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Research Article

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Planting dates and irrigation regimes influence on growth and yield of quinoa (*Chenopodium quinoa*) in a semi-arid area

R. Talebnejad[1,2]*, M. Bahrami[1], A. R. Sepaskhah[1,2]

[1]Water Engineering Department, School of Agriculture, Shiraz University, Shiraz, I. R. Iran
[2] Drought Research Center, School of Agriculture, Shiraz University, Shiraz, I. R. Iran

* Corresponding Author: rtalebnejad@shirazu.ac.ir
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ABSTRACT- Planting crops with less vulnerability to environmental stresses, especially drought in semi-arid areas, can remarkably improve irrigation water use efficiency (IWUE). Therefore, in this study, planting quinoa (*Chenopodium quinoa*) under different irrigation regimes and planting dates was investigated. Irrigation regimes included full irrigation (FI) and 50% of full irrigation (0.5FI), where planting dates consisted of six planting dates in the early spring and six planting dates in the early fall. Results indicated that the highest grain yield, dry matter, root dry weight, leaf area index, harvest index, and yield components were obtained in early spring cultivation on February 19 and in the early fall on August 23 planting dates. The maximum leaf area index on the planting date of August 23 was 21% higher than that on the planting date of February 19 under FI conditions. The highest harvest index was 0.32 in FI and the planting date of August 23. The planting date of August 23 increased water use efficiency for grain (IWUEG) by 30% compared to planting on February 19 under FI conditions. There was no significant difference in specific root length between planting dates on February 19 and August 23. Applying 0.5FI compared to FI increased root dry weight to shoot dry weight ratio to 142% on the planting date of August 23. Generally, the planting date of August 23 is suggested as the best planting time for quinoa in the study area with no water scarcity, while planting on February 19 is recommended in the conditions of scarce water resources by applying 0.5FI.

INTRODUCTION

Future food security is dependent on increasing edible grains by 2% annually (Sajjad et al., 2014), which has been restricted by the lack of water resources. Environmental hazards, additionally, limited the agricultural production growth (Jacobsen et al., 2003). Therefore, planting crops with less vulnerability to environmental stresses, especially during drought in developing countries, can remarkably improve the irrigation water use efficiency (IWUE) of the crop. In this regard, crops like quinoa (*Chenopodium quinoa* willd) have received worldwide attention due to being well-adapted to adverse environmental conditions such as drought, frost, and salinity (Jacobsen et al., 2003). This plant grows in the mountainous areas of the Andes and Bolivia, Peru, and Ecuador, which has recently become a source of income for the poor-dwelling parts of these countries through exports to European countries and the Middle East (Hellin & Higman, 2003).

Quinoa grains can be used in bread, soup, or other nutrients. It is considered one of the most popular healthy foods, although its grain contains saponin, which gives it a bitter taste. Therefore, removing saponins before consumption is necessary (FAO, 2011). Quinoa grain is one of the few grains containing all nine essential amino acids. Further, it contains fiber, magnesium, vitamin B, iron, potassium, calcium, phosphorus, vitamin E, and other useful antioxidants (Dini et al., 2005; Geerts et al., 2008; Repo-Carrasco et al., 2003). On the basis of the FAO report, quinoa potential grain yield considering its cultivar, weather conditions, soil, applied water, and planting date is different (FAO, 2011).

Deficit irrigation is one of the common strategies dealing with water scarcity considering water resources limitations. In this way, a reasonable yield would be produced by reducing irrigation water to lower than crop water demand even at sensitive growth stages (English & Raja, 1996; Geerts et al., 2008). Therefore, deficit irrigation is suggested as a useful strategy against drought to achieve acceptable yields in arid and semi-arid regions (Kaya et al., 2015).

Recently, applying deficit irrigation to quinoa is extensively attracted many researchers' attention (Garcia et al., 2003; Geerts et al., 2006; Kaya et al., 2015). Field experiments by Geerts et al. (2009a) in Bolivia indicated that deficit irrigation significantly increased quinoa IWUE. They also suggested 55% of full irrigation as the threshold value under deficit irrigation conditions to prevent significant dry matter reduction. In addition, in an experiment conducted in southern Italy, Riccardi et al. (2014) declared that applying irrigation water at 25% of full irrigation led to maximum quinoa IWUE (1.12 kg m^{-3} and 0.95 kg m^{-3} in 2009 and 2010, respectively). Furthermore, Talebnejad and Sepaskhah (2015a) investigated that a 70% reduction of full irrigation at the presence of 0.8 m saline groundwater depth resulted in only a 36% reduction in seed yield of quinoa. Razzaghi et al. (2012) reported that 17-32% water savings occurred at deficit irrigation depending on different soil textures. By comparing IWUE in Iran and Denmark, Razzaghi et al. (2016) stated that under deficit irrigation conditions, quinoa could produce a higher yield in the wet regions than that in arid and semi-arid regions.

Although the quinoa demonstrated flowering ability over a wide range of photoperiods, it is mostly known as a short-day species (Risi & Galwey, 1984). The length of the quinoa flowering and maturity stages might be sensitive to the planting date; however, different cultivars vary in their response to the day length. This plant is well-known for its remarkable adaptation to harsh climatic conditions, but the very high (Bertero et al., 1999; Walters et al., 2016) and low (Bertamini et al., 2005; Bois et al., 2006; Jacobsen et al., 2005) temperatures are still considered the most important environmental stresses during the growing season. Therefore, an appropriate planting date has a vital impact on quinoa grain yield (Hirich et al., 2014a; Sajjad et al., 2014). Findings by Peterson & Murphy (2015) and Walters et al. (2016) showed that temperatures higher than 35 °C at the grain filling phenological stage caused incomplete and weak quinoa seeds. Nurse et al. (2016) in southern Canada suggested mid-May to late June as a proper time to plant quinoa, while planting quinoa in July decreased grain yield by more than 50%.

Although planting quinoa in Iran has been considered recently and attracted the interest of Iranian farmers as a plant with the potential to produce grain yield under harsh weather conditions, little basic information is available regarding the proper date of planting quinoa. Appropriate planting date is considered the first step in the planting of agricultural products, which itself plays an important role in plants adapting to new climatic conditions for optimal yield. Therefore, it is necessary to investigate the suitable planting date in quinoa cultivation in non-native areas. On the other hand, due to the scarcity of water resources and the need to increase IWUE in the agricultural sector, this study aimed to explore the effect of twelve planting dates including six early spring planting dates and six early fall planting dates, and also two irrigation regimes on growth, yield and yield components of quinoa (cv. Titicaca, no. 5206) under semi-arid conditions.

MATERIALS AND METHODS

This study was conducted during 2017-2018 under a transparent shelter (2 m high) located in the Experimental Research Station of the School of Agriculture, Shiraz University, Shiraz, Iran. The experimental area is located in northern Shiraz at 52°32′E longitude and 29°36′N latitude and at an altitude of 1810 meters above mean sea level. Fig. 1 displays the maximum and minimum daily temperatures below transparent shelter and the mean relative humidity during the quinoa growing period.

To evaluate the interaction of planting date and different irrigation regimes on quinoa (cv. Titicaca, no. 5206) yield and yield components, a factorial experiment was conducted in a randomized complete block design with 24 treatments (2×12) in three replications. Experimental treatments included two irrigation strategies [full irrigation (FI) and 50% of full irrigation (0.5FI)] and 12 planting dates. Planting dates included six early spring planting dates from February 19, 2017, to May 5, 2018, with 15-day intervals and six early fall planting dates from August 23, 2018, to November 6, 2018, with 15-day intervals. Five Quinoa seeds were planted in pots of 23 cm diameter and 23 cm height. Before planting, in 0.5FI treatments, perforated plastic pipes with 17 mm diameter were placed in the pots to distribute irrigation water uniformly and facilitate water movement through the soil mass. A gravel layer (10 mm thickness) with an average 7 mm diameter was placed at the bottom of pots to ease drainage. Nine kg of air-dried soil (silty clay loam) collected from 0-30 cm field soil layer, passing through a 2 mm sieve was added to the pots.

Five seeds (Titicaca cultivar) were planted in each pot at 2-3 cm depth. After plant establishment (14 days after planting), the seedling was thinned, and two seedlings remained in each pot. Soil chemical properties were retrieved (with their permission) from the previous investigations including Yarami & Sepaskhah, (2015) and Mehrabi & Sepaskhah, (2019) which were determined by them at the same experiment site with similar soil texture in pots and fields conditions, respectively . Therefore, the fertilizer application rate in this research was chosen according to those nitrogen and phosphorus fertilizer application rate recommendations based on soil testing. Nitrogen (N) fertilizer as urea (46% nitrogen) at 1.24 g pot^{-1} (300 kg ha^{-1}) was applied to the soil in equal proportions at two growth stages, including the vegetative stage and the beginning of the grain filling. In addition, after filling the pots, 0.12 g pot^{-1} (30 kg ha^{-1}) of phosphorus was mixed with the soil surface layer in the form of triple superphosphate fertilizer ($Ca\ (H_2PO_4)$) containing 46% P_2O_5 (Razzaghi & Sepaskhah, 2012). Table 1 presents the physicochemical properties of the used soil.

Irrigation treatment was initiated in the early vegetative stage (at the 5 leave stage). Total irrigation water depth before applying irrigation regimes was on average 250 mm and 210 mm in the early spring and early fall planting dates, respectively. Irrigation water depth was determined by weighing pots every other day and irrigation water was applied at two days intervals. In FI, irrigation water depth was determined using the difference between the mean weight of pots before irrigation and field capacity (Field Capacity, F.C.). Deficit irrigation water depth was 50% of FI irrigation treatments, in which half was added to the soil surface and the remaining half was poured into the perforated plastic tube inside the pot to avoid water moving from the cracks between the soil and pot wall.

Actual evapotranspiration (ET_a) was determined as the following using the water balance equation:

$$ET_a = I + P - D_p \pm \Delta S \quad (1)$$

where I and P are irrigation depth (m) and precipitation (m), respectively. Besides, D_p and ΔS are the deep percolation (m) and soil water content changes (m) between two irrigation events, respectively. Notably, D_p was considered zero because the pots irrigated to reach the F.C. Precipitation is also considered zero due to placing the pots under shelter.

In each pot, one plant was marked to measure the leaves' length and width during the growing season. The quinoa leaf area was determined using the following relationship obtained by Talebnejad & Sepaskhah (2015b):

$$LA = 0.64(L \times W) \quad (2)$$

where LA is the leaf area (cm^2), L and W are the leaf length and width in cm. Then leaf area index (LAI) was determined by dividing the total area of leaves of each crop (A) by the area occupied by the crop (A_c) as follows:

$$LAI = A/A_c \quad (3)$$

Considering the canopy cover of quinoa, the area occupied by each plant was determined to be equal to 450 cm^2.

Before harvesting, the length of main and lateral panicles, and the number of lateral panicles (longer than 10 mm) were measured. Plants were completely harvested within 4-7 days after the last irrigation in the early spring plantation and 8-12 days after the last irrigation in the early fall plantation. During the growing season, physiological stages including germination, early vegetative, vegetative, flowering, anthesis, grain filling, and maturity were recorded according to Jacobsen & Stølen (1993). After harvesting, grain yield (GY), total dry matter (TDM), and 1000-grain weight were determined. Afterward, the soil of the pot was divided into two parts (0-10 cm and 10-20 cm) and the root parameters were reported as the average of two layers. Soil samples were washed to separate roots as suggested by Ahmadi et al. (2011). Finally, mean root length was measured using the Newman method (Newman, 1966). Average root length density (RLD, m m^{-3}) and average root weight density (RWD, kg m^{-3}) of two depths (0-10 cm and 10-20 cm) were determined considering the soil section volume. Afterward, specific root length (SRL) was estimated using the ratio of root length to root dry weight (m g^{-1}). Root shoot ratio (RSR, kg kg^{-1}) was determined as the ratio of root dry weight to shoot dry weight.

The following equation was used to calculate the Growing-Degree Day (GDD) for each growth stage.

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base} \quad (4)$$

where T_{max} and T_{min} are the maximum and minimum air temperatures, respectively, and T_{base} is the base temperature of the quinoa, which is 3 °C, as reported by Jacobsen & Bach (1998). Further, the maximum threshold temperature was considered at 35 °C (Alvar-Beltrán et al., 2019).

Pests control management

Generally, direct observation in the field experiments by farmers in Fars province in Iran indicated that quinoa is an appropriate bed for feeding the pests. In this study, aphid, lace bug, cutworm, true bug nymph, beet armyworm larva, and mites were observed in the spring cultivation, and aphid, true bug nymph, and thrips were observed in the autumn cultivation. The pests were controlled mechanically by handpicking or through pesticide use.

Statistical analysis

The SAS software (Statistical Analysis System) version 9.4 was used for statistical analyses. The interaction effects between irrigation method and planting date on quinoa growth and yield were evaluated by using analysis of variance (ANOVA) and means were compared by Duncan's Multiple Range Tests (DMRT) at a 5% level of probability.

Table 1. The physical and chemical properties of the soil used in this study which was retrieved (with their permission) from Yarami & Sepaskhah, (2015) and Mehrabi & Sepaskhah (2019).

Physical and chemical properties	Soil depth (cm)
	0-30
Field capacity (cm cm^{-3})	0.24**
Permanent wilting point (cm cm^{-3})	0.11**
Bulk density (g cm^{-3})	1.14**
Sand %	11
Silt %	56
Clay %	33
Texture	SCL*
EC (dS m^{-1})	0.74
Cl^- (meq l^{-1})	5.31
Na^+ (meq l^{-1})	3.29
Ca^{2+} (meq l^{-1})	5.43
Mg^{2+} (meq l^{-1})	3.5
N %	0.02
Available P (mg kg^{-1})	20

* Silty clay loam

** Measured from experimental pots

RESULTS AND DISCUSSION

Quinoa development

The coldest month was December with a minimum temperature of -9.2 °C, whereas the warmest month was June with a maximum temperature of 45 °C (Fig. 1). The analysis of variance showed that spring or autumn cultivation had no significant effect on total GDD. Fig. 2 shows the total GDD at each phenological growth stage of quinoa at different planting dates of the Titicaca cultivar. The cumulative degree-days (Cd-d) required at each growth stage were not affected by the irrigation regimes, and only slightly varied (775 to 1061 Cd-d) on different planting dates. Bois et al. (2006) reported that the Real Blance and Surumi cultivars of the quinoa require a total of 989 and 871 GDD, respectively, to reach the flowering stage. However, in this study, the Titicaca cultivar required an average of 938 GDD to reach the flowering stage. Proper seed germination is one of the most important factors in quinoa planting. In this study, the mean temperature at germination changed from 5 °C (February 19 planting date) to 25 °C (August 23 planting date). According to Bertero (2003), the minimum germination base temperature and the maximum temperature for the Titicaca cultivar of quinoa were 1 °C and 54 °C, respectively. Generally, Mamedi et al. (2017) considered the temperature of 22-35 °C as the optimal temperature for the proper Titicaca germination. Additionally, they reported that the planting dates at the end of August and the beginning of September showed the optimal germination temperature.

Planting quinoa has increasingly expanded as a tolerant crop to a wide range of air temperatures (Bertamini et al., 2005; Bois et al., 2006; Jacobsen et al., 2005). However, many studies reported the crop vulnerability at flowering and grain filling stages to the temperature stress (Peterson & Murphy, 2015; Walters et al., 2016). Table 2 indicates the mean maximum and minimum temperatures at the flowering and grain filling stages of the quinoa for each planting date. Crops with planting dates on March 23, April 4, April 23, and May 5 completed both phenological growth stages (flowering and grain filling). During these two stages, the mean daily relative humidity was 25.4% and the mean daily maximum temperature varied between 37.8 to 41.9 °C.

Shifting the planting date from February 19 to September 6 shortened the growing season duration from 128 to 96 days. Results indicated that receiving only half of the full irrigation depth accelerated quinoa maturity (Fig. 2). In the early spring planting, deficit irrigation significantly played an important role to decrease the growing season duration. On the other hand, cold stress shortened the phenological period in both irrigation regimes and two planting dates in the early fall planting (Table 3).

Generally, deficit irrigation and cold stress resulted in completing the growing period quickly by the plant. Quinoa could not complete the phenological stages in both irrigation regimes at planting dates of September 23, October 7, October 23, and November 6. On the planting date of September 23, a few days after flowering, the minimum daily temperature reached -3 °C; therefore, the crops received FI, could not complete the flowering stage and were frozen (93 days after planting). In this regard, Bois et al. (2006) reported no serious damage at -3 °C on 10 varieties of quinoa. However, no plant survived when it was exposed to a temperature of -6 °C for about four hours.

Generally, delayed sowing in the spring resulted in high-temperature stress during the flowering and seed filling stages. Although quinoa could complete the phenological growth stages, there was a risk of yield reduction due to observed high temperatures (42 °C) in the climatic conditions of the study area. In this regard, Hatfield & Prueger (2015) indicated that vapor pressure deficit resulted in drying out the pollen moisture and consequently reducing the pollen survival. On the contrary, delayed sowing in the fall resulted in frost damage at the vegetation growth stage, and the crop could not enter the other growth stages. Even if quinoa completed the vegetation stage, frost damage would result in quinoa seed sterility. Finally, in the current study, the threshold temperature value was -3 °C during the flowering and grain filling stages, and -6 °C during the vegetation stage with a 2-day continuation.

Water use

Postponing the planting date to warmer months (early spring planting dates) resulted in higher irrigation depth than planting dates in the early fall so that the highest given water depth was achieved as 960 mm in FI and planting date on April 23 (Fig. 3). The lowest depth of irrigation water among all treatments which could produce grain yield was in the early fall planting date (September 6) at 0.5FI as 378 mm. Although planting dates in the early fall resulted in the frost risk, the planting date of September 6 under 0.5FI conditions was able to complete the phenological growth stages of the crop by receiving 303 mm water depth during the growing season. However, the crop in other planting dates in the early fall (September 23, October, and November) was affected by cold weather, and the crop vegetation growth stopped with no difference in irrigation water depth (Fig. 3).

The results of the analysis of variance showed a significant effect of interaction between irrigation regimes and planting dates on the soil water content before each irrigation event ($P < 0.05$). Fig. 4 presents the seasonal mean volumetric soil water content before irrigation during the growing season for each treatment. Mean volumetric soil water content in FI and planting dates in the early fall was significantly higher than that (23%) of the FI and planting dates in the early spring. Applying deficit irrigation at 0.5FI in the early spring decreased soil water content by about 47.4% for all the planting dates, except for the first planting date (August 23) in the early fall. There was no significant difference in soil water content between FI and 0.5FI and the other planting dates.

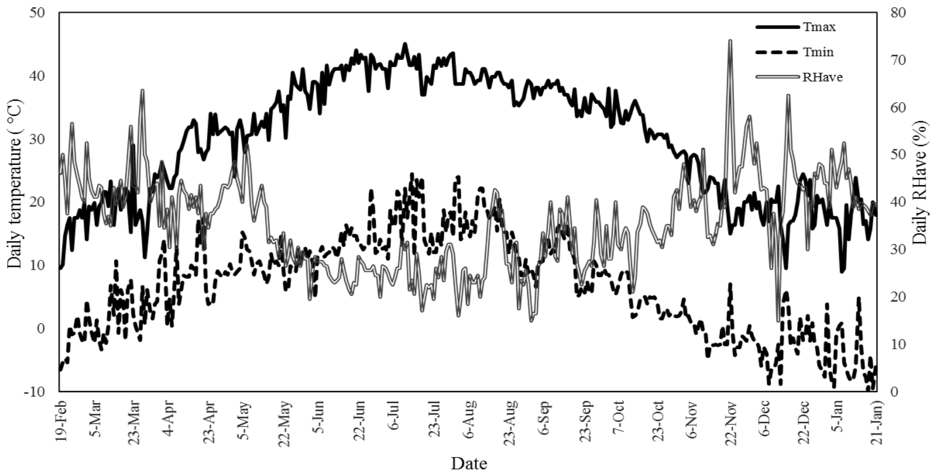

Fig. 1. Maximum daily air temperature (T_{max}), Minimum daily air temperature (T_{min}), and mean daily relative humidity (RH_{ave}) under the transparent shelter used in this study during the growing period (2017-2018)

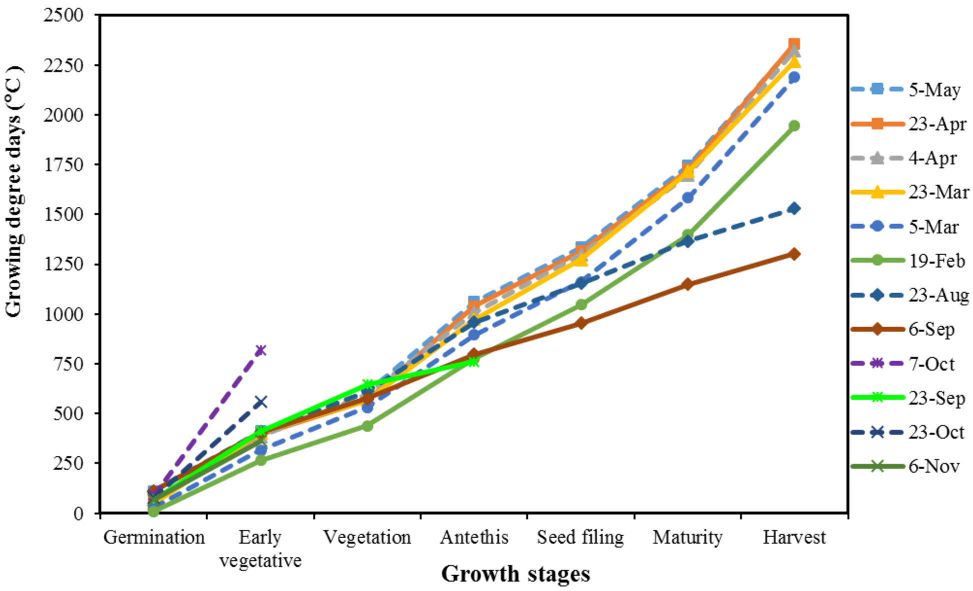

Fig. 2. Growing degree days (GDDs) for different developmental stages of quinoa (cv. Titicaca, no. 5206) at different planting dates. (Planting dates from 25 September to 6 November could not complete developmental growth)

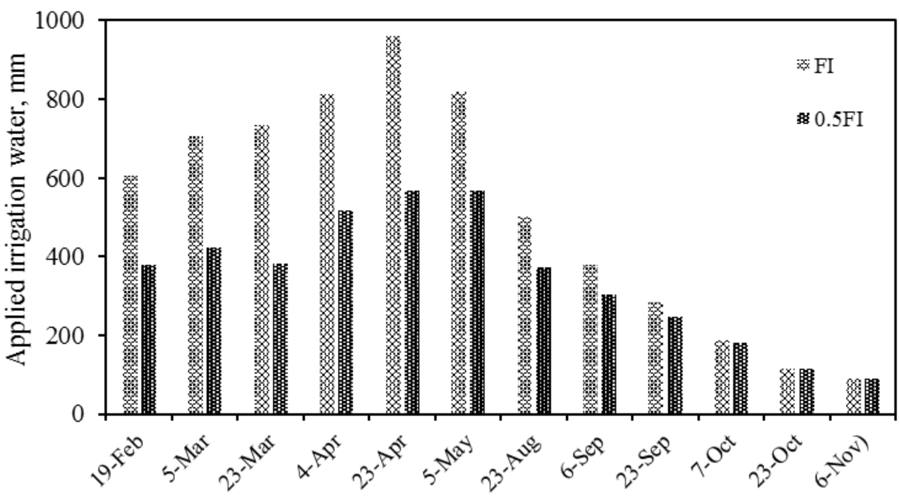

Fig 3. Applied irrigation water (mm) at different planting dates and irrigation regimes.

Table 2. Mean daily maximum (T_{max}) and minimum (T_{min}) air temperature (°C) at flowering and grain filling stages for different planting dates

Sowing date	Flowering		Grain filling	
	T_{max}	T_{min}	T_{max}	T_{min}
19-Feb	31.0	10.3	36.5	10.4
5-Mar	34.0	9.4	38.6	11.2
23-Mar	37.8	10.3	41.1	13.4
4-Apr	38.3	11.4	41.8	14.6
23-Apr	41.7	14.0	41.6	15.5
5-May	41.7	14.2	41.9	18.9
23-Aug	33.4	5.4	28.8	2.8
6-Sep	31.2	3.9	26.6	1.5
23-Sep	20.1	-1.6	18.9	-3.0
7-Oct	-	-	-	-
23-Oct	-	-	-	-
6-Nov	-	-	-	-

-: no data is available

Table 3. Harvesting date, growing seasonal duration (SD, day), and growing degree day (GDD, °C) at different planting dates and irrigation regimes

Sowing date	Irrigation regimes					
	FI	0.5FI	FI	0.5FI	FI	0.5FI
	Harvesting date		GDD		SD	
19-Feb	26-Jun	23-Jun	1943	1872	128 a*	125 c
5-Mar	8-Jul	30-Jun	2190	1985	126 b	118 d
23-Mar	16-Jul	11-Jul	2269	2128	116 e	111 f
4-Apr	23-Jul	18-Jul	2324	2208	111 f	106 g
23-Apr	3-Aug	31-Jul	2357	2273	105 h	102 i
5-May	12-Aug	4-Aug	2355	2151	100 j	92 m
23-Aug	28-Nov	28-Nov	1530	1530	98 k	98 k
6-Sep	10-Dec	10-Dec	1302	1302	96 l	96 l
23-Sep	24-Dec	22-Dec	-	-	-	-
7-Oct	11-Jan	11-Jan	-	-	-	-
23-Oct	10-Jan	10-Jan	-	-	-	-
6-Nov	1-Jan	1-Jan	-	-	-	-

* Means followed by the same letters are not significantly different at a 5% level of probability.
- No data is available

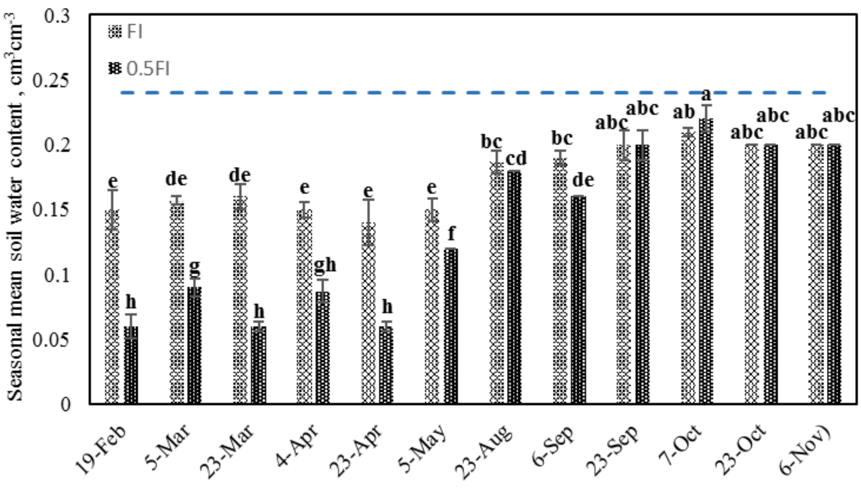

Fig 4. Seasonal mean soil water content (cm^3cm^{-3}) before irrigation event at different planting dates and irrigation regimes. Means followed by the same letters are not significantly different at a 5% level of probability...

Quinoa evapotranspiration remarkably increased by postponing the planting date from February to May in both irrigation regimes, in which the highest evapotranspiration was obtained on planting dates of April 23 and May 5 in the FI and 0.5FI, respectively (Fig. 5). Quinoa evapotranspiration significantly decreased in the early fall planting dates and gradually decreased in later planting dates.

Maximum leaf area index

In the early spring planting dates, the highest LAI_{max} was 1.95 in FI and the planting date of February 19, which was significantly different from that in other planting dates (Table 4). Compared to FI, 0.5FI did not show a significant difference in LAI_{max}, among different early spring planting dates, except for the planting date of February 19, which remarkably decreased LAI_{max} by 34%. However, postponing the planting date from February 19 to March 5 dropped LAI_{max} by 64% and 55% in FI and 0.5FI, respectively. Additionally, postponing the planting date from April to May dropped LAI_{max} by 79% and 77.5% in FI and 0.5FI, respectively.

In the early fall planting dates, the highest LAI_{max} was observed in FI, and the planting date of August 23 as 2.36, which increased by 21% compared to the planting date of February 19. Applying an irrigation regime of 0.5FI decreased LAI_{max} by 60% and 72% compared to FI on the planting date of August 23 and September 6, respectively. Postponing the planting date of August 23 to September 6 dropped LAI_{max} by 36% and 54% in FI and 0.5FI, respectively. Furthermore, the lowest LAI_{max} occurred in treatments facing frost.

Yield and yield components

Grain Yield

The interaction effect of irrigation regimes and planting date on grain yield was statistically significant. The maximum grain yield observed in the FI and planting dates of February 19 and August 23 were 9.38 and 9.96 (g pot^{-1}) equivalent to 2.26 and 2.4 Mg ha^{-1}, respectively, which had no statistically significant difference (Table 5). However, the highest obtained quinoa grain yield was reported in southern Morocco weather conditions (Hirich et al., 2014a) and greenhouse conditions in Iran (Talebnejad & Sepaskhah, 2015b) as 3.07 and 3.11 Mg ha^{-1}, respectively. On the other hand, applying 0.5FI for planting dates of February 19 and August 23 resulted in a 30% and 50% reduction in grain yield compared to FI of the same planting date, respectively.

Postponing planting dates from February 19 to March 5 significantly decreased grain yield by higher than 50% under 0.5FI conditions. While postponing planting dates from August 23 to September 6 significantly dropped grain yield by 65% under 0.5FI conditions. Therefore, delaying the planting date in the early fall accelerated the effect of water stress on grain yield. Despite the results reported by Walters et al. (2016) and Peterson & Murphy (2015) which showed that grain yield was destroyed due to high air temperature above 35 °C at the flowering stage, Alvar-Beltrán et al. (2019) reported just a reduction in grain yield due to high air temperature, which is consistent with the findings of this study.

In the current study, the same grain yield was produced on planting dates of March 23, April 4, April 21, and May 5 (Table 5) with mean daily maximum temperature between 37.8 and 41.9 °C at both flowering and grain filling stages. The obtained grain yield in both irrigation regimes and the planting date of February 19 significantly differed from the other planting dates in the spring; therefore, this planting date was suggested to be the best to reach the highest grain yield in the early spring planting in the study region. Changing planting dates to March 5 onward reduced grain yield on average by 49% and 59% in the FI and 0.5FI, respectively. Yazar et al. (2017) reported a higher grain yield in planting quinoa (Titicaca cultivar) on April 11 than that on April 30 in the Mediterranean climate in Turkey.

Planting quinoa on September 23, October 7, October 23, and November 6 ended in no grain yield due to facing cold stress. There was no significant difference in grain yield between the two irrigation regimes when quinoa was planted on September 6. However, 0.5FI with the planting date of August 23 showed a 51% reduction in grain yield compared to FI. Postponing the planting date from August 23 to September 6 caused a remarkable decrease in grain yield by 80% in full irrigation, whereas a reduction of 34.8% occurred in the 0.5FI. Therefore, in the conditions of water stress, postponing the planting dates would result in a lower reduction of grain yield in early fall plantations.

Considering the importance of grain yield production based on seasonal evapotranspiration, equations (7) to (10) were obtained for different planting dates in the early spring and early fall. The following equations would be applicable to predict grain yield by agricultural planners. Equation (7) estimates grain yield based on quinoa ET and GDD for planting dates in early spring as follows:

$$GY = 0.047\ ET - 1.8 \times 10^{-5}\ ET \times GDD \quad (7)$$

R^2=0.87, n=36, SE=1.78 ,P<0.001

where GY, ET, and GDD are the grain yield (g pot^{-1}), seasonal evapotranspiration (mm), and growing degree-days (°C), respectively. Based on Eq. (7) grain yield decreases by increasing the multiplication of ET and GDD, which interprets GY reduction by postponing the planting date from March to April and May which results in high air temperature above 30 °C at the flowering stage.

Equation (8) represents the relationship among the grain yield (GY, g pot^{-1}), seasonal ET (mm), and threshold maximum air temperature at the flowering stage within two days (T_{MAX}, °C) in the spring planting dates.

$$GY = 1.66 \times 10^{-4}\ ET \times T_{MAX} \quad (8)$$

R^2=0.72, n=36, SE=2.64 ,P<0.001

Besides, Eq. (9) estimates the quinoa grain yield (GY, g pot^{-1}) for the spring planting dates based on seasonal ET (mm) and length of growing season (LG, day) as follows:

$$GY = -0.17\ ET + 22 \times 10^{-5}\ ET \times LG \quad (9)$$

R^2=0.86, n=36, SE=1.85, P<0.001

Evidence from this study indicated that the length of the growing season had a direct effect on the grain yield, where the longer period in the early spring planting dates (in February compared to March and April) led to higher grain yield.

Regarding planting dates in the early fall, minimum air temperature at the flowering stage (T_{MIN}) showed an influential impact on grain yield. Therefore, a relationship obtained among the grain yield (GY, g pot^{-1}), seasonal ET (mm), GDD and T_{MIN} (°C) as follows:

$$GY = 0.01\ ET + 4.5 \times 10^{-4}\ GDD\ T_{MIN} \quad (10)$$

R^2=0.77, n=36, SE=1.66, P<0.001

In this relationship, T_{MIN} describes the minimum air temperature at the flowering stage pre-frost within two days. Equation (10) shows the impact of air temperature changes on the quinoa's grain yield at the flowering stage in early fall planting dates.

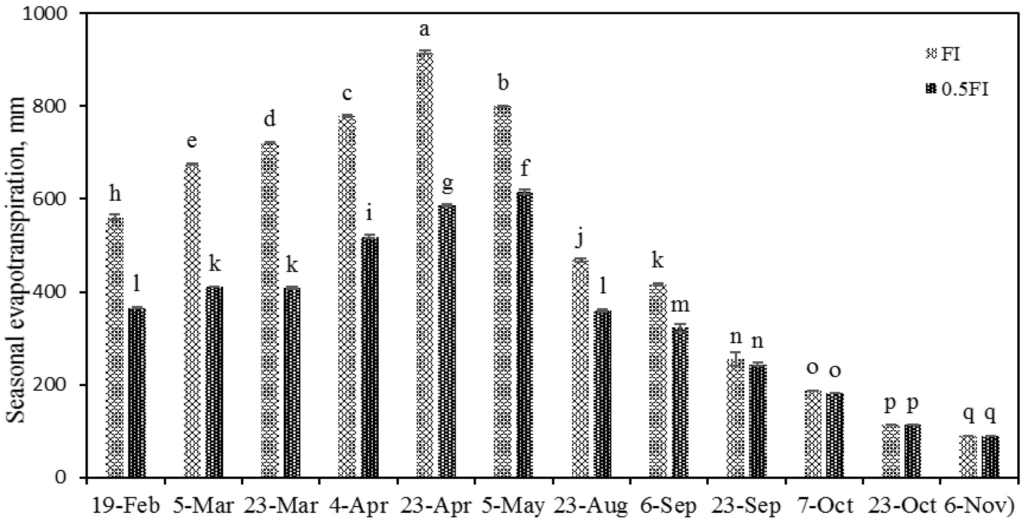

Fig. 5. Seasonal evapotranspiration (mm) at different planting dates and irrigation regimes

Means followed by the same letters are not significantly different at a 5% level of probability....

Table 4. Maximum leaf area index (LAI_{max}) at different planting dates and irrigation regimes

Sowing date	Irrigation regimes	
	FI	0.5FI
	LAI_{max}	
19-Feb	1.95 b*	1.29 d
5-Mar	0.71 ef	0.58 fghi
23-Mar	0.39 ghij	0.31 ijk
4-Apr	0.45 fghij	0.33 ij
23-Apr	0.35 hij	0.29 ijk
5-May	0.41 ghij	0.23 jk
23-Aug	2.36 a	0.95 e
6-Sep	1.56 c	0.44 fghij
23-Sep	0.62 fgh	0.65 fg
7-Oct	0.27 jk	0.16 jk
23-Oct	0.03 k	0.02 k
6-Nov	0.02 k	0.02 k

* Means followed by the same letters are not significantly different at a 5% level of probability.

Total Dry Matter

Table 5 presents the total dry matter (TDM) at different planting dates and irrigation regimes. The interaction effect between planting dates and irrigation regimes was significant (P < 0.05). The highest dry matter belonged to the FI and the planting date of February 19 as 36.9 g pot^{-1}, (8.9 Mg ha^{-1}), which was significantly different from those of other planting dates in the early spring in both irrigation regimes. Some studies reported the total dry matter as 8, 7.9, and 7.89 Mg ha^{-1} in the Mediterranean conditions (Geerts et al., 2009b; Hirich et al., 2014b,c; Razzaghi et al., 2012). However, the highest dry matter was obtained as 12 Mg ha^{-1} in the greenhouse conditioFns in the same study region (Talebnejad & Sepaskhah, 2015b).

Compared to FI, applying 0.5FI on the planting date of February 19 only resulted in a 12% reduction in total dry matter, whereas it was reduced by 63.5% by postponing the planting date to August 23. In FI and the planting date of August 23, total dry matter decreased by 15.7% compared to the planting date of February 19. There was no significant difference in the total dry matter between the planting dates after March 5, while it was significantly different comparing these planting dates to the planting date of February 19. Postponing the planting date of February 19 decreased mean dry matter by 19.7% and 24.7% in FI and 0.5FI, respectively. Considering the quinoa as a neutral day-length plant (Adolf et al., 2012) and obtaining a higher grain yield on the planting date of August 23, it is concluded that the short growing period at this planting date resulted in short duration of vegetation stage and produced a higher grain yield.

Root Dry Matter

Table 5 also presents the root dry matter (RDM) at different irrigation regimes and planting dates. The effect of the irrigation regimes and planting dates on RDM was significant (P < 0.05). The irrigation regime of 0.5FI compared to FI remarkably decreased RDM on the planting dates of March 5 and March 23 as 31.7% and 34%, respectively. However, there was no significant difference in RDM between the two irrigation regimes on the other planting dates. Likewise, Talebnejad & Sepaskhah (2014) and Sanchez et al. (2003) reported similar results. The FI and planting date of February 19 had the highest RDM, which did not differ from 0.5FI significantly. Additionally, there was no significant difference in RDM between the planting date of February 19 and August 23.

Harvest Index

Significant interaction effect of irrigation regimes and planting dates on harvest index (HI) (P <0.05) was obtained; while the effect of irrigation regimes on HI was not significant. Table 5 shows that both irrigation regimes with planting dates of February 19 had the highest HI with a significant difference from other early spring planting dates. Generally, postponing the planting date from February 19 to May 5 caused a 36% and 45% reduction in HI on average in FI and 0.5FI, respectively. Therefore, results indicated that the long delay in the planting date enhanced the reduction of HI in 0.5FI, so that deficit irrigation reduced HI by 21% and 45% on the planting dates of February 19 and May 5, respectively.

In the early fall planting dates, 0.5FI and the planting date of August 23 had the highest HI by approximately 0.43, which was significantly different from FI in the same planting date. Postponing the planting date to September 6 significantly dropped HI by 54% and 19% in FI and 0.5FI, respectively. Besides, applying 0.5FI increased HI by 136% compared to FI with the same planting date of September 6. Furthermore, planting on August 23 compared to February 19 raised HI by 26% and 135% in FI and 0.5FI, respectively. Hirich et al. (2014a) also pointed to the impact of planting date on HI in southern Morocco conditions. They reported the highest HI as 0.45 of planting date in early November and the lowest HI as 0.12 of planting date in early January.

1000-Seed Weight

Irrigation regimes, planting dates, and the interaction between them had a significant effect on 1000-seed weight, length of the main panicle (LMP), length of secondary panicle per plant (LPP), and the number of panicles per plant (PPP) (Table 6). In FI, there was no significant difference in 1000-seed weight between planting dates of February 19, March 5, and March 23. Likewise, no significant difference was observed in 1000-seed weight between planting dates of April 4, April 23, and May 5. Generally, postponing the planting date from April 4 to 5 May decreased 1000-seed weight by 19.8% under FI conditions, which can be due to the high air temperature during the grain filling stage.

The planting date of August 23 compared to September 6 increased 1000-seed weight by 34% and 24% in FI and 0.5FI, respectively. The highest 1000-seed weight obtained in this study was 2.4 g, which was lower than those of 2.75 g, 2.65 g, and 3.4 g reported for quinoa by Sajjad et al. (2014), Talebnejad & Sepaskhah (2015b), and Razzaghi et al. (2012), respectively. These higher values might be due to planting quinoa in more humid weather or under greenhouse conditions in the aforementioned studies. 1000-seed weight is very important in the commercial market; therefore, according to this study, the best time to plant quinoa would be August 23 in the autumn planting dates. However, in the spring planting dates the best time for quinoa cultivation would be the planting dates before March 23 due to the higher 1000-seed weight. Furthermore, under the current study conditions in pots, 0.5FI had no significant effect on 1000-seed weight compared to FI in the autumn and spring planting dates, except on the planting date of 23 March.

Length of the Main and Secondary Panicle per Plant

In the early spring planting dates, the 0.5FI regime compared to FI on planting dates before April 23 significantly reduced the length of the main panicle (LMP) by 18.4% (Table 6).

However, in the early fall planting dates, the 0.5FI regime on the planting date of August 23 in comparison with FI dropped LMP by 22.8%. Additionally, planting dates of October 7, October 23, and November 6 resulted in no main panicle due to cold stress in the vegetative stage. Generally, the 0.5FI regime reduced LPP significantly on all planting dates except for the planting date of September 6. There was no secondary panicle on plants on planting dates of October 7, October 23, and November 6. Similarly, the planting date of September 23 led to small secondary panicles, which could not pass the flowering stage and produce grains.

Number of Panicles per Plant

Postponing planting dates of February 19 and August 23 to March 5 and September 6, respectively, significantly decreased the number of panicles per plant (PPP) (Table 6). Deficit irrigation of 0.5FI significantly reduced PPP on planting dates of March 23 and April 4 by 50%, and on August 23, and September 6 by 40%. Overall, regarding the higher LMP and PPP in FI than those in 0.5FI, it seems that LPP and 1000-seed weight have had an influential role in increasing grain yield by 63% in 0.5FI compared to FI on the planting date of Aug 23.

Table 5. Grain yield (GY), total dry matter (TDM), root dry matter (RDM) in (g pot^{-1}), and harvest index (HI) at different planting dates and irrigation regimes

Sowing date	Irrigation regimes							
	FI	0.5FI	FI	0.5FI	FI	0.5FI	FI	0.5FI
	GY		TDM		RDM		HI	
19-Feb	9.38 a*	6.55 b	36.99 a	32.56 b	3.57 a	3.24 ab	0.253 c	0.200 d
5-Mar	4.49 dc	3.19 de	29.27 c	23.44 d	2.40 cd	1.64 efg	0.153 def	0.133 efgh
23-Mar	4.20 dc	2.14 e	31.47 bc	22.93 d	2.24 cde	1.48 g	0.132 efgh	0.093 h
4-Apr	5.48 bc	3.16 de	30.07 bc	25.07 d	1.74 efg	1.46 g	0.183 de	0.123 fgh
23-Apr	4.83 c	2.80 e	28.99 c	28.25 c	1.65 efg	1.58 fg	0.167 def	0.100 gh
5-May	4.95 c	2.18 e	28.67 c	22.95 d	1.34 g	1.60 fg	0.173 def	0.097 gh
23-Aug	9.96 a	4.88 c	31.19 bc	11.37 ef	3.15 ab	2.78 bc	0.320 b	0.427 a
6-Sep	1.95 e	3.18 de	13.86 e	8.98 fg	2.16 def	1.71 efg	0.147 efg	0.347 b
23-Sep	-	-	6.34 gh	5.62 h	1.22 gh	1.27 gh	-	-
7-Oct	-	-	1.81 i	1.34 i	0.75 hi	0.60 hi	-	-
23-Oct	-	-	0.22 i	0.27 i	0.15 i	0.25 i	-	-
6-Nov	-	-	0.17 i	0.20 i	0.14 i	0.18 i	-	-

* Means followed by the same letters are not significantly different at a 5% level of probability.
- No data is available

Table 6. 1000-seed weight, length of the main panicle (LMP), length of secondary panicle per plant (LPP), and number of panicles per plant (PPP) at different planting dates and irrigation regimes

Sowing date	Irrigation regimes							
	FI	0.5FI	FI	0.5FI	FI	0.5FI	FI	0.5FI
	1000-seed weight (g)		LMP (cm)		LPP (cm)		PPP	
19-Feb	2.07 abcd	2.13 abc	14.33 a*	11.50 bcd	3.37 a	2.03 bc	16.00 ab	14.00 bc
5-Mar	2.26 ab	1.86 bcde	12.73 b	10.30 def	2.60 b	1.30 d	11.00 def	10.00 efg
23-Mar	2.22 ab	1.51 efg	12.53 b	10.17 def	2.57 b	1.17 d	12.30 cde	6.30 ij
4-Apr	1.78 cdef	1.88 bcde	11.73 bcd	9.87 ef	2.70 b	1.13 d	9.30 fgh	4.30 j
23-Apr	1.77 cdef	1.37 fg	11.30 cbde	10.3 def	2.40 b	1.37 d	7.67 ghi	6.67 hij
5-May	1.70 defg	1.33 g	10.63 cdef	10.07 def	2.77 b	1.23 d	10.00 efg	8.30 fghi
23-Aug	2.39 a	2.40 a	12.27 bc	9.47 f	3.40 a	1.50 cd	17.00 a	10.30 efg
6-Sep	1.80 cdef	1.94 bcd	9.43 f	9.00 g	2.57 b	2.07 bc	13.3 cd	7.67 ghi
23-Sep	-	-	3.83 g	3.60 h	0.80 ef	0.50 f	1.30 k	1.00 k
7-Oct	-	-	-	-	-	-	-	-
23-Oct	-	-	-	-	-	-	-	-
6-Nov	-	-	-	-	-	-	-	-

* Means followed by the same letters are not significantly different at a 5% level of probability.
- No data is available

Water Use Efficiencies

Irrigation and Evapotranspiration Water Use Efficiency for Grain Yield

The effect of planting dates, as well as the interaction effect of planting date and irrigation regimes on irrigation water use efficiency for grain (IWUEG),were significant (*P* <0.05). The highest IWUEG value was 0.44 kg m^{-3} in FI and the planting date of August 23, which was significantly different from those of other planting dates (Table 7). This treatment received lower applied water by 16% compared to the planting date of March 5, but it increased IWUEG by about 30%.

In early spring planting dates, the highest IWUEG was obtained on the planting date of February 19 in both irrigation regimes (Table 7). Planting quinoa on March 5 compared to February 19 increased applied water by 16.6% and 12% in FI and 0.5FI, respectively, which decreased IWUEG by 58.8% and 55%, respectively. Research in Italy and Morocco reported the IWUEG by 1.2 and 1.7 kg m^{-3} in deficit irrigation (Hirich et al., 2014a; Riccardi et al., 2014). Likewise, Talebnejad & Sepaskhah (2015a) reported a 12% increase in IWUEG by applying 0.3FI for quinoa. In the current study, the 0.5FI regime in early spring planting dates did not show a significant difference in IWUEG, while in the early fall planting dates, 0.5FI decreased IWUEG by 34% on the planting date of August 23, compared to FI. Planting on August 23 increased applied water and IWUEG by 24.8% and 72.7%, respectively, compared to the planting date of September 6. Therefore, the planting date of August 23 is recommended in scarce water conditions to achieve the highest IWUEG.

Similar to IWUEG, the interaction effect of the planting date and irrigation regimes on evapotranspiration water use efficiency for grain yield ($WUE_{grain-ET}$) was significant (*P* <0.05). There was no significant difference in $WUE_{grain-ET}$ between irrigation regimes on the planting date of February 19 but postponing the planting date to March 5 decreased $WUE_{grain-ET}$ by 59% and 56% in FI and 0.5FI, respectively. No significant difference was observed in $WUE_{grain-ET}$ between irrigation regimes on planting dates after March 5. The highest $WUE_{grain-ET}$ value was 0.47 kg m^{-3}, in FI on the planting date of August 23. Postponing the planting date of August 23 to September 6 dropped $WUE_{grain-ET}$ by 78.7% and 26.7% in FI and 0.5FI, respectively.

Irrigation and Evapotranspiration Water Use Efficiency for Total Dry Matter

Irrigation regimes, planting dates, and the interaction between them had a significant effect (*P* <0.05) on irrigation water use efficiency for dry matter ($IWUE_{TDM}$) and evapotranspiration use efficiency for dry matter (WUE_{TDM-ET}). Table 7 shows that in both irrigation regimes, postponing the planting date of February 19 to later dates had a significant effect on $IWUE_{TDM}$. The highest $IWUE_{TDM}$ was about 1.91 kg m^{-3}, which belonged to 0.5FI on the planting date of February 19. In FI, the highest $IWUE_{TDM}$ was obtained on the planting date of August 23 as 1.38 kg m^{-3}, which did not differ significantly from $IWUE_{TDM}$ on the planting date of February 19. Compared to FI, applying 0.5FI increased $IWUE_{TDM}$ significantly by 28.8% on the planting date of February 19, and decreased it by 50.7% on the planting date of August 23.

Overall, applying 0.5FI compared to FI increased $IWUE_{TDM}$ significantly in all early spring planting dates except for May 5. However, applying 0.5FI dropped $IWUE_{TDM}$ by 51% on the planting date of August 23 compared to FI due to total dry matter reduction resulting from air temperature drop during the crop vegetative developmental stage.

The highest WUE_{TDM-ET} was 1.98 kg m^{-3} in 0.5FI on the planting date of February 19, which was 80% and 131% higher than WUE_{TDM-ET} in FI and 0.5FI on other planting dates in early spring, respectively. In both irrigation regimes, the reduction of WUE_{TDM-ET} was not significant because of postponing the planting date from March 5 to April 4 (Table 7). In all early spring planting dates except for May 5, applying 0.5FI compared to FI increased significantly WUE_{TDM-ET}. For instance, applying 0.5FI on the planting date of February 19 increased WUE_{TDM-ET} by 34.7% compared to FI. Similarly, in West Africa, deficit irrigation applied on planting dates of December and November increased WUE_{TDM} (Alvar-Beltrán et al., 2019). Generally, in the early fall planting dates, applying 0.5FI decreased WUE_{TDM-ET} compared to FI; however, the reduction was not significant except for the planting date of August 23 when the reduction was 55%.

Root Specification

Root Length Density

Irrigation regimes, planting dates, and the interaction between them had a significant effect (*P* <0.05) on root average length density (RLD) at the two tested depths. Table 8 presents the comparison of mean RLD at different planting dates and irrigation regimes using DMRT at a 5% probability level. Furthermore, Fig. 6 illustrates RLD at the two soil depths of 0-10 cm and 10-20 cm.

Generally, in the early spring planting dates, the irrigation regime of 0.5FI compared to FI significantly decreased RLD by 18.8% and 33% on the planting date of February 19 and March 5, respectively. In FI, postponing the planting date from February 19 to March 23 decreased significantly RLD by 36%. In the same manner, in 0.5FI, postponing the planting date from February 19 to March 5 showed a significant drop in RLD by 25%. However, except for the two first planting dates of early spring, the irrigation regime of 0.5FI compared to FI did not change RLD significantly on the other planting dates. RLD was higher in the topsoil layer (0-10 cm) (Fig. 6) on the August 23 planting date under FI conditions; although, the lower depth enclosed by the pot limited the root extension. Talebnejad & Sepaskhah (2016) also reported a similar result in the presence of shallow groundwater.

In the early fall planting dates, there was no significant difference between FI and 0.5FI for RLD. Besides, the highest RLD in 0.5FI was measured on the planting date of August 23 (Table 8), which was predictable due to high water content before irrigation events. Postponing the planting date from August 23 to September 6 dropped RLD by 46.5% and 45% in FI and 0.5FI, respectively. Fig. 6 shows that RLD was higher at the topsoil layer (0-10 cm) in FI and on planting dates of August 23 and September 6, while 0.5FI increased RLD in the soil depth of 10-20 cm by 16.5% and 28.8% on the planting dates of August 23 and September 6, respectively. In these conditions, roots expanded to absorb more soil water in lower soil depth, which the pot bottom limited root growth in some situations.

Root weight density

Table 8 also presents the mean root weight density (RWD) at different planting dates and irrigation regimes. Postponing the planting date from February 19 to March 5 decreased RWD by 30% and 54% in FI and 0.5FI, respectively. Overall, 0.5FI caused a significant reduction in RWD only on the planting dates of March 5 and March 23 as 35.3% and 37.5% compared to FI at similar planting dates, respectively.

In the early fall planting dates, the highest RWD was measured in FI on the planting date of August 23 as 0.64 mg cm^{-3}, which was not significantly different from that obtained on the planting date of February 19. Postponing the planting date from August 23 to September 6 also dropped RWD by 33% and 42% in FI and 0.5FI, respectively.

Root Dry Weight to Shoot dry weight Ratio (Root Shoot Ratio)

Table 8 also presents the ratio of root dry weight to shoot dry weight values at different planting dates and irrigation regimes. Results showed a significant effect of irrigation regimes and planting dates on the root shoot ratio (RSR). In early spring planting dates, 0.5FI, in comparison with FI did not cause a significant difference in RSR. Similarly, González et al. (2009) reported no significant differences in RSR for quinoa in the controlled irrigation, deficit irrigation, and flood irrigation. Moreover, in the current study, postponing the planting date did not cause any significant difference in RSR in both irrigation regimes, which means both root and shoot growth were restricted to same extent.

Generally, RSRs in the early fall planting dates were higher than those obtained in the early spring planting dates (Table 8) due to the reduction in shoot growth. The highest RSR was obtained on the planting date of November 6, which shows quinoa's root growth is less susceptible to air temperature reduction than that of the shoot. Considering the results of this study, a 63% reduction in the produced total dry matter on the planting date of August 23 due to deficit irrigation led to a significant increase of 142% in RSR (Table 8).

Specific root length

Planting dates and interaction between planting dates and irrigation regimes had a significant effect ($P < 0.05$) on specific root length (SRL). Results indicated that in 0.5FI postponing the planting date from February 19 to later dates in early spring caused a significant increase in SRL and thinner roots production. Besides, compared to FI, 0.5FI significantly raised SRL on the planting date of March 23, but significantly decreased SRL on the planting date of May 5 (Table 8).

On the autumn planting dates, the application of deficit irrigation had no significant effect on SRL. However, postponing the planting date from August 23 to September 23 resulted in a 31% decrease in SRL under deficit irrigation treatment.

Literary, deficit irrigation resulted in higher thinner roots production because of higher SRL. According to Fig. 7b, deficit irrigation on the planting date of March 5 and March 23 led to a 39.4% and 57.8% increase in SRL in 10-20 cm depth of tested soil in comparison to FI. Therefore, a higher percentage of hairy roots was produced in lower soil depth (10-20 cm). In this regard, Padilla & Pugnaire (2007) suggested a primary investment for crops to develop root length into deeper layers where reliable water sources exist. Furthermore, Zurita-Silva et al. (2015) stated although deficit irrigation reduced total root length, it increased developing quinoa (Salar cultivar) root length in deep layers in the water scarcity conditions.

Table 7. Irrigation water use efficiency (kg m $^{-3}$) for grain yield (IWUEG) and total dry matter ($IWUE_{TDM}$) and transpiration water use efficiency (kg m $^{-3}$) for grain yield ($WUE_{grain-ET}$) and total dry matter (WUE_{TDM-ET}) at different planting dates and irrigation regimes.

Sowing date	Irrigation regimes							
	FI	0.5FI	FI	0.5FI	FI	0.5FI	FI	0.5FI
	IWUEG (kg m^{-3})		$WUE_{grain-ET}$ (kg m^{-3})		$IWUE_{TDM}$ (kg m^{-3})		WUE_{TDM-ET} (kg m^{-3})	
19-Feb	0.34 bc	0.38 ab	0.37 b*	0.39 b	1.36 b	1.91 a	1.47 b	1.98 a
5-Mar	0.14 ef	0.17 e	0.15 def	0.17 ed	0.93 def	1.23 bc	0.96 de	1.27 c
23-Mar	0.12 ef	0.12 ef	0.13 ef	0.11 ef	0.95 de	1.33 b	0.97 de	1.25 c
4-Apr	0.15 ef	0.13 ef	0.16 ed	0.13 ef	0.82 efg	1.08 cd	0.86 ef	1.07 d
23-Apr	0.11 ef	0.10 ef	0.11 ef	0.10 f	0.67 g	1.11 c	0.7 fgh	1.07 d
5-May	0.13 ef	0.08 f	0.14 ef	0.07 f	0.78 fg	0.90 ef	0.80 f	0.83 ef
23-Aug	0.44 a	0.29 cd	0.47 a	0.30 c	1.38 b	0.68 g	1.48 b	0.7 fgh
6-Sep	0.12 ef	0.23 d	0.10 ef	0.22 d	0.82 efg	0.66 g	0.74 fg	0.62 ghi
23-Sep	-	-	-	-	0.49 h	0.51 h	0.55 hi	0.51 i
7-Oct	-	-	-	-	0.21 i	0.16 ij	0.21 j	0.16 jk
23-Oct	-	-	-	-	0.04 j	0.05 j	0.04 k	0.05 k
6-Nov	-	-	-	-	0.04 j	0.05 j	0.04 k	0.05 k

* Means followed by the same letters are not significantly different at a 5% level of probability.

* - No data is available.

Table 8. Root length density (RLD), root weight density (RWD), root shoot ratio (RSR), and specific root length (SRL) at different planting dates and irrigation regimes

Sowing date	Irrigation regimes							
	FI	0.5FI	FI	0.5FI	FI	0.5FI	FI	0.5FI
	RLD (cm cm^{-3})		RWD (mg cm^{-3})		RSR		SRL (m g^{-1})	
19-Feb	32.30 a*	26.24 c	0.73 a	0.71 a	0.096 efg	0.099 efg	458.6 de	378.9 efg
5-Mar	31.65 a	21.91 de	0.51 bc	0.33 efg	0.082 fg	0.070 fg	626.4 ab	696.1 ab
23-Mar	22.68 d	21.10 de	0.48 cd	0.30 efgh	0.071 fg	0.064 fg	482.9 cde	693.7 ab
4-Apr	21.26 de	20.88 de	0.37 def	0.31 efg	0.058 fg	0.058 fg	577.0 abcd	679.4 ab
23-Apr	19.91 de	18.86 ef	0.34 efg	0.34 efg	0.057 fg	0.056 fg	596.9 abc	566.7 abcd
5-May	18.70 ef	16.10 fg	0.27 fghi	0.29 fgh	0.047 g	0.070 fg	699.7 a	560.9 bcd
23-Aug	30.01 ab	27.66 bc	0.64 a	0.62 ab	0.101 efg	0.245 d	464.0 de	452.4 de
6-Sep	16.04 fg	15.19 g	0.43 cde	0.36 def	0.161 defg	0.196 defg	373.0 efg	424.7 ef
23-Sep	7.43 h	8.31 h	0.22 ghi	0.27 fghi	0.197 defg	0.228 de	353.6 efgh	311.9 fghi
7-Oct	4.18 i	3.95 i	0.18 hij	0.15 ijk	0.416 c	0.520 c	234.5 hi	268.8 ghi
23-Oct	0.94 j	1.30 j	0.04 k	0.06 k	0.718 b	0.941 a	258.8 ghi	224.1 hi
6-Nov	0.80 j	0.88 j	0.04 k	0.05 k	0.861 a	0.946 a	235.7 hi	196.4i

* Means followed by the same letters are not significantly different at a 5% level of probability.

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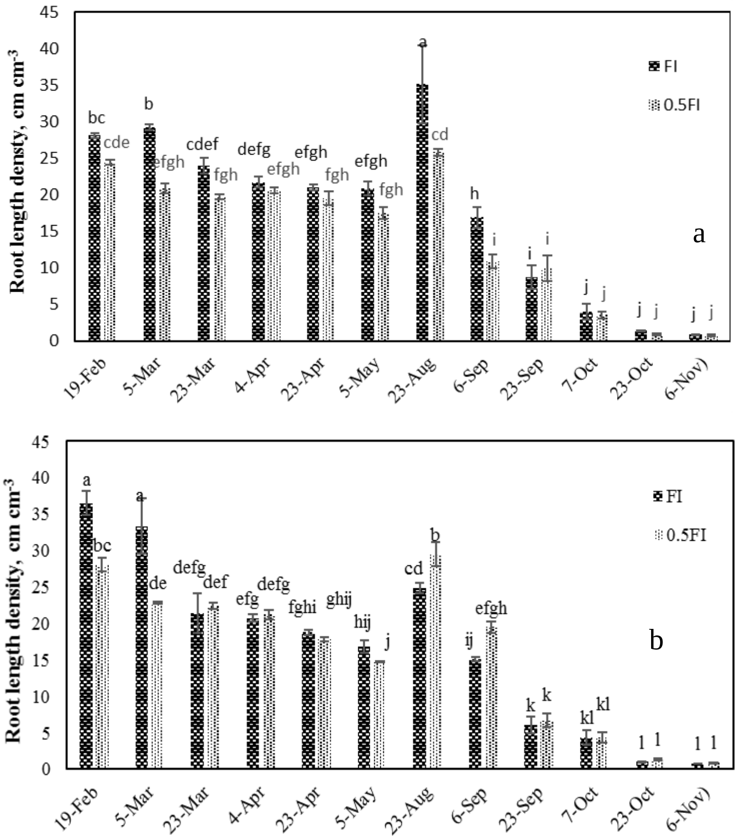

Fig. 6. Root length density (cm cm^{-3}) at different planting dates and irrigation regimes in (a): 0-10 cm soil layer, (b): 10-20 cm soil layer. Means followed by the same letters are not significantly different at a 5% level of probability.

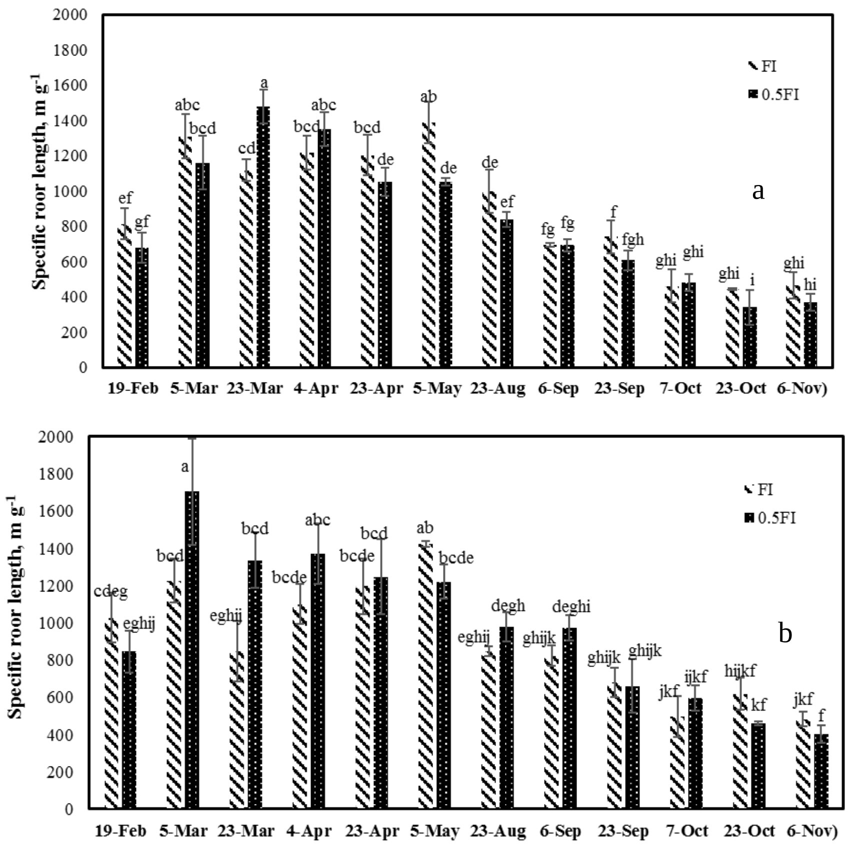

Fig. 7. Specific root length (m g^{-1}) at different planting dates and irrigation regimes in (a): 0-10 cm soil layer, (b): 10-20 cm soil layer. Means followed by the same letters are not significantly different at a 5% level of probability.

CONCLUSIONS

It was indicated that an appropriate planting date has an influential role in increasing yield and irrigation water use efficiency (IWUE). The maximum grain yield observed in the FI and planting dates of February 19 and August 23 were 2.26 and 2.4 Mg ha^{-1}, respectively, which had no statistically significant difference. Furthermore, the highest quinoa grain IWUE (0.44 kg m^{-3}) was achieved in FI on the planting date of August 23. In the field conditions, this planting date would be more effective due to using fall precipitation during the growing season, especially in areas with water resource scarcity. Results indicated that delayed sowing in the spring resulted in high-temperature stress during the flowering and seed filling stages. However, delaying the planting date in the early fall accelerated the effect of water stress on grain yield. Furthermore, deficit irrigation of 0.5FI significantly decreased quinoa yield and IWUE. However, in water resource scarcity conditions, deficit irrigation as 0.5FI is suggested for planting on February 19 in early spring. Considering the importance of planting date on quinoa yield, more investigations are deserved to be continued in field conditions.

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REFERENCES

Adolf, V. I., Shabala, S., Andersen, M. N., Razzaghi, F., & Jacobsen, S. E. (2012). Varietal differences of quinoa’s tolerance to saline conditions. *Plant and Soil*, 357(1), 117-129.

Ahmadi, S. H., Plauborg, F., Andersen, M. N., Sepaskhah, A. R., Jensen, C. R., & Hansen, S. (2011). Effects of irrigation strategies and soils on field grown potatoes: Root distribution. *Agricultural Water Management*, 98(8), 1280–1290.

Alvar-Beltrán, J., Saturnin, C., Dao, A., Dalla Marta, A., Sanou, J., & Orlandini, S. (2019). Effect of drought and nitrogen fertilisation on quinoa (*Chenopodium quinoa* Willd.) under field conditions in Burkina Faso. *Italian Journal of Agrometeorology*, 1, 33–43.

Bertamini, M., Muthuchelian, K., Rubinigg, M., Zorer, R., & Nedunchezhian, N. (2005). Low-night temperature (LNT) induced changes of photosynthesis in grapevine (*Vitis vinifera* L.) plants. *Plant Physiology and Biochemistry*, 43(7), 693–699.

Bertero, H. D. (2003). Response of developmental processes to temperature and photoperiod in quinoa (*Chenopodium quinoa* Willd.). *Food Reviews International*, 19(1–2), 87–97.

Bertero, H. D., King, R. W., & Hall, A. J. (1999). Photoperiod-sensitive development phases in quinoa (Chenopodium quinoa Willd.). *Field Crops Research*, 60(3), 231–243.

Bois, J. F., Winkel, T., Lhomme, J. P., Raffaillac, J. P., & Rocheteau, A. (2006). Response of some Andean cultivars of quinoa (*Chenopodium quinoa* Willd.) to temperature: Effects on germination, phenology, growth and freezing. *European Journal of Agronomy*, 25(4), 299–308.

Dini, I., Tenore, G. C., & Dini, A. (2005). Nutritional and antinutritional composition of Kancolla seeds: an interesting and underexploited andine food plant. *Food Chemistry*, 92(1), 125–132.

English, M., & Raja, S. N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management*, 32(1), 1–14.

FAO (2011). Quinoa, An ancient crop to contribute to world food security. *Regional Office for Latin America and the Caribbean*, 2, 73–87.

Garcia, M., Raes, D., & Jacobsen, S. E. (2003). Evapotranspiration analysis and irrigation requirements of quinoa (*Chenopodium quinoa*) in the Bolivian highlands. *Agricultural Water Management*, *60*(2), 119–134.

Geerts, S, Raes, D., Garcia, M., Condori, O., Mamani, J., Miranda, R., Cusicanqui, J., Taboada, C., Yucra, E., & Vacher, J. (2008). Could deficit irrigation be a sustainable practice for quinoa (*Chenopodium quinoa* Willd.) in the Southern Bolivian Altiplano? *Agricultural Water Management*, 95(8), 909–917.

Geerts, S, Raes, D., Garcia, M., Del Castillo, C., & Buytaert, W. (2006). Agro-climatic suitability mapping for crop production in the Bolivian Altiplano: A case study for quinoa. *Agricultural and Forest Meteorology*, 139(3–4), 399–412.

Geerts, S, Raes, D., Garcia, M., Miranda, R., Cusicanqui, J. A., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., & Condori, O. (2009a). Simulating yield response of quinoa to water availability with AquaCrop. *Agronomy Journal*, 101(3), 499–508.

Geerts, S., Raes, D., Garcia, M., Taboada, C., Miranda, R., Cusicanqui, J., Mhizha, T., & Vacher, J. (2009b). Modeling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altiplano. *Agricultural Water Management*, 96(11), 1652–1658.

González, J. A., Gallardo, M., Hilal, M. B., Rosa, M. D., & Prado, F. E. (2009). Physiological responses of quinoa (*Chenopodium quinoa*) to drought and waterlogging stresses: dry matter partitioning. Botinical Studies 50(1), 35-42.

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, 10, 4–10.

Hellin, J., & Higman, S. (2003). *Feeding the market: South American farmers, trade and globalization*. Londen. UK: Intermediate Technology Development Group and Latin American Bureau.

Hirich, A, Choukr-Allah, R., & Jacobsen, S.-E. (2014a). Quinoa in Morocco – Effect of sowing dates on development and yield. *Journal of Agronomy and Crop Science*, 200(5), 371–377.

Hirich, A, Choukr Allah, R., & Jacobsen, S. -E. (2014b). Deficit irrigation and organic compost improve growth and yield of quinoa and pea. *Journal of Agronomy and Crop Science*, 200(5), 390–398.

Hirich, Abdelaziz, Choukr-Allah, R., & Jacobsen, S.-E. (2014c). The combined effect of deficit irrigation by treated wastewater and organic amendment on quinoa (*Chenopodium quinoa* Willd.) productivity. *Desalination and Water Treatment*, 52(10–12), 2208–2213.

Jacobsen, S.-E. E., Monteros, C., Christiansen, J. L., Bravo, L. A., Corcuera, L. J., & Mujica, A. (2005). Plant responses of quinoa (*Chenopodium quinoa* Willd.) to frost at various phenological stages. *European Journal of Agronomy*, 22(2), 131–139.

Jacobsen, S.-E., Mujica, A., & Jensen, C. R. (2003). The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. *Food Reviews International*, 19(1–2), 99–109.

Jacobsen, S.-E., & Stølen, O. (1993). Quinoa-morphology, phenology and prospects for its production as a new crop in Europe. *European Journal of Agronomy*, 2(1), 19–29.

Jacobsen, S. -E., & Bach, A. P. (1998). The influence of temperature on seed germination rate in quinoa (*Chenopodium quinoa* Willd. *Seed Science and Technology (Switzerland)*, 26(2), 515–523.

Kaya, Ç. I., Yazar, A., & Sezen, S. M. (2015). SALTMED Model performance on simulation of soil moisture and crop yield for quinoa irrigated using different irrigation systems, irrigation strategies and water qualities in Turkey. *Agriculture and Agricultural Science Procedia*, 4, 108–118. https://doi.org/10.1016/j.aaspro.2015.03.013

Mamedi, A., Tavakkol Afshari, R., & Oveisi, M. (2017). Cardinal temperatures for seed germination of three quinoa (*Chenopodium quinoa* Willd.) cultivars. *Iranian Journal of Field Crop Science*, 48(Special Issue), 89–100.

Mehrabi, F., & Sepaskhah, A. R. (2019). Partial root zone drying irrigation, planting methods and nitrogen fertilization influence on physiologic and agronomic parameters of winter wheat. *Agricultural Water Management*, 223, 105688.

Newman, E. I. (1966). A method of estimating the total length of root in a sample. *Journal of Applied Ecology*, 3(1), 139–145.

Nurse, R. E., Obeid, K., & Page, E. R. (2016). Optimal planting date, row width, and critical weed-free period for grain amaranth and quinoa grown in Ontario, Canada. *Canadian Journal of Plant Science*, 96(3), 360–366.

Padilla, F. M., & Pugnaire, F. I. (2007). Rooting depth and soil moisture control Mediterranean woody seedling survival during drought. *Functional Ecology*, 21(3). 489–495.

Peterson, A. J., & Murphy, K. M. (2015). Quinoa cultivation for temperate North America: Considerations and areas for investigation. In: Murphy, K. M., Matanguihan, J., (Eds.), *Quinoa: Improvement and sustainable production* (pp. 173-192). Hoboken, NJ: John Wiley & Sons, INC.

Razzaghi, F., Plauborg, F., Jacobsen, S.-E. E., Jensen, C. R., & Andersen, M. N. (2012). Effect of nitrogen and water availability of three soil types on yield, radiation use efficiency and evapotranspiration in field-grown quinoa. *Agricultural Water Management*, 109, 20–29.

Razzaghi, F., & Sepaskhah, A. R. (2012). Calibration and validation of four common ET0 estimation equations by lysimeter data in a semi-arid environment. *Archives of Agronomy and Soil Science*, 58(3), 303–319.

Razzaghi, F., Henriksen, S., Naghdyzadegan, J. M., Anderson, M. N., & Jacobsen, S. E. (2016) Potentioal of quinoa production in humid and dry regions under different irrigation and soil conditions: Denmark and Iran. International quinoa conference 2016, (pp.142). UAE: Dobai.

Repo-Carrasco, R., Espinoza, C., & Jacobsen, S.-E.-E. (2003). Nutritional value and use of the Andean crops quinoa (*Chenopodium quinoa*) and kañiwa (*Chenopodium pallidicaule*). *Food Reviews International*, 19(1–2), 179–189.

Riccardi, M., Pulvento, C., Lavini, A., d'Andria, R., & Jacobsen, S. E. (2014). Growth and ionic content of quinoa under saline irrigation. *Journal of Agronomy and Crop Science*, 200(4), 246–260.

Risi, J. C. & Galwey N. W. (1984). The *Chenopodium* grains of the Andes: Inca crops for modern agriculture. *Advances in Applied Biology*, 10, 145–216.

Sajjad, A., Munir, H., Ahmed Anjum, S., Tanveer, M., & Rehman, A. (2014). Growth and development of C at different sowing dates. *Chenopoduim quinoa* genotypes. *Journal of Agricultural Research*. 52(4), 595-546

Sanchez, H. B., Lemeur, R., Damme, P. Van, & Jacobsen, S.-E. (2003). Ecophysiological analysis of drought and salinity stress of quinoa (*Chenopodium quinoa* Willd.). *Food Reviews International*, 19(1–2), 111–119.

Talebnejad, R., & Sepaskhah, A. R. (2015a). Effect of deficit irrigation and different saline groundwater depths on yield and water productivity of quinoa. *Agricultural Water Management*, 159, 225–238.

Talebnejad, R., & Sepaskhah, A. R. (2015b). Effect of different saline groundwater depths and irrigation water salinities on yield and water use of quinoa in lysimeter. *Agricultural Water Management*, 148, 177–188. https://doi.org/10.1016/j.agwat.2014.10.005

Talebnejad, R, & Sepaskhah, A. R. (2014). Effects of deficit irrigation and groundwater depth on root growth of direct seeding rice in a column experiment. *International Journal of Plant Production*, 8(4), 563–586.

Talebnejad, R., & Sepaskhah, A. R. (2016). Physiological characteristics, gas exchange, and plant ion relations of quinoa to different saline groundwater depths and water salinity. *Archives of Agronomy and Soil Science*, 62(10), 1347–1367. 5

Walters, H., Carpenter-Boggs, L., Desta, K., Yan, L., Matanguihan, J., & Murphy, K. (2016). Effect of irrigation, intercrop, and cultivar on agronomic and nutritional characteristics of quinoa. *Agroecology and Sustainable Food Systems*, 40(8), 783–803. 5

Yarami, N., & Sepaskhah, A. R. (2015). Saffron response to irrigation water salinity, cow manure and planting method. *Agricultural Water Management*, 150, 57–66.

Yazar, A., Sezen, S. M., Bozkurt Çolak, Y., Ince Kaya, Ç., & Tekin, S. (2017). Effect of planting times and saline irrigation of quinoa using drainage water on yield and yield components under the Mediterranean environmental contitions. *International Journal of Research in Agriculture and Forestry*. 4(7), 8–16.

Zurita Silva, A., Jacobsen, S.-E., Razzaghi, F., Álvarez Flores, R., Ruiz, K. B., Morales, A., & Silva Ascencio, H. (2015). Quinoa drought responses and adaptation. In Bazile, D., Bertero, D., & Nieto, C. (Eds.), *State-of-the-art report of quinoa around the world in 2013* (pp. 157-171). Italy: FAO & CIRAD.

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اثر تاریخ کشت و رژیم‌های آبیاری بر رشد و محصول کینوا (*Chenopodium quinoa*) در منطقه نیمه خشک

رضوان طالب‌نژاد[۱و۲*]، مریم بهرامی[۱]، علیرضا سپاسخواه[۱و۲]

[۱] بخش مهندسی آب، دانشکده کشاورزی، دانشگاه شیراز، ج. ا. ایران
[۲] مرکز مطالعات خشکسالی، دانشکده کشاورزی، دانشگاه شیراز ، ج. ا. ایران

*نویسنده مسئول

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چکیده - کشت گیاهان مقاوم به تنش های محیطی به ویژه تنش خشکی، کارایی مصرف آب را در مناطق نیمه خشک به طور قابل ملاحظه ای بهبود می بخشد. لذا، در این تحقیق اثر رژیم های مختلف آبیاری و تاریخ کاشت بر محصول کینوا (*Chenopodium quinoa*) بررسی گردید. تیمار مقدار آب آبیاری شامل آبیاری کامل و۵۰ درصد آبیاری کامل و تیمار تاریخ کاشت شامل شش تاریخ کاشت در اوایل بهار و شش تاریخ کاشت در اوایل پاییز انتخاب شد. نتایج نشان داد که بیشترین محصول دانه، ماده خشک، وزن خشک ریشه، شاخص سطح برگ، شاخص برداشت و اجزای محصول در کشت بهاره در اول اسفند و در کشت پاییزه در اول شهریور به دست آمد. بیشینه شاخص سطح برگ در تاریخ کاشت اول شهریور مشاهده گردید که ۲۱ درصد بیشتر از تاریخ کاشت اول اسفند بود. همچنین، بیشترین شاخص برداشت برابر ۰/۳۲ و در تاریخ کاشت اول شهریور در آبیاری کامل مشاهده شد. کشت پاییزه در اول شهریور، باعث افزایش ۳۰ درصدی کارایی مصرف آب برای تولید دانه نسبت به کاشت بهاره در اول اسفند در آبیاری کامل شد. درحالیکه،تفاوت معناداری در طول ویژه ریشه بین تاریخ کاشت اول اسفند و اول شهریور وجود نداشت. اعمال کم آبیاری به میزان ۵۰ درصد آبیاری کامل در تاریخ کاشت اول شهریور، وزن خشک ریشه به اندام هوایی را ۱۴۲ درصد نسبت به آبیاری کامل افزایش داد. به طور کلی، تاریخ کاشت اول شهریور در صورت وجود آب کافی در اختیار کشاورز به عنوان بهترین زمان کاشت کینوا در منطقه مورد مطالعه پیشنهاد می شود، ضمن اینکه در شرایط کم آبیاری به میزان ۵۰ درصد، تاریخ کشت اول اسفند ماه توصیه می‌گردد.