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Evaluating Effect of Continuous and Supplementary Irrigation Regimes on Vegetative and Reproductive Growth of Quinoa

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ABSTRACT

Quinoa is a nutritious pseudo-cereal with considerable tolerance to various environmental stresses, making it a promising candidate for introduction into Iran's agro-systems. In this study, effect of seven irrigation treatments on growth and yield of quinoa was investigated at the Sarayan Agricultural Faculty, during 2017. Irrigation treatments included continuous irrigation (CI) during the growing season with intervals of 1, 2, and 3 weeks (CI-1W, CI-2W, and CI-3W, respectively), supplementary irrigation (SI) with 1, 2, and 3 times during the last month of plant growth (SI-1T, SI-2T, and SI-3T, respectively) and stopping irrigation after plant emergence (SIAE: Just two times irrigation for germination and emergence). The effect of irrigation management was significant on chlorophyll index (measured by SPAD meter: Soil Plant Analysis Development), panicle length (PL), 1000-grain weight, biological yield (BY), seed yield (SY), and harvest index (HI). Irrigation management affected all measure parameters, such as SI, in particular SI3T, which improved the amount of SPAD compared to the other treatments. The highest PL was gained in CI treatments, while there was no significant difference between all SI treatments with SIAE. The best treatment in terms of BY, was CI-1W (2440 kg/ha) followed by CI-2W and CI-3W, while SIAE showed the lowest BY (1092 kg/ha). SY for both CI (250, 211, and 245 kg/ha for CI-1W, CI-2W, and CI-3W, respectively) and SI (225, 173 and 143 kg/ha for SI-3T, SI-2T, and SI-1T, respectively) managements was more than SIAE (78 kg/ha). SI had a positive effect on HI, thereby the highest value of this index was gained in SI-3T (21.6%) and SI-2T (18.5%). In summary, quinoa showed substantial tolerance to drought stress, producing viable SY even under semi-rainfed (SIAE) conditions. These results highlight quinoa's potential as a robust crop for arid and semi-arid regions, where water availability is a limiting factor.

Keywords: Chlorophyll index; drought stress; grain yield; new crops; panicle, pseudo-cereal.

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INTRODUCTION

Cultivation of new crops with high adaptability to drought stress is one of the most effective methods for sustainable crop production and food security in arid regions (Samadzadeh et al., 2020). In dry areas with low or unreliable rainfall, increasing crop productivity with the least water consumption is the major challenge of crop production (Sadak & Bakhoum, 2022). Quinoa (*Chenopodium quinoa* Willd.) a native plant of the Andes Mountains in Latin America, is well adapted to drought and saline regions (Tourajzadeh et al., 2024; Golestanifar, 2024). This crop has different mechanisms to cope with drought stress, including changes in phenology, such as accelerating flowering and shortening seed filling stage, morphology such as reduction of total leaf surface, or physiology such as increments in leaf chlorophyll contents (Maestro-Gaitán et al., 2022). In addition, this medicinal and gluten-free plant makes it suitable for people with coeliac disease, which has many nutritional values (Olmos et al., 2024; Tourajzadeh et al., 2024). This plant has a higher protein and oil content than cereals, with a well-balanced profile of all essential amino acids, as well as a high concentration of minerals and vitamins, which has contributed to its rapidly growing global interest (Ahmadi et al., 2019). Therefore, this underutilized crop has a unique opportunity to be introduced all around the world. This trend is evident in practice, as quinoa has expanded beyond its primary distribution centers in Peru, Bolivia, and Ecuador to various regions worldwide, including several European countries, particularly in the Mediterranean (Olmos et al., 2024), United States and Canada, as well as in Kenya, Iran, the Himalayas, and India (Vahidi et al., 2021; Romano & Ferranti, 2023).

Quinoa has a vigorous root system that may extend down to 1.2 m, which can supply enough water for its requirement (Ahmadi et al., 2019). This plant has more than 3000 varieties, with acceptable adaptability to extreme climatic conditions (Olmos et al., 2024). However, the response of quinoa to water stress is genotype-dependent (Maestro-Gaitán et al., 2022). For example, in the study of Maestro-Gaitán et al. (2023), cultivar F16 kept its seed yield (SY) under low water availability, but the seed nutritional quality decreased, while the SY of Titicaca cultivar reduced but the seed quality increased, specifically in secondary panicles. Golestanifar et al., (2024a) found that on the planting date of July, the Giza-1 variety and in March Redcarina variety were the most tolerant varieties and Titicaca was the most sensitive cultivar to drought stress.

In quinoa plant, the root-to-shoot ratio and water use efficiency increase under drought conditions, showing that this plant under reduced water conditions can use lower water for the production of a unit of biomass. Thereby, it is a promising alternative crop for arid and semi-arid regions (Miranda-Apodaca et al., 2018). Tourajzadeh et al. (2024) found that decreasing the depth of irrigation water from 100 to 60% of quinoa water requirement increased water productivity. In a study conducted by Talebnejad & Sepaskhah (2015), it was concluded that a 70% reduction in full irrigation resulted in only a 36% reduction in the SY of quinoa. In another study conducted by Kayaa et al. (2015) on quinoa, grain yield was 6.38, 5.77, 4.55, 4.11, and 2.21 t/ha, while irrigation water productivity was 2.06, 2.45, 2.77, and 5.55 kg/m^3, for a full and three deficit (80, 50 and 20%, water requirement) irrigations along with a rain-fed treatment, respectively.

In a study carried out on quinoa (cv. Titicaca), plant is tolerant to soil drying during seed-filling. The basal crop coefficient (*Kcb*) values were found to be 0.20, 1.2, and 0.4 for the initial, mid, and late stages of the plant development (Razzaghi et al., 2012). In the investigation carried out by Golestanifard et al. (2024b) the SY of quinoa on planting date of 8th August, was 2820 and 1263 kg/ha, for irrigation levels of 100 and 25% of water requirement, respectively. Ghorbany et al. (2023) found that an increase in water stress severity (irrigation after 70, compared to 210 mm pan evaporation) caused a reduction in biological yield (BY) and 1000-grain weight of quinoa, but the SY did not decrease.

In another study, it was reported that exposure of quinoa to deficit irrigation (60% water requirement) decreased the shoot growth, SY and its components, pigments content, carbohydrates, protein, and main

Table 1. The main climatic factors during the experimental period in Sarayan

Climatic parameters	April	May	June	July	August	September	October
Average relative humidity (%)	37.22	38.56	18.19	18.19	17.91	16.14	12.5
Total rainfall (mm)	42.2	24.71	0	0	0	0	0.01
Max. temperature (°C)	24.95	27.31	35.49	35.49	36.87	33.93	26.07
Min. temperature (°C)	12.1	14.92	20.89	20.89	22.33	17.12	11.18

macro elements of produced seeds. While, increasing the root length, phenolic compounds, soluble sugars, proline , and free amino acids, compared with the plants grown under full irrigation (Sadak & Bakhoum, 2022). Aziz et al. (2018), also found that water deficit (40% and 20% FC) significantly decreased quinoa plant growth and its photosynthetic rate, while it increased relative membrane permeability, malondialdehyde, glycine betaine and activities of superoxide dismutase and peroxidase.

This study aimed to investigate effect of water availability levels, through irrigation intervals, on growth and yield of quinoa. The innovation of this result was to compare the continuous irrigation (CI) system with the supplemental irrigation method as well as rainfed cultivation of quinoa in a dry region without any rainfall during most of the plant-growing season.

METHODS

Experimental Area

This study was carried out in Sarayan (33ºN, 58ºE, and 1450 masl), South Khorasan province, located in the eastern part of Iran. The experimental site was characterized by a semi-arid climate, with an average annual precipitation of 150 mm and a mean annual temperature of 17 ºC. The main climatic factors of the study site are shown in Table 1.

Experimental Design

In this experiment, effect of different irrigation regimes (water availability levels) was investigated on growth and yield of quinoa. The experiment was carried out using a randomized complete block design with four replicates in 2017. Experimental treatments were CI during the growing season with intervals of 1, 2, and 3 weeks (CI-1W, CI-2W, and CI-3W, respectively), supplementary irrigation (SI) with 1, 2, and 3 times during the last month of the plant growth (SI-1T, SI-2T, and SI-3T, respectively) and stopping irrigation after plant emergence (SIAE: Just two times irrigation for germination and emergence).

Land Preparation and Planting

Before the land preparation, a soil sample was collected from the experimental field, and its key physical and chemical properties were analyzed in the laboratory (Table 2). Land preparation was carried out on 22 April, which continued with the creation of experimental plots (2×2 m). Then, cow manure was used in all plots at the rate of 30 t/ha, as pre-planting.

Planting was carried out using Titicaca cultivar, on 4th May, and the distances between and on the rows were 50 and 10 cm, respectively. Thinning was carried out three weeks after emergence (on 26 May) to obtain a density of 20 plants per m^2. Basin irrigation was performed immediately and three days after planting for appropriate germination and emergence. Then, irrigation was applied in each plot according to the relevant irrigation treatment, and a one-time hand weeding was carried out on 26 May.

Measured Parameters

SPAD index was determined in 20 healthy and fully developed green leaves from the upper layer of canopy in each plot, on 11th July. In the last stage of the vegetative phase, eight plants were selected randomly in each plot, and then some morphological traits including plant height, panicle number per plant, length, and dry weight of panicle, were measured. Subsequently, the 1000-grain weight was also determined in each plot, and the remained plants were used to measure grain yield, BY, and harvest index (HI).

Data Analysis

Data analysis was carried out using Statistical Analysis System (SAS) 9.2 and means were compared by Least Significant Difference (LSD) test at 5% level of probability.

Results and Discussion

Chlorophyll Index

Water availability (irrigation management) had a significant effect on chlorophyll index (SPAD) in leaves of quinoa (Table 3), and on average, SPAD in the supplemental irrigation method (SI) was more than in CI. The highest amount of SPAD was obtained in SI with three (SI-3T) or two (SI-2T) times irrigation during the last month of the plant growing season. There was no significant difference between the

Table 2. Some physical and chemical properties of soil in the experimental site

Soil texture	Silt (%)	Clay (%)	Sand (%)	EC (dS m^{-1})	pH	Organic carbon (%)	Total N (%)	P_{ava} (ppm)	K_{ava} (ppm)
Sandy Loam	31.6	15.4	53	2.56	7.85	0.38	0.032	10.6	248

three treatments of CI in terms of SPAD, and they showed the lowest values (Figure 1). Lin et al. (2021) also found that the decrease in water availability for quinoa from 90 to 25% of plant requirement, some enhancement was observed in the total chlorophyll content at vegetative stage. The increase in chlorophyll index of quinoa under deficit irrigation (Figure 1) contrasts with the results of El-Shamy et al. (2022) but aligns with those of Golestanifard (2024), who suggested that under water stress conditions, the leaf-specific weight of quinoa may increase as cell size decreases. As a result, the number of cells per unit weight of the leaf increases, leading to enhanced chlorophyll content. Solimaninya et al. (2021) also in a study on quinoa reported that under deficit irrigation, the accumulation of chlorophyll *a* and *b* increased due to the decrease in the leaf surface, but the amount of photosynthesis reduced due to the decrease in the relative water content of the plant. Arunyanark et al. (2008) also found that drought stress reduced the content of chlorophyll per plant but significantly increased chlorophyll content per unit of leaf area in peanuts. The study also confirmed that SPAD chlorophyll meter readings could be used as a rapid tool to estimate the relative chlorophyll content. The stability of chlorophyll under drought stress is one of the indicators that show the plant's resistance to drought (Chutteang et al., 2023). Therefore, it appears that drought-resistant quinoa cultivars, as observed in the present experiment, show resilience under water-limited conditions (Figure 1) and maintain their chlorophyll content under drought conditions to resist stress.

Morphological Parameters

Effect of irrigation management was not significant on the plant height, number of sub-panicles and panicles per plant, and panicle dry weight. However, it has a significant effect on the PL (Table 3). Subsequently, PL in three CI treatments was on average 38.3% more than SI and semi-rain-fed (stopping irrigation after plant emergence, SIAE) treatment. There was no significant difference between the three types of SI with SIAE, in terms of PL. In addition, CI-1W and CI-3W were in the same statistical group (Table 4). This observation is similar to those reported by Ghorbany et al. (2023), where there was no significant difference between irrigation after 70, 140, and 210 mm evaporation from the pan, in terms of PL.

Grain and BY

Irrigation management had a significant effect on the 1000-grain weight of quinoa (Table 3). The highest 1000-gain weight (2.69 g) was obtained in SI-3T, followed by SI-2T, while the other treatments were in the same statistical group (Figure 2). According to the study by Golestanifar (2024), decreasing water availability from 125 to 100, 75, 50 and 25% of quinoa water requirement caused a decrease of 6.6, 11.7, 17.1 and 20.2%, respectively, in 1000-grain weight.

Table 3. Mean squares for effect of irrigation management on vegetative growth parameters, yield, and yield components of quinoa

Source of Variation	df	Chlorophyll index (SPAD)	Plant height	Number of sub-panicles per main panicle	Number of panicles per plant	Panicle length
Replication	3	72.34ns	114.57ns	6.03ns	18.52ns	3.34ns
Irrigation	6	153.61**	37.65ns	10.48ns	46.23ns	14.44**
Error	18	43.81	79.13	4.99	33.96	2.96
Coefficient of Variation (C.V.) (%)	-	23.25	12.73	16.45	19.85	18.88
Source of Variation	**df**	**Panicle dry weight**	**1000-grain weight**	**Biological yield**	**Seed yield**	**Harvest index**
Replication	3	0.018ns	0.042ns	122635.7ns	546.0ns	1.31ns
Irrigation	6	0.048ns	0.183*	1022953.7**	15311.9**	100.46**
Error	18	0.032	0.072	105558.8	865.0	8.06
Coefficient of Variation (C.V.) (%)	-	32.92	11.98	21.72	15.63	20.81

ns=no-significant, * and ** significant at 5 and 1% level of probability.

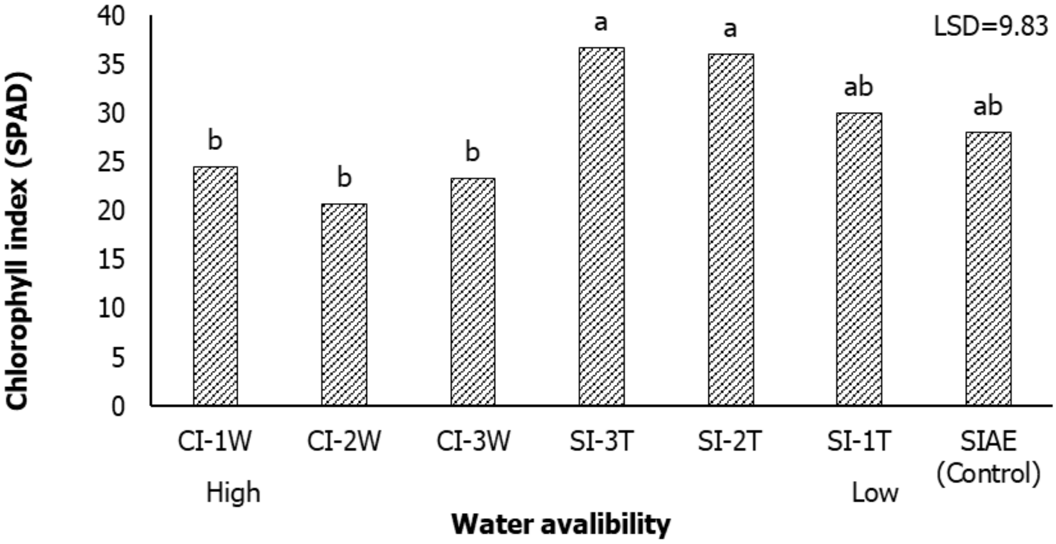

Figure 1. Effect of water availability on chlorophyll index (SPAD) of quinoa leaves
CI-1W, CI-2W, and CI-3W represent CI during the growing season with intervals of 1, 2, and 3 weeks, respectively. SI-1T, SI-2T, and SI-3T represent SI with 1, 2, and 3 times during the last month of plant growth, respectively. SIAE shows stopping irrigation after plant emergence

Table 4. Mean comparisons for effect of water availability on morphological parameters of quinoa

Irrigation treatments	Plant height (cm)	Number of sub-panicles per main panicle	Number of panicles per plant	Panicle length (cm)	Panicle dry weight (g)
CI-1W	70.7a	14.57ab	31.50ab	10.27ab	0.72a
CI-2W	74.0a	15.87a	35.25a	9.45bc	0.64ab
CI-3W	70.0a	11.72b	26.50b	12.77a	0.45b
SI-3T	64.0a	14.81ab	29.00ab	8.20bc	0.53ab
SI-2T	68.7a	12.27b	25.75b	7.90bc	0.40b
SI-1T	71.5a	13.88ab	30.75ab	7.37c	0.55ab
SIAE	70.1a	11.93b	26.75ab	7.90bc	0.55ab
LSD	13.21	3.31	8.65	2.55	0.26

El-Shamy et al. (2022), also found that the 1000-grain weight of quinoa was 3.49 and 1.91 g, for regular and deficit irrigation regimes, respectively. However, Lin et al. (2021) reported that the 1000-grain weight of quinoa under providing of 90, 75, 50, and 25% of water requirements was 1.61, 1.73, 1.63, and 1.57 g, respectively. In the investigation carried out by Ghorbany et al. (2023) 1000-grain weight between two treatments of irrigation after 70 and 210 mm evaporation from the pan, had no significant difference. Beyrami et al. (2020) reported the weight of 1000 grains of quinoa at irrigation intervals of 3 and 20 days was 2.7 and 2.1 g, respectively, while, there was no significant statistical difference between irrigation intervals of 10 to 20 days. It seems that these differences are mainly caused by the differences in grain yield. In this experiment, similar to those reported by Ghorbany et al. (2023), grain yield was very low (Figure 4), compared to those obtained by El-Shamy et al. (2022) and Golestanifar (2024), probably due to a low number of grains per panicle caused by the occurrence of high temperature during the pollination stage. Therefore, even in the conditions of reduced water availability, there were enough photoassimilates to fill the limited number of formed grains.

BY of quinoa was significantly affected by irrigation management at a 0.01 level of probability (Table 3).

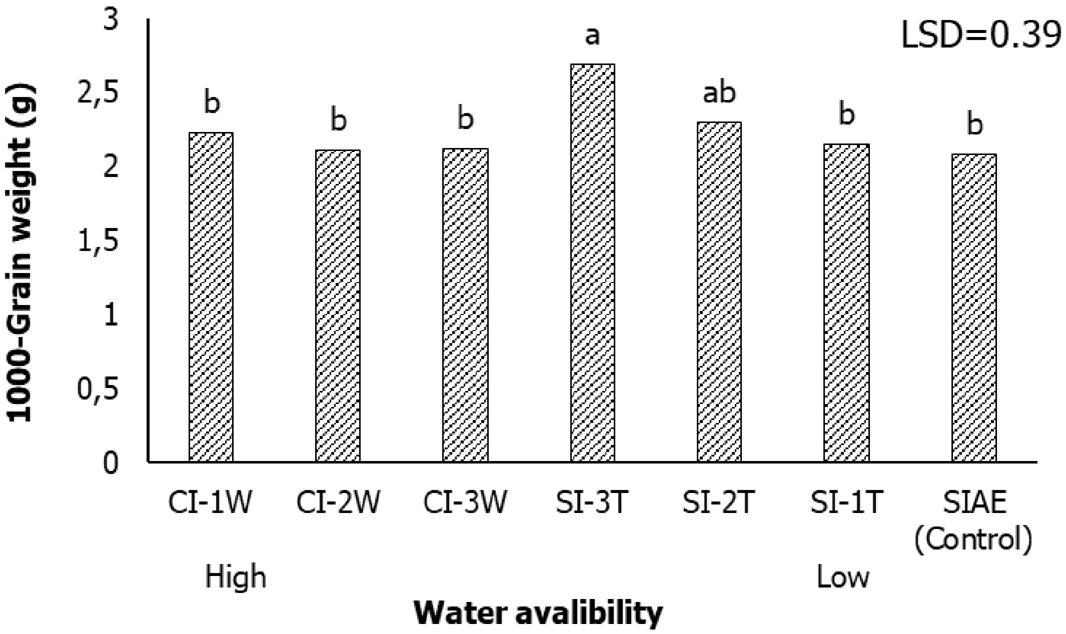

Figure 2. Effect of water availability on the 1000-grain weight of quinoa
CI-1W, CI-2W, and CI-3W represent CI during the growing season with intervals of 1, 2, and 3 weeks, respectively. SI-1T, SI-2T, and SI-3T represent SI with 1, 2, and 3 times during the last month of plant growth, respectively. SIAE shows stopping irrigation after plant emergence

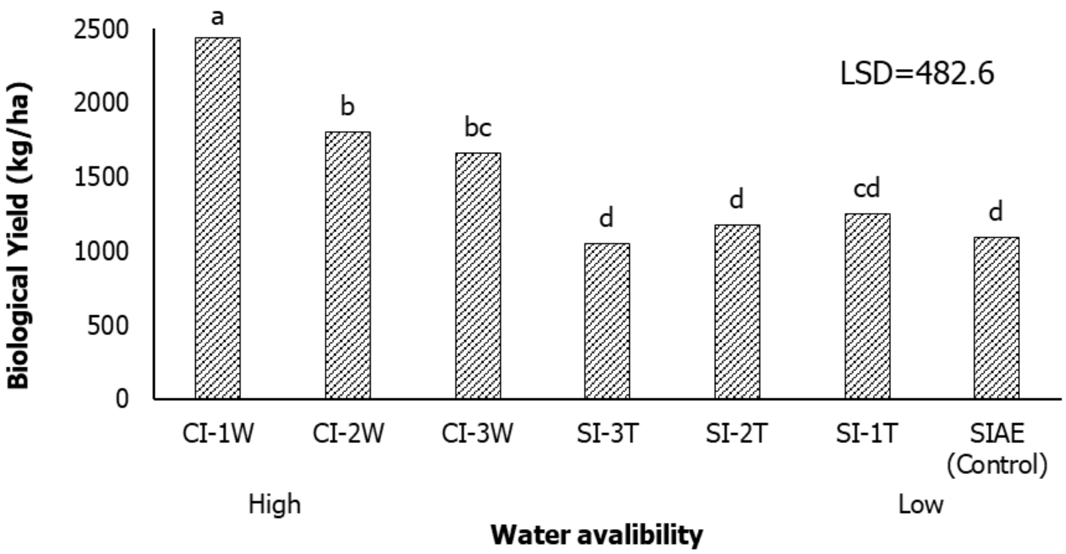

Figure 3. Effect of water availability on BY of quinoa
CI-1W, CI-2W, and CI-3W represent CI during the growing season with intervals of 1, 2, and 3 weeks, respectively. SI-1T, SI-2T, and S-I3T represent SI with 1, 2, and 3 times during the last month of plant growth, respectively. SIAE shows stopping irrigation after plant emergence

BY decreased significantly by decreasing the water availability. The highest amount of this index (2440 kg/ha) was obtained in CI-1W, followed by CI-2W and CI-3W, while three types of SI and SIAE were in the same statistical group with the lowest BY (Figure 3). Similar results have been obtained by El-Shamy et al. (2022), in which quinoa BY was 7.36 and 5.47 t/ha, under regular and deficit irrigation regimes, respectively. Similarly,

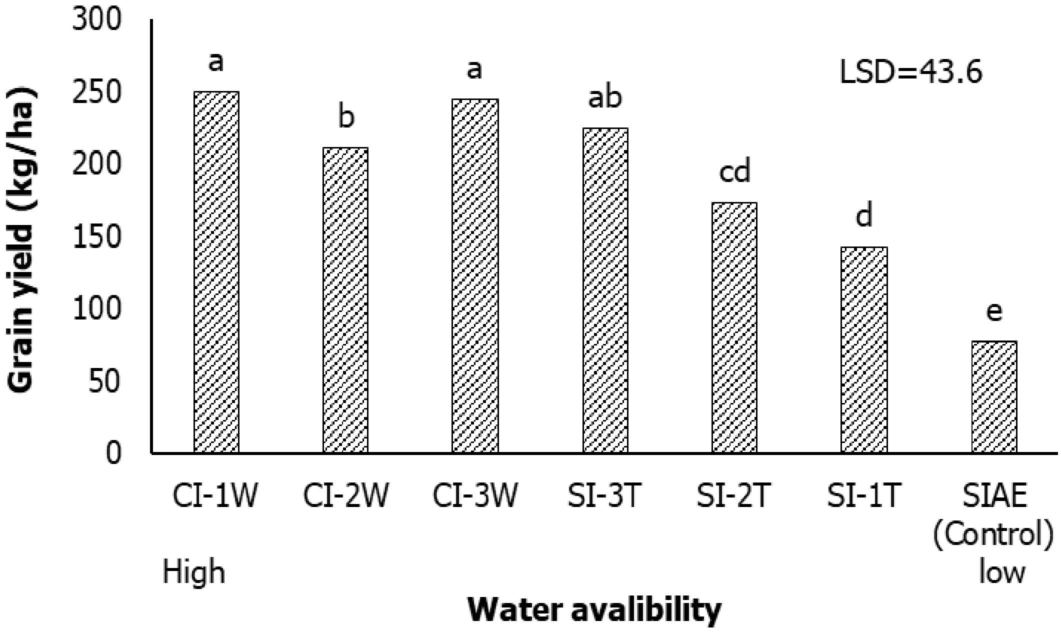

Figure 4. Effect of water availability on grain yield of quinoa
CI-1W, CI-2W, and CI-3W represent CI during the growing season with intervals of 1, 2, and 3 weeks, respectively. SI-1T, SI-2T, and SI-3T represent SI with 1, 2, and 3 times during the last month of plant growth, respectively. SIAE shows stopping irrigation after plant emergence

Golestanifar (2024) reported that by decreasing water availability from 125 to 100, 75, 50, and 25% of quinoa water requirement, BY was reduced by 10.4, 18.6, 38.5, and 58.0%, respectively. The reduction in quinoa biomass accumulation under drought stress is related to the reduction in nutrient uptake by the root, reduced stomatal conductance, and consequently reduced photosynthesis rate (Mohammadi et al., 2021).

Irrigation management significantly affected grain yield of quinoa (Table 3). On average, grain yield in CI was 30.5% more than SI, and 202.9% more than SIAE. The highest and the lowest (250.0 and 77.6 kg/ha) amounts of grain yield were gained in CI-1W and SIAE, respectively. SI-3T, among the three types of SI, was superior in such a way that it was not statistically different even with CI treatments (Figure 4). In the study of El-Shamy et al. (2022) the SY of quinoa under regular and deficit irrigation was 2.93 and 1.98 t/ha in the first year and 3.10 and 2.17 t/ha in the second studied year, respectively. Mohammadi et al. (2021) reported that grain yield of quinoa for 60, 90, and 120% (severe stress) evaporation from class A evaporation pan was 1878, 1538, and 1088 kg/ha, respectively. Severe drought stress reduces the leaf area and photosynthesis rate of quinoa, and its consequence is a decrease in grain yield (Golestanifar, 2024).

The results showed that grain yield of quinoa in CI-1W and CI-3W was, respectively, 250 and 245 kg/ha, with no significant difference (Figure 4). Similarly, in the study of Ghorbany et al. (2023), grain yield in irrigation treatments after evaporation of 70, 140 and 210 mm from the evaporation pan, was respectively, 171, 192 and 197 kg/ha. SY in this funding is similar to the results of Ghorbany et al. (2023), which was much lower than those reported by the majority of the previous investigations such as Beyrami et al. (2020), Mohammadi et al. (2021), Moradi et al. (2023), and Golestanifar (2024), due to the occurrence of heat stress during pollination stage, i.e. reducing the number of grains, which was caused by the improper planting date. Therefore, it appears that when the number of photosynthetic sinks (i.e., grains) is limited, quinoa's grain yield remains similar under moderate drought stress. However, severe water stress such as SI-2T, SI-1T, and SIAE, in the present study (Figure 4), will also show a reduced grain yield. However, it should be noted that even the production of 77 kg/ha of grain in SIAE (compared to the 250 kg/ha in CI-1W), is a considerable yield in a dry region, which shows the appropriate resistance of quinoa to drought.

Effect of irrigation management was significant on the HI of quinoa (Table 3). The HI increased as water availability decreased up to SI-3T; however, further

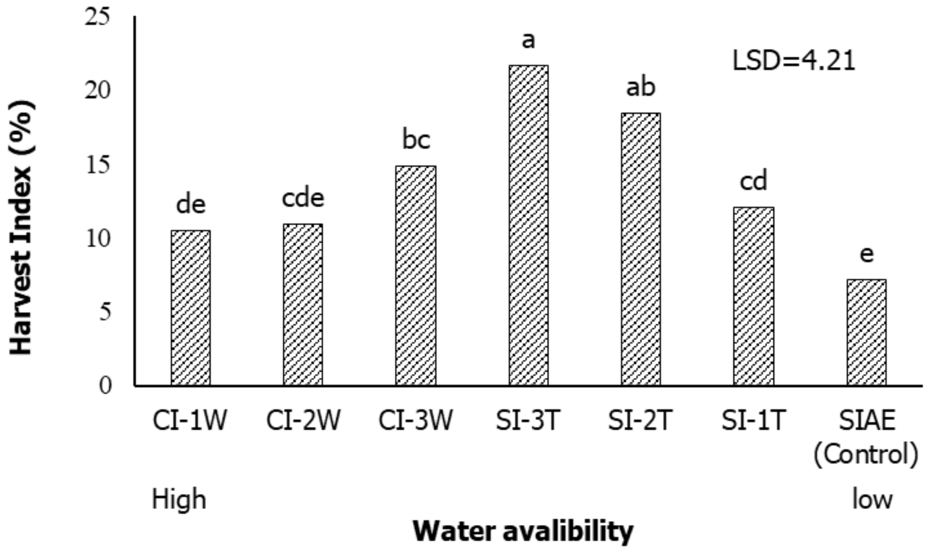

Figure 5. Effect of water availability on the HI of quinoa
CI-1W, CI-2W, and CI-3W represent CI during the growing season with intervals of 1, 2, and 3 weeks, respectively. SI-1T, SI-2T, and SI-3T represent SI with 1, 2, and 3 times during the last month of plant growth, respectively. SIAE shows stopping irrigation after plant emergence

reduction in water availability led to a decline. Despite this, SI-2T remained superior to all CI treatments. Among all treatments, the highest (21.6%) and the lowest (7.1%) values of HI were observed in SI-3T and SIAE, respectively. The mean values of the HI for three types of CI and SI were 12.09 and 17.37%, respectively (Figure 5). In the study carried out by Mohammadi et al. (2021), the HI was not reduced by severe water stress and was about 34%. In another study conducted by Moradi et al. (2023) the lowest (43.9%) and the highest (50.8%) values of HI were gained by irrigation intervals of 4 and 16 days, respectively. This is similar to the results obtained in this study which shows that middle levels of drought stress may increase the HI of quinoa (Figure 5). The increase in the rate of reallocation of stored photoassimilates in vegetative organs to grains, under the relative water scarcity can increase the HI in some plants (Moradi et al., 2023). Based on this study, SI during the last phase of growth is important for improving the HI of quinoa (Figure 5), Moradi et al. (2023) reported that the HI was reduced from 38.1% in the full irrigation regime to 29.8%, when irrigation stopped during seed filling stage of quinoa.

The average HI of all irrigation treatments in this study was 13.6%, which is much lower than those reported by Mohammadi et al. (2021), Yazdanpoor et al. (2023), and Moradi et al. (2023). The reason for the low HI (Figure 5), is due to the low grain yield (Figure 4) caused by the unperfected pollination and the decrease in the number of grains. In the study of Samadzadeh et al. (2020), it was confirmed that delay in the spring planting of quinoa causes pollination to collide with the high temperatures and a sharp decrease in grain yield. Studies have reported that quinoa is sensitive to temperatures above 25 °C and below 20 °C during the reproductive growth period. Temperatures outside this range, as observed in the present study (Table 1), significantly reduce both yield and HI (Salehi & Dehghani, 2017; Ghorbany et al., 2023).

CONCLUSION

In conclusion, based on grain yield of quinoa, the seed-filling stage is important to obtain a satisfactory yield. Three irrigation events during this stage (ST-3T) resulted in yield equivalent to that of CI throughout the entire growing season. These results show that quinoa is a suitable crop for dryland agriculture. Even in arid and hot regions, it achieved yields equivalent to 33% of the weekly irrigation treatment (CI-1W) when irrigation was discontinued after plant emergence (SIAE).

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CONFLICT OF INTEREST

There were no conflict of interest during the study period or the journal writing process.

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