of drought-induced water deficiency. Analyzing the CY variation trend over the three years of the study period revealed that the use of SAH, under the first, second, and third water supply regimes, increased CY by 13.1 %, 20.5 %, and 21.5 %, respectively, compared to the control. This outcome emphasizes the more pronounced effects of SAH application in improving CY under conditions of severe water deficit. Other studies also confirm the role of SAH in reducing the adverse impacts of drought stress on plants (Mahalleh et al., 2011; Satriani et al., 2018; Nassaj-Bokharaei et al., 2021). In this regard, it has been noted that SAH improves water uptake and transport of water and nutrients in plants by storing and gradually releasing them during the periods when soil water is decreasing, which ultimately improves the growth and development parameters of the plant (Jnanesha et al., 2021). Examining the interaction between irrigation regimes and SAH, saffron plants benefiting from better water availability and treated with SAH exhibited elevated CY values. Specifically, the W1H1 treatment yielded the highest CY values over the three years (19.8 t ha^{-1}, 31.7 t ha^{-1}, and 45.1 t ha^{-1}, respectively), while the W3H0 treatment recorded the lowest values (13.5 t ha^{-1}, 18.3 t ha^{-1}, and 0.28 t ha^{-1}, respectively) (Fig. 5b).

3.4. *Flower-to-stigma conversion factor and water productivity*

Flower-to-stigma conversion factor (FSC) showed significant variations under the main and interaction effects of experimental treatments (Table 5). The measurement of the FSC data during the study period showed a negligible value for the first to the third year (0.83, 0.86, and 0.85 %, respectively). The highest values of FSC for the three years (0.94, 1.01, and 0.95 %, respectively) belonged to moderate water deficit (W2). The mean comparison of the irrigation intervals with SAH interaction treatments revealed that SAH significantly improved FSC for all the irrigation regimes. The highest FSC values during the experiment years (0.98, 1.1, and 0.1, respectively) were obtained by the W2H1 treatment, followed by the W2H0 treatment. Several studies have shown that the use of SAH, in addition to improving nutrient holding and release capacity, enhances plant growth and related yield parameters (Borivoj et al., 2006; Neethu et al., 2018; Roy et al., 2019).

As shown in Fig. 6b, the water productivity (WP) of saffron showed a gradually increasing trend over the experiment years (about 52 % more than the previous year). The results also indicate a significant increase in the WP of saffron under water deficit conditions. This increase was higher for the second and third years compared to the first year. Recently, an increase in the WP of saffron due to deficit irrigation has been reported (Dastranj and Sepaskhah, 2019). Some researchers have stated that the WP index has a negative relationship with the total amount of water consumed by the plant during the growth period. In other words, to achieve higher WP, it is necessary to reduce water use to a level below the required for obtaining the maximum yield (Zhang et al., 2008). Our results also revealed that SAH had a significant effect on improving the WP of saffron (Fig. 6b). An increase in saffron water use efficiency due to the use of SAH has been reported in another study (Fallahi et al., 2016). Moreover, SAH improves the root and shoot growth of the plant (Islam et al., 2011) and ultimately improves the WP of the crop (El-Asmar et al., 2017; Yu et al., 2017) by holding water and

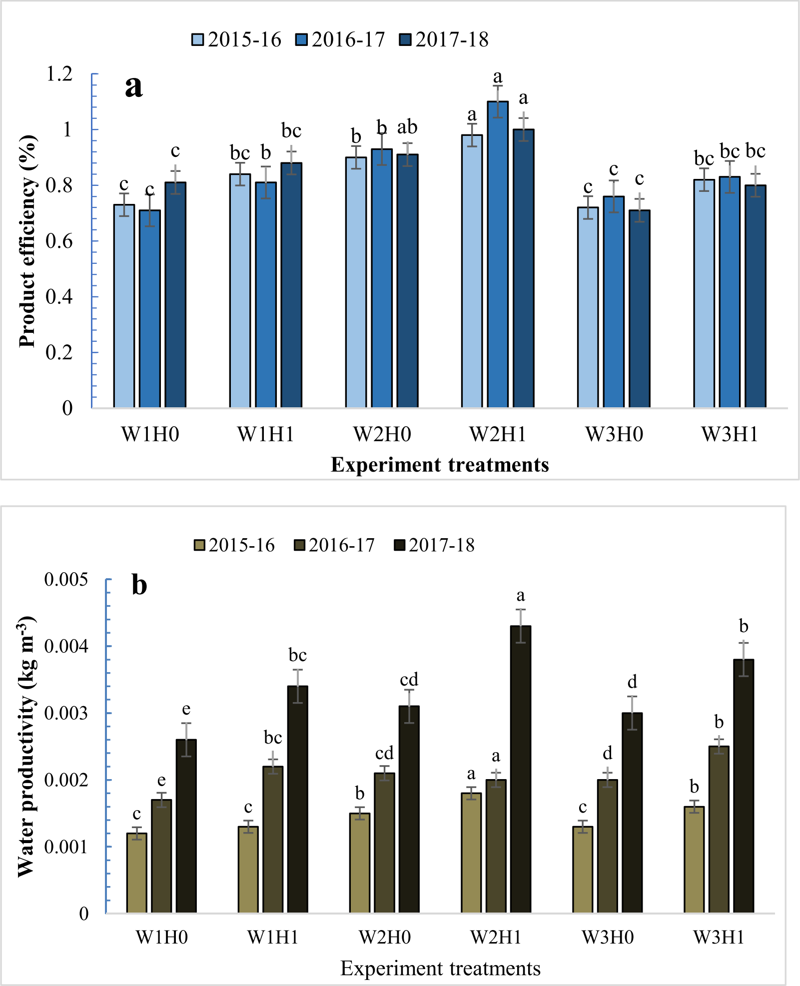

Fig. 6. Interaction effects of SAH × irrigation interval on product efficiency (a), water productivity (b) of saffron.

nutrients reducing losses through deep drainage (Abedi-Koupai et al., 2008; Narjary et al., 2012; Montesano et al., 2015), while providing gradual release during dry periods (Satriani et al., 2018; Besharati et al., 2021). As shown in Fig. 6b, the WP values among the interaction treatments ranged between 0.0012 and 0.0043 g m^{-3}. The W2H1 treatment resulted in the highest WP during the experiment years (0.0018, 0.0028, and 0.0043 g m^{-3}, respectively), followed by the W3H1 treatment.

3.5. Main volatile compounds of saffron stigma

According to the ANOVA results, the differences in the effects of experiment treatments and their interactions on the main volatile compounds of saffron stigma (crocin, picrocrocin, and safranal) were significant (Table 5). The effect of the experiment year on crocin content was not significant, while significantly influenced the picrocrocin and safranal content. In general, the content of the mentioned compounds showed a little decrease during the third year compared to the second

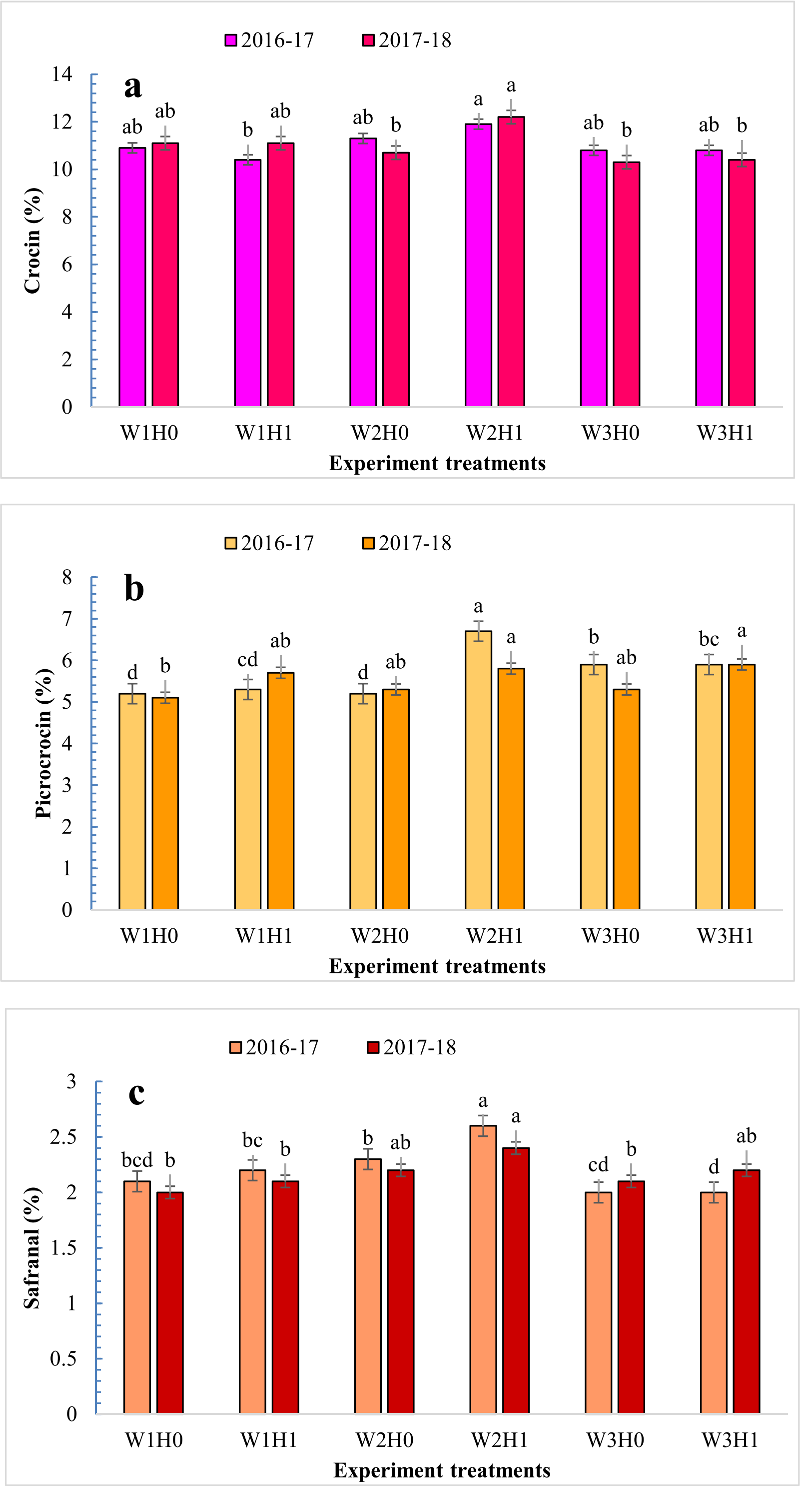

Fig. 7. Interaction effects of SAH × irrigation interval on crocin (a), picrocrocin (b), and safranal (c) of saffron.

year (Fig. 7a). Generally, when saffron plants were exposed to lower water availability due to water deficit regimes, the stigma compounds improved. Hoverer, these changes were few and did not show a consistent trend. Measurements of the saffron stigma compounds showed that the highest amount of crocin (11.5 %), picrocrocin (5.8 %), and safranal (2.4 %) was obtained from the W2 treatment (Figs. 7a, b, c). Other researchers have also examined the effect of different irrigation intervals on the quality of saffron and have claimed that the content of crocin, picrocrocin, and safranal would increase by reducing the amount of irrigation. These authors attributed this increase in the main volatile compounds of saffron stigma in response to the limitation in water availability as one of the mechanisms of adaptation and resistance to stress in saffron plants (Koocheki et al., 2016). Our findings indicate that, in most scenarios, the use of SAH enhanced the content of volatile compounds, especially under water deficit conditions. The W2H1 treatment exhibited the highest crocin content (11.9 % and 12.2 % for the second and third year, respectively) (Fig. 6a). Additionally, the W2H1 treatment yielded the highest picrocrocin content in the second year (6.7 %), while the W3H1 treatment achieved the highest in the third year (5.9 %) (Fig. 6b). The Safranal content experienced the most significant increase in both years of the experiment (2.6 % and 2.4 %, respectively) due to the W2H1 treatment (Fig. 7c). The positive impact of SAH application under water deficit conditions on the main essential oil compounds of dill (*Anethum graveolens*) (Javadi et al., 2021) and anise (*Pimpinella anisum*) (Arabi et al., 2016) has also been reported.

4. Conclusions

Results of the present study revealed that the growth parameters (LN and LDY), economic yields (FFY and DSY), and corm indices (CN and CY) of saffron significantly responded to the irrigation intervals and the SAH application. The studied traits of saffron showed significant improvements due to proper water availability, so the best results were obtained from the 20-day irrigation interval. The current study also revealed a significant variation in the saffron traits due to applying SAH under all irrigation regimes. However, measured parameters of saffron showed more significant improvements when the SAH was applied under deficit irrigation conditions (35 and 50-day irrigation intervals) than full irrigation (20-day irrigation interval), indicating the positive effect of this soil amendment on improving the access of the plant to water and nutrients as well as on reducing the adverse effects of drought on the saffron plants. The water productivity of saffron demonstrated a significant enhancement under water deficit regimes. Stigma quality indices, including crocin, picrocrocin, and safranal, experienced notable improvements when saffron plants were subjected to water deficit conditions, particularly with a 35-day irrigation interval, compared to full irrigation. The utilization of SAH further contributed to the significant improvement of saffron quality indices under water deficit conditions. In conclusion, although the highest quantitative yield of saffron was obtained from the full irrigation along with SAH application, the best result in terms of saffron quality was obtained from the 35-day irrigation interval and SAH application, that due to the limited water resources in the study area and the importance of water efficiency it is recommended as the best treatment in the sustainable production of saffron in regions with similar edaphoclimatic conditions to the experimental site.

CRediT authorship contribution statement

Ahmad Ahmadian: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Yasser Esmaeilian:** Writing – original draft, Methodology, Investigation, Formal analysis. **Abolfazl Tavassoli:** Writing – original draft, Project administration, Methodology, Investigation, Formal analysis. **Jesús Fernández-Gálvez:** Writing – review & editing, Validation, Methodology, Data curation. **Andrés Caballero-Calvo:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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