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Saffron Irrigation Regime

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Abstract

Saffron is grown in arid and semi-arid regions in Iran in late autumn, winter and late spring with rainy season. It should be irrigated by supplemental basin irrigation. Since rainfall is usually delayed in autumn, therefore, a pre-flowering irrigation of about 100 mm is needed. In areas with a seasonal rainfall of 600 mm a post- flowering irrigation of about 50 mm is adequate for economical yield. In areas with seasonal rainfall of 400 and 200 mm continuous supplemental irrigation is needed with intervals of 24 and 15 days or irrigation regimes of 50% ET_p and 75% ET_p, respectively. In these areas, irrigation regimes can be planned based on crop water stress index (CWSI) of 0.60 and 0.27, respectively. Monthly values of crop coefficient (K_c) and pan coefficient (K_p) for saffron are presented with the highest values of 1.10 and 0.84, respectively, that occurred in January. For the three-, four-and five-year old fields with higher amount of corm intensity the optimum irrigation water is zero for about 300 mm of rainfall. While for the six-and seven-year old fields the optimum irrigation water is zero for about 500 mm of rainfall. Flower production decreased 49% by using irrigation water with salinity level of 1.7 dS m^{-1} and no flower produced at salinity level of 4.0 dS m^{-1}, while leaf growth occurred in this salinity. Furthermore, 50% flower yield is produced at soil water salinity of 3.6 dS m^{-1}.

Keywords: Irrigation interval; Irrigation scheduling; Supplemental irrigation; Rain-fed; Crop water stress index; Crop and pan coefficients; Irrigation salinity; Optimum irrigation water.

Introduction

Traditional agriculture in Iran is based on development of cropping systems with low water requiring crops such as saffron (*Crocus sativus* L.). However, not much research has been conducted on this crop to improve technology for its production.

Saffron belongs to Iridaceae family and it is mostly distributed in Irano-Touranian region and west of Asia with low annual rainfall, cold winters and hot summers. At present, saffron is cultivated in Iran and a few countries with old civilization. Iran is leading country in saffron production with 47200 ha cultivated area and 160 ton annual production (3.4 kg ha^{-1} yield) (Kafi et al., 2006). The main saffron production areas in Iran are located in Khorasan, Fars and Kerman provinces. Its cultivation area increased by an annual rate of about 22% in last decade (Anonymous, 2002), however, its annual production increased by about 14%. This indicates that the saffron yield (kg ha^{-1}) decreased about 50% that may be due to occurrence of drought and newly cultivated fields with low yield.

The three-branch style of saffron flowers is the most important economic part of the plant. Saffron is used as a spice and a natural food color. In traditional medication, saffron has several properties. Further, its petals are a food color and its leaves are used as animal feed.

There are distinct differences between eco-physiological behavior of saffron and other crops. Flowers appear before development of other plant organs. Occurrence of flowers coincides with cold temperature in fall. In contradiction of the economic yield of most conventional crops, saffron yield is style/stigma that is a small part of its flower. Harvest index of saffron is less than 0.5% compared with 30 to 60% for other crops (Ingram, 1984). Most of the conventional crops positively respond to irrigation in summer, while summer irrigation is avoided for saffron. Therefore, saffron irrigation is considered as supplemental irrigation. These indicate that the eco-physiological criteria of saffron are quite different from other crops. These differences have been reviewed by Kafi (2006). However, as he indicated, there is a great deal of controversy related to ecological, physiological and phonological characteristics of saffron that should be examined. Traditionally, saffron is irrigated four times during October to May, however, to achieve high yield, appropriate irrigation scheduling should be used (Alizadeh, 2006).

Environmental requirements

Temperature

Saffron growth in temperate and dry climate is favored. However, vegetative growth of saffron coincides with cold air temperature with freezing conditions in winter. The mean monthly maximum, minimum and absolute minimum air temperatures in the saffron production areas, *i.e.,* Khorasan and Fars provinces for cold months of growing season are shown in Table 1. The mean monthly maximum and minimum air temperatures in October to December in southern parts of Khorasan are 20 and 0.0˚C, and for Fars province are 15.0 and -8.9˚C, respectively (Kafi, 2006). According to this reference, absolute minimum temperature of -22˚C occurred in Torbate-Hydarieh (saffron production area) in northern part of Khorasan province while this value is -20.0˚C for Fars province. Monthly air and soil temperature at different depths is shown in Figure 1. These data obtained in a soil texture similar to that in a saffron field in Bajgah (Fars province, Iran). In summer, soil temperature at depth of 5.0 cm (about 40.0˚C) is higher than air temperature that is measured at a height of 2.0 m and may inhibit corm physiological activity planted at this depth in furrow irrigation. However, soil temperature at depth of 30.0 cm (30.0˚C) is lower than air temperature that enhances the corm physiological activity planted at this depth in basin irrigation. In winter, soil temperature in 30.0 cm depth (5.0˚C) is higher than that in 10.0 cm (2.0˚C) depth may enhance saffron corm growth planted at this depth.

Table 1. Temperature variation in cold season for the saffron growing provinces in Iran.

Temperature, ˚C	Khorasan*	Fars
Monthly maximum	20.0	15.0
Monthly minimum	0.0	-8.9
Absolute minimum	-22.0	-20.0

* Kafi (2006)

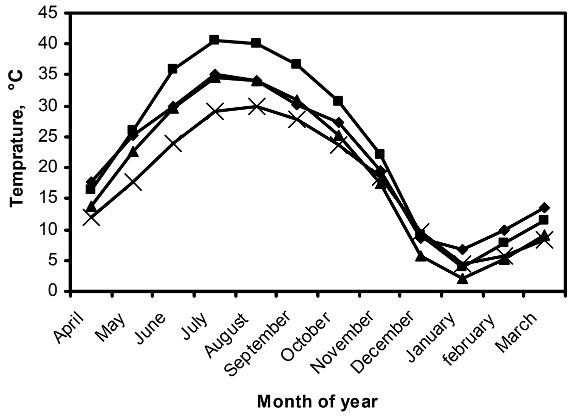

Figure 1. Monthly air and soil temperatures at different depths in 2006 in Bajgah, Fars province: ♦, air temperature at 2.0 m height; ■, soil temperature at 5.0 cm depth; ▲, soil temperature at 10.0 cm depth; ×, soil temperature at 30.0 cm depth

Irrigation methods

Irrigation methods and flowering

The first irrigation is usually applied at mid to end of October. The flowering is initiated 2-3 weeks after the first irrigation. Flowering period is 15-20 days and the flower harvest period is about 10-15 days. The longer flowering period decreases the problem of labor shortage, however, it enhances the risk of flower damage by frost. Therefore, the effect of irrigation methods on flowering period investigated by Azizi-Zohan et al. (2005) and results are shown in Table 2.

Table 2. Flowering period (day) as influenced by irrigation methods and intervals for two successive years.

Irrigation interval (day)	Basin	Furrow	Mean
		First year	
12	16a*	16a	16A
24	17a	15a	16A
36	17a	14ab	15A
Rain-fed	11b	7c	9B
Mean	15A	13A	
		Second year	
12	21ab	22a	21A
24	21ab	20ab	21A
36	18ab	17b	18A
Rain-fed	17b	13c	15B
Mean	19A	18A	

*Means followed by the same lower case letter in each column and capital letters in each column and row are not different significantly at 5% probability level by Duncan multiple range test.

In general, flowering period is not affected by irrigation method and irrigation interval, however, it is significantly lower in rain-fed conditions (Table 2). Flowering initiation is the same in different irrigation method and interval, however, it is delayed in rain-fed conditions. Furthermore, it is indicated that for rain-fed conditions, pre-flowering irrigation at mid to end of October results in flowering initiation similar to that occurred in irrigation treatments. Therefore, it is concluded that for rain-fed conditions, a pre-flowering irrigation should be applied when irrigation water is available.

Irrigation method and saffron yield

Although saffron is planted in arid and semi-arid regions in Iran and is adapted to these conditions, however, according to the findings of Goliaris (1999) in Greece, saffron should not be under water stress in some of the growth stages. In Greece, saffron corms grow in March and April, and September it is the time of flower initiation, therefore, saffron should not be under water stress in these periods. Aitoubahou and El-Otmani (1999) reported that in Morocco, saffron is irrigated by basin irrigation. In these fields, 30-50 mm of irrigation water is used weekly in September to November and the amount of applied irrigation water is 35-50 mm during December to March that is applied with 2-week interval. Furthermore, saffron is not irrigated during April to August. By this irrigation regime, saffron yield of these fields reported to be 2-2.5 kg ha^{-1} and it is much lower than those reported in Italy (10-16 kg ha^{-1}) and Spain (10-12 kg ha^{-1}) (Aitoubahou and El-Otmani, 1999).

Almost similar irrigation schedule is practiced in saffron plantation in Iran (Abrishami, 1997) that results in low saffron yield (3.4 kg ha^{-1}) as reported by Kafi et al. (2006). Therefore, it hypothesized that other irrigation methods, *i.e.,* furrow and appropriate irrigation interval may improve saffron yield.

Table 3. Saffron yield (kg ha^{-1}) as influenced by different irrigation intervals and methods.

Irrigation interval (day)	Applied irrigation water (mm)	Basin	Furrow
First year (437 mm rainfall)			
12	610	2.59ab*	0.69c
24	386	2.71a	0.60c
36	373	1.93b	0.29c
Rain-fed	182**	0.71c	0.19c
Second year (208 mm rainfall)			
12	647	5.81a	2.09d
24	364	5.19b	0.69ef
36	295	3.20c	0. 51fg
Rain-fed	0	1.09e	0.07g

*Means followed by the same letters in each year are not significantly different at 5% probability level by Duncan multiple range test.
**It is the amount of two irrigations water as pre-flowering and post-flowering for the corm establishment.

The effects of different irrigation intervals investigated by Azizi-Zohan et al. (2006) in basin and furrow irrigation methods with the same amount of water at each interval for different methods. The results are depicted in Table 3. It is indicated that basin irrigation with corm planting depth of about 25.0 cm is superior to furrow irrigation with corm planting depth of about 10.0 cm. This may be resulted from the difference in temperature regimes in different soil depths as shown in Figure 1. In winter, soil temperature in 30.0 cm depth (5.0˚C) is higher than that in 10.0 cm (2.0˚C) depth may enhance saffron corm growth planted at this depth. Further, irrigation intervals of 12 and 24-day are preferred with seasonal rainfall of about 200 and 400 mm, respectively. Similar appropriate irrigation interval reported by Mosaferi (2001). He indicated that saffron yield is significantly higher with 15-day interval with up to 41% increase compared with that obtained in rain-fed conditions in Mashhad area (northeast of Iran) an arid region with low seasonal rainfall.

Saffron pre-irrigation

For flower initiation an irrigation is required that facilitates flowering. However, timing of this irrigation is crucial. It should be scheduled at a proper time that flowers to be appear before the vegetative growth to be started. Otherwise, flowering and leaf growth occur simultaneously and the later may interfere with harvesting practice. Mosaferi (2001) reported the effects of different dates and amounts of the first irrigation on saffron yield in Mashhad (northeast of Iran). Results are presented in Table 3. It is shown that pre-flowering irrigation at mid October resulted in the highest saffron yield. Therefore, it is appropriate time to apply the first irrigation that is in accordance with that of indigenous knowledge of local farmers.

Table 4. Saffron yield as influenced by time of pre-flowering irrigation.

Time of first irrigation	Flower dry weight (g m^{-2})	Saffron yield (g m^{-2})
Early October	8.25	0.156
Mid October	11.02	0.226
Late October	8.47	0.170
Mid November	6.74	0.114

Irrigation methods and saffron leaf growth

Effects of irrigation method and interval on leaf dry weight of saffron in two-year old field reported by Azizi-Zohan et al. (2006) (Table 5). Differences in leaf dry weight in different irrigation treatments are not distinct as those reported for saffron yields (Table 3). In basin irrigation, leaf dry weight is not statistically different in different irrigation intervals and rain-fed conditions. This is true for different irrigation intervals in furrow irrigation (Table 5). To study the effects of irrigation on the vegetative growth, the effects of irrigation intervals and methods on corm growth were investigated.

Table 5. Leaf dry weight of saffron (kg ha^{-1}) as influenced by different irrigation intervals and methods at the second growing season.

Irrigation interval(day)	Basin	Furrow
12	732.9a*	555.2ab
24	702.2a	502.8ab
36	815.3a	303.8bc
Rain-fed	512.5ab	259.6c

*Means followed by the same letters are not significantly different at 5% probability level by Duncan multiple range test.

Irrigation regimes and corm growth

Effects of irrigation intervals and methods on corm numbers and weight with different sizes are shown in Table 6 as reported by Azizi-Zohan et al. (2006). The numbers of corms in basin irrigation are lower than those obtained in furrow irrigation, but the numbers of corm heavier than 8.0 g are higher in basin irrigation than those in furrow irrigation. These differences resulted in higher flowering and saffron yield in basin irrigation (Table 3). There are no differences between the medium weight corms (4.0-8.0 g) in basin and furrow irrigation (Table 6), however, the numbers and yield of light corms (lighter than 4.0 g) in furrow irrigation are higher than those in basin irrigation. Therefore, it is indicated that furrow irrigation enhances the corm propagation and inhibited its growth. The small size of corms is the main reason for lower saffron yield in furrow irrigation (Table 3).

Table 6. Number of corms per m^{-2} and yield (kg ha^{-1}) for different corm sizes as influenced by irrigation intervals and methods at second growing season.

Irrigation method	Irrigation interval	Total corm per m^{-2}	Corm yield t ha^{-1}	No. of corm per m^{-2}	Corm yield t ha^{-1}
		Total and heavier than 8 g			
Basin	12	206.3	15.6	72.9	11.8
	24	193.9	11.8	52.9	7.7
	36	187.7	11.5	64.6	8.3
	Rain-fed	181.5	4.3	17.9	1.7
Furrow	12	323.5	10.7	37.1	4.3
	24	330.0	7.2	16.5	1.6
	36	257.8	6.2	15.9	1.7
	Rain-fed	289.4	1.8	0.0	0.0
		Medium (4-8 g) and lighter than 4 g			
Basin	12	41.9	2.3	94.4	1.5
	24	41.3	2.2	99.7	1.8
	36	31.6	1.8	91.4	1.5
	Rain-fed	27.5	1.5	136.1	1.1
Furrow	12	46.8	2.7	229.6	3.7
	24	30.9	1.7	282.6	3.8
	36	36.4	2.0	206.3	2.5
	Rain-fed	6.9	0.4	282.6	1.5

In general, the effects of irrigation intervals is not significant on corm numbers, however, lower numbers of large and medium corm obtained in rain-fed saffron (Table 6). Corm yield in general and heavier corms yield decreased as irrigation interval increased. However, this is not obtained for medium and light weight corms, and their yield decreased under rain-fed conditions.

Data differences in Tables 3 and 6 indicate that in furrow irrigation the corms are located not deep enough in soil, therefore, they are under more water stress due to faster depletion of soil water at the soil surface layer. Further, corms experience lower soil temperature in winter and high soil temperature in fall and spring that may show inverse effects on the vegetative and reproductive growth of saffron in furrow irrigation.

Irrigation Scheduling

Irrigation scheduling and saffron yield

Saffron yields as influenced by different amounts of water as percentage of potential crop evepotranspiration (100% ETp, 75% ETp, 50% ETp, and 0% ETp, *i.e.,* rain-fed) applied with 24-day interval are shown in Table 7 (Monfared, 2005). In general, higher yield is produced in basin irrigation, and irrigation scheduling based on 50% ETp is sufficient in producing acceptable yield under seasonal rainfall of about 400 mm. However, under seasonal rainfall of about 240 mm, irrigation scheduling based on 75% ETp is required to produce acceptable saffron yield. It is indicated that in higher seasonal rainfall (about 400 mm) more deficit irrigation (50% ETp) is allowed, while, in lower seasonal rainfall (about 200 mm) lower deficit irrigation (75% ETp) is allowable.

Table 7. Saffron yield (kg ha^{-1}) as influenced by different irrigation scheduling and methods.

Irrigation schedule	Applied irrigation water (mm)	Basin	Furrow
	Wet year (413 mm rainfall)		
100% ET_p	299	9.43a*	5.95a
75% ET_p	250	9.13a	5.83a
50% ET_p	202	8.82a	5.79a
Rain-fed	0	5.16b	2.03b
	Dry year (244 mm rainfall)		
100% ET_p	307	7.26a	4.67a
75% ET_p	257	7.00a	4.27a
50% ET_p	207	6.25b	4.02a
Rain-fed	0	3.35c	1.68b

*Means followed by the same letters in each year and each column are not significantly different at 5% probability level by Duncan multiple range test.

Another experiment conducted by Mosaferi (2001) in Mashhad area. He used four levels of applied water (10, 20, 40, and 80 mm) with 15-day interval during a six months period. Saffron yields are illustrated in Table 8. It is indicated that the amount of applied water of 20 mm at each irrigation event with 15-day interval resulted in the highest saffron yield. This amount of water is equivalent to about 240 mm of seasonal applied water that is in accordance to findings of Monfared (2005) with 200 mm seasonal rainfall.

Crop water stress index of saffron

Crop water stress index (CWSI) is an appropriate parameter for irrigation scheduling for many crops (Idso, 1982). Shirmahammadi-Aliakbarkhani et al. (2006) determined this parameter for saffron using data obtained from an experiment based on four different levels of irrigation water application (100% ETp, 75% ETp, 50% ETp, and 0% ETp, *i.e.,* rain-fed). They developed the lower and upper limit lines as follows (Idso, 1982):

$(T_c\text{-}T_a)_{ll}=12.2-0.25\times VPD$, $R^2=0.95$, SE=0.31, $P<0.001$ (lower limit) (1)

$(T_c\text{-}T_a)_{ul}=11.0$ C (upper limit) (2)

where T_c and T_a are the crop canopy and air temperatures in C, respectively, VPD is the air vapor pressure deficit in mb, R^2 is the coefficient of determination, SE is the standard error, and p is the probability level. CWSI is calculated as follows (Idso, 1982):

$$CWSI= \{(T_c\text{-}T_a)_m\text{-}[a\text{-}b(VPD)_m]\}/\{(T_c\text{-}T_a)_{ul}\text{-}[a\text{-}b(VPD)_m]\} \quad (3)$$

Table 8. Saffron yield as influenced by different amounts of applied water at each irrigation event.

Applied irrigation water (mm)	Flower dry weight (g m^{-2})	Saffron yield ($g\ m^{-2}$)
10	25.0b*	0.150b
20	37.0a	0.190a
40	34.0ab	0.153b
80	27.1b	0.117b

*Means followed by the same letters in each column are not significantly different at 5% probability level by Duncan multiple range test.

where a is 12.2 C, b is 0.25 C mb^{-1}, $(VPD)_m$ is the measured vapor pressure deficit in mb, and $(T_c\text{-}T_a)_m$ is the measured difference between crop canopy and air temperatures in C. Crop water stress index for saffron was calculated based on Eqs. (1), (2), and (3) for different irrigation treatments during the growing season and their mean values are 0.04, 0.27, 0.60, and 0.92 for 100% ETp, 75% ETp, 50% ETp, and 0% ETp, respectively. Further, the relationship between CWSI and relative evapotranspiration reported as follows (Shirmahammadi-Aliakbarkhani et al., 2006):

$CWSI=1.60(1\text{-}ET_a/ET_p)$, R^2=0.99, SE=0.011, P<0.001 (4)

Where ET_a and ET_p are the actual and potential seasonal evapotranspirations, respectively.

According to the findings of Monfared (2005) optimum required irrigation water is determined based on 75% ETp and 50% ETp for areas with seasonal rainfall of 200 and 400 mm, respectively, that are corresponding to the CWSI of 0.27 and 0.6, respectively. Therefore, these values of CWSI can be used in saffron scheduling.

Table 9. Saffron yield (kg ha^{-1}) as influenced by different supplemental irrigation with a seasonal rainfall of 600 mm.

Applied irrigation water (mm)	Basin	Furrow
149	6.91a*	3.96a
144	4.92b	3.21b
137	4.03c	2.18c
Rain-fed	0.84d	0.35d

*Means followed by the same letters in each column are not significantly different at 5% probability level by Duncan multiple range test.

Supplementary irrigation

In an experiment conducted by Shirmohammadi-Aliakbarkhani (2002), the effects of supplementary irrigation on saffron yield, under high seasonal rainfall (600 mm) was investigated. Pre-flowering irrigation water was applied as 125 mm and after 37 days with no rainfall, three levels of irrigation water were applied as 100% ETp, 75% ETp, 50% ETp, and 0% ETp. Saffron yields are shown in Table 9. Again, it is indicated that basin irrigation is preferred to furrow irrigation. Furthermore, supplemental irrigation as pre-flowering and post-flowering irrigation in case of no occurrence of rainfall for 37 days produced considerable yield compared with rain-fed saffron. This is due to the fact that when rainfall is delayed at autumn, soil surface is dry and it is not in favor of flower emergence. In this situation, most of the emerging flowers are remained in soil, therefore, saffron yield is reduced drastically. However, supplementary pre-flowering and post-flowering irrigation enhanced flower emergence and saffron yield. Therefore, it is proposed that for rain-fed saffron, when rainfall is delayed, for soil wetting at pre-flowering, irrigation water should be used for good saffron yield to be obtained.

Saffron water requirement

Saffron growing season coincides with late autumn, winter and early spring with cold to moderate temperatures. However, during the summer where water shortage is a limiting factor for growth of many crops, saffron is in its dormant stage with no water requirement. High yield of saffron depends on a strong vegetative growth that requires enough water after flowering in late autumn to early spring. Therefore, for irrigated saffron or supplementary irrigated saffron for rain-fed conditions, proper planning for irrigation regimes is necessary.

Potential crop evapotranspiration for saffron is determined based on following equation:

$$ET_p=K_c\times ET_o \qquad (5)$$

Where ET_p is the potential crop evapotranspiration of saffron, K_c is the crop coefficient and ET_o is the reference crop evapotranspiration. According to Sepaskhah (1999), ET_o can be estimated based on Penman-FAO and Penman-Monteith equations using weather data from the reference and non-reference weather stations, respectively.

Based on the pan evaporation data, ET_p of saffron can be determined by the following equation:

$$ET_p=K_p\times E_p \qquad (6)$$

Where K_p is the pan coefficient for saffron and E_p is the pan evaporation. In general, K_c and K_p for saffron should be determined in field experiment.

Crop coefficient

Shirmohammadi-Aliakbarkhani (2002) determined ET_p for a three-year old saffron field in Bajgah (Fars province, I.R. of Iran) by using field water balance procedure as described by Sepaskhah and Ilampour (1995). Three-year old saffron field produces almost the economical yield for which K_c and K_p are determined. The values of saffron potential evapotranspiration rate, reference crop evapotranspiration rate and class A pan evaporation rate are presented in Table 10. These data were used to determine monthly values of crop coefficient (K_c) and pan coefficient (K_p) for saffron. The highest value of K_c and K_p obtained during January (1.1 and 0.84, respectively). These are higher than those reported by Alizadeh (2006) for Khorasan province that might be occurred due to difference in climate conditions. Furthermore, Azizi-Zohan et al. (2008) reported that the values of K_c varied through the growing season from 0.22-0.24 to 0.94-1.05, and 0.68-0.78 at the beginning, middle and end of the crop's cycle for one- and two-year old saffron fields.

Saffron vegetative cover increases due to corm propagation and canopy development in successive years. Therefore, its water requirement increases with the age of field. The values of K_c for a saffron field with age of one and two-year determined by Yarami (2008) in a water balance lysimeter in Bajgah (Fars province, I.R. of Iran). The highest values of K_c for the mid season of saffron were 0.93 and 1.05 for one and two-year old field, respectively (Yarami, 2008). It is obvious that these values are lower than that for the three-year old field as shown in Table 10.

Table 10. Reference crop evapotranspiration rate (ET_O), class A pan evaporation rate (E_p), saffron potential evepotranspiration rate (ETp), crop coefficient (K_c) and pan coefficient (K_p) for different months ofsaffron growing season (3-year old field).

Month	ET_o mm d^{-1}	E_p mm d^{-1}	ETp mm d^{-1}	K_c	K_p
October	2.55	3.00	1.15	0.45	0.38
November	2.27	2.67	1.24	0.55	0.46
December	1.65	1.98	1.54	0.93	0.78
January	1.66	2.17	1.83	1.10	0.84
February	2.25	3.15	2.10	0.93	0.68
March	3.51	4.80	2.39	0.68	0.50
April	5.61	6.84	2.80	0.50	0.41
May	7.25	8.12	3.01	0.42	0.37

According to Allen et al. (1998), K_c curve is usually plotted by dividing the plant growing season into four stages and a linear change of K_c is assumed for each growth stage. Shirmohammadi-Aliakbarkhani (2002) presented the four-stage K_c curve for a three-year old saffron field as shown in Figure 2. Duration of the four growth stages for saffron in Bajgah with semi-arid climate in Fars province and their corresponding values of K_c are presented in Table 11. The presented values of K_c for different stages of growth are a little different from those reported by Alizadeh (2006) that is due to difference in climatic conditions. The reported values of K_c for initial, mid and late seasons are 0.4, 0.85 and 0.55, respectively (Alizadeh, 2006) in Khorasan province with arid climate.

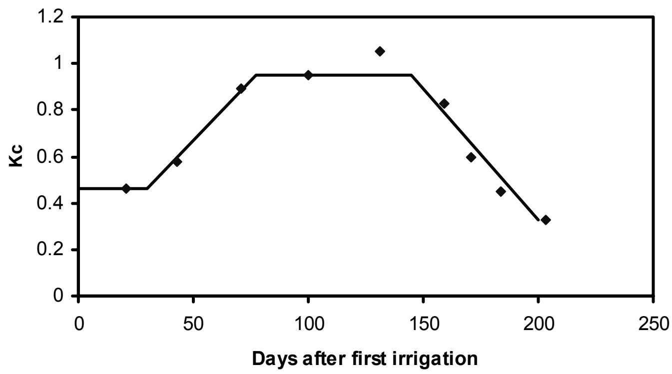

Figure 2. Crop coefficient for saffron at different growth stages.

Evapotranspiration

Seasonal potential crop evapotranspiration of saffron (ET_p) was determined by field soil water balance (Azizi-Zohan et al., 2008) as 485 and 670 mm for one- and two-year old fields, respectively in Bajgah area, Fars province, with a warm semi-arid climate. Higher value of ET_p in two-year old field is mainly due to the higher corm population compared with that in one-year old field. Further, value of ET_p for saffron was determined in a water balance lysimeter in the same location (Yarami, et al., 2007) as 520 mm for one-year old field in a different year. This value is in accordance to that reported by Aziziu-Zohan et al. (2008). The value of ET_p for a two-year old field in Khorasan province (cold arid climate) measured by a water balance lysimeter as 320 mm (Mahdavi, 1999). The difference between this value and that reported in Fars province is due to the difference in climate.

Table 11. Duration of growth stages of saffron and corresponding values of K_c in Bajgah (Fars Province).

Growth stage	Duration (day)	Crop coefficient (K_c)
Initial	30	0.46
Development	45	-
Mid-season	70	0.95
Late season	55	0.33

Irrigation water salinity

Saffron (*Crocus sativus* L.) is the most important export crop in Iran. It is mostly produced in Khorasan, and Fars provinces with arid and semi-arid climates under irrigated condition (Abrishami, 1987). However, renewable water resources with high quality in these areas are limited. The main water source for saffron irrigation is groundwater that is overdrawn with increasing salinity. Furthermore, because of restricted water resources, wastewater and saline water are used in irrigation. Therefore, effects of irrigation water salinity on saffron yield should be examined.

An experiment was conducted by Sepaskhah and Yarami (2008) to determine the effect of water salinity on yield and yield components of saffron in pot experiment in open space under transparent shelter in Bajgah (Fars province, I.R. of Iran). The results are illustrated in Table 12. Response of different growth traits to salinity levels of irrigation water is not similar. Flower fresh weight and corm and root growth decreased drastically by increasing salinity level. Flower production decreased 49% by using salinity level of 1.7 dS m^{-1} and no flower produced at salinity level of 4.0 dS m^{-1}, while leaf growth occurred in this salinity. Flower yield reduction is in accordance with very low corm and root growth (about 18 and 25% of control salinity for corm and root, respectively). However, by increase in salinity level, lower reduction in leaf growth and seasonal evapotranspiration occurred. In contradiction to flower yield, it is indicated that vegetative growth is not sensitive to water salinity and showed a low vegetative growth reduction (18%) even at salinity level of 4.0 dS m^{-1}. This is similar to reduction in seasonal evapotranspiration at salinity level of 4.0 dS m^{-1} (21%).

Yield-salinity functions

Relationship between relative yield and seasonal mean drainage water salinity reported by Sepaskhah and Yarami (2008) as follows:

For flower yield:

$y_f/y_{fm}=1-0.142(EC_{ss}-0.08)$, $R^2=0.83$ (7)

For leaf dry weight:

$y_l/y_{lm}=1-0.029(EC_{ss}-0.29)$, $R^2=0.40$ (8)

For corm growth:

$y_c/y_{cm}=1-0.108(EC_{ss}-0.29)$, $R^2=0.54$ (9)

For root dry weight:

$y_r/y_{rm}=1-0.091(EC_{ss}-0.67)$, $R^2=0.64$ (10)

Table 12. Effects of salinity levels of irrigation water on saffron growth and seasonal evepotranspiration in pot experiment.

Salinity level (dS m^{-1})	Flower fresh weight (g pot^{-1})	Leaf dry Weight (g pot^{-1})	Corm growth (g pot^{-1})	Root dry weight (g pot^{-1})	Seasonal evapotranspirati on (mm)
0.5	2.86a*	9.46a	11.24a	9.84a	624a
1.7	1.46b	8.79b	8.65b	6.38b	543b
2.9	0.43c	8.78b	5.11c	4.34c	535b
4.0	0.00d	7.75c	2.06d	2.46d	492b

*Means followed by the same letters in each column are not significantly different at 5% probability level by Duncan multiple range test.

where y/y_m is the relative yield for different plant components, *i.e.,* f for flower, l for leaf, c for corm and r for root. The slopes of these equations are the yield reduction (fraction) per unit of increase in drainage water salinity. Further, the values in parentheses are the threshold salinity of drainage water for different yield reduction initiation. These values show that the flower is the most sensitive part of plant with the highest and lowest values of yield reduction (%) per unit salinity and salinity threshold, respectively. According to these values in Eqs (7) to (10), the leaf is the least sensitive part of the plant. Further, the sensitivity of corm and root to salinity lay in between of leaf and flower. Based on Eq. (7), 50% flower yield is produced at soil water salinity of 3.6 dS m^{-1}.

Irrigation water productivity

Saffron yield ratio to the amount of applied irrigation water considered as water productivity (WP). This parameter determined by using data reported by Azizi-Zohan et al. (2006), Shirmahammadi-Aliakbarkhani (2002) and Monfared (2005) for different irrigation methods, intervals and regimes in successive growing seasons in Bajgah (Fars province). Results are depicted in Table 13. In general, WP is lower in furrow irrigation compared with basin irrigation. In older fields, the reduction in WP for furrow irrigation is decreased from about 80% to 30%. This indicates that corm growth in older furrow irrigation fields is adapted to new conditions of plantation and resulted in improved saffron yield in older furrow irrigation fields.

In one-and two-year old fields irrigated with different irrigation intervals, WP is the highest with 24-day interval in basin irrigation. This indicates that 24-day irrigation interval is appropriate for the semi-arid region in Fars province. In 4-year old field with supplementary irrigation, in a season with higher seasonal rainfall, WP is the highest for the irrigation regime based on 100% ET_p. Furthermore, the maximum WP(about 3.0-4.6 g m^{-3}).

Table 13. Water productivity of saffron (g m^{-3}) as influenced by different irrigation scheduling and methods in different years with different seasonal rainfall.

Field age (year)	Seasonal rainfall (mm)	Irrigation schedule/ interval (day)	Basin	Furrow
1	437	12	0.43	0.11
		24	0.70	0.16
		36	0.52	0.08
2	208	12	0.90	0.32
		24	1.43	0.19
		36	1.09	0.17
4	620	100% ET_p	4.64	2.66
		75% ET_p	3.42	2.23
		50% ET_p	2.94	1.59
6	413	100% ET_p	3.15	1.99
		75% ET_p	3.65	2.33
		50% ET_p	4.37	2.87
7	244	100% ET_p	2.37	1.52
		75% ET_p	2.72	1.66
		50% ET_p	3.02	1.94

is obtained in 4- to 6-year old saffron fields with basin irrigation. Similarly, WP in furrow irrigation is the highest in fields with the same age. For irrigation regimes based on different percentages of ET_p, and different seasonal rainfall in 6-year and 7-year old saffron fields, the most appropriate WP is obtained for 50% ET_p and 75% ET_p with seasonal rainfall of about 400 and 200 mm, respectively.

Optimum deficit irrigation for saffron

In analyzing the water-scarcity issues, the contribution of green water (rainfall through evapotranspiration use) is usually not included in terms of fresh water to cover crop water requirements (Rockstrom et al., 2003). By considering the green water in this analysis water productivity (WP) is increased. To increase WP of blue-water, deficit irrigation is used. The optimum water use in deficit irrigation is obtained by an economic analysis using water production and cost functions as described by English (1990) and applied for saffron (Sepaskhah et al., 2008).

Saffron in Iran is planted as a perennial crop and its yield varies in successive years (Sepaskhah et al., 2008). The crop production function for water is dependent on the year of production. This is due to the fact that the amount of corm per unit area (corm intensity) varies in successive years. Therefore, the crop production function of saffron for water is dependent not only on the amount of applied water but also it depends on the amount of corm per unit area. Sepaskhah et al. (2008) derived equations for determination of required water at variable seasonal rainfall and different prices of water and corm leading to maximum crop yield or profit with limited water conditions for saffron. The equations for optimum irrigation water, w_w, are obtained as follows:

$$w_w=(R^2-1.24R+8.52\times10^{-4}O^2-0.046O+0.798)^{0.5} \quad (11)$$

Where w_w is the optimum irrigation water at water limiting condition in m, R is the seasonal rainfall in m and O is the corm planting intensity t ha^{-1}. Using different values of R and O for different years of experiment, the values of w_w are calculated and the results are shown in Figure 3. The least amount of water is required for the three-year old field with the highest amount of corm planting intensity (Figure 3). For the three-, four- and five-year old fields with higher amount of corm planting intensity the optimum irrigation water is zero for about 300 mm of rainfall. While for the six- , and seven-year old fields the optimum irrigation water is zero for about 500 mm of rainfall. However, for one-, and two-year old fields the lowest optimum irrigation water is obtained for 650 mm of rainfall (Figure 3). In this Figure, it is shown that the optimum amounts of irrigation water are 0.25 and 0.16 m for the one-, and two-year old fields, respectively.

Summary

Saffron is grown in arid and semi-arid regions in Iran. Its flower appears in mid autumn and coincides with cold temperature. It shows positive response to irrigation in autumn, and winter with rainy season, but summer irrigation should be avoided. Therefore, saffron irrigation is supplemental irrigation especially in semi-arid region. In contradiction to most other crops, basin irrigation should be used for saffron with a pre-flowering irrigation for economical production. Even for rain-fed saffron with seasonal rainfall of about 600 mm, pre-flowering irrigation is required in area that rainfall delayed until late in autumn. The most appropriate time for pre-flowering irrigation is mid October in saffron plantation areas in Iran. In rain-fed saffron with occasional seasonal rainfall of about 600 mm, pre-flowering irrigation of about 150 mm is needed, while continuous supplemental irrigation is needed for regions with seasonal rainfall of about 400 mm or lesser.

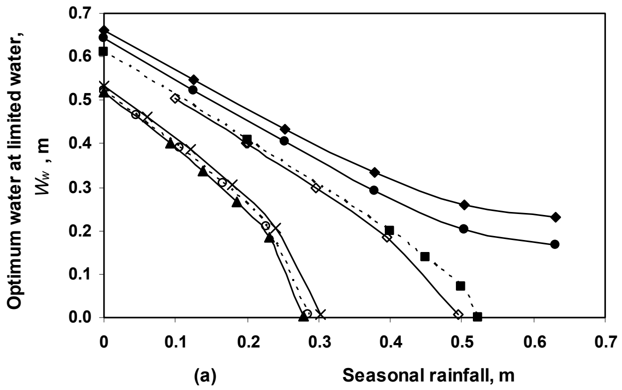

Figure 3. Relationships between optimum water and seasonal rainfall under water limiting conditions in different years after planting with different corm intensity: ♦, 1 year (9.5 t ha^{-1}); ■, 2 years (11.8 t ha^{-1}); ▲, 3 years (16.7 t ha^{-1}); ×, 4 years (15.8 t ha^{-1}); ○, 5 years (16.4 t ha^{-1}); ●, 6 years (10.4 t ha^{-1}); ◊, 7 years (12.0 t ha^{-1})

For scheduling supplemental irrigation of saffron by irrigation intervals, the appropriate irrigation interval is 24 and 15 days in semi-arid and arid regions, respectively. Furthermore, irrigation regime should be planned based on 75% and 50% ET_p for seasonal rainfall of about 200 mm (arid region) and about 400 mm (semi-arid region), respectively. This irrigation scheduling resulted in higher water productivity. Saffron irrigation scheduling can be conducted based on crop water stress index (CWSI) of 0.27 and 0.60 in areas with seasonal rainfall of about 200 and 400 mm, respectively.

For 3-year old saffron fields, duration of initial, development, mid season and late season stages is 30, 45, 70, and 55 days, respectively and estimated values of crop coefficients (K_c) for these successive stages are 0.46, 0.95 and 0.33. Furthermore, monthly values of K_c and pan coefficient (K_p) for saffron are presented with the highest values of 1.10 and 0.84, respectively, that occurred in January.

It is shown that the optimum amounts of irrigation water are 0.25 and 0.16 m for the one- and two-year old fields, respectively. For the three-, four-and five-year old fields with higher amount of corm intensity the optimum irrigation water is zero for about 300 mm of rainfall. While for the six-and seven-year old fields the optimum irrigation water is zero for about 500 mm of rainfall.

Flower production decreased 49% by using irrigation water with salinity level of 1.7 dS m^{-1} and no flower produced at salinity level of 4.0 dS m^{-1}, while leaf growth occurred in this salinity. Furthermore, 50% flower yield is produced at soil water salinity of 3.6 dS m^{-1}.

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