

Article

Deficit Irrigation-Based Improvement in Growth and Yield of Quinoa in the Northwestern Arid Region in China

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Abstract: Given the current global water scarcity issues, which particularly affect arid regions such as northwestern China, it is crucial to find crop planting patterns that result in efficient water resource utilization. Quinoa, as a drought-resistant and highly nutritious crop, has garnered significant attention from agricultural researchers in recent years. From 2019 to 2020, a series of experimental studies were conducted under non-mulching drip irrigation conditions to investigate the growth adaptability and the response to different irrigation levels of quinoa in an arid region in northwestern China. A comparative analysis of quinoa's dry matter accumulation, yield, thousand-grain weight, harvest index, and water use efficiency under varying irrigation levels revealed that increasing irrigation significantly enhanced quinoa's dry matter accumulation and yield. By optimizing the irrigation strategies, we found that the water-saving practice of initiating moderate irrigation in the sensitive water-demanding stages (flowering and fruiting) of quinoa increased the yield. The experiment results showed that, in 2020, the optimal irrigation amount was $3675 \text{ m}^3 \cdot \text{ha}^{-1}$ during a 14-day irrigation cycle, meeting quinoa's growth requirements while improving water resource utilization efficiency. This study not only provides a scientific basis for the efficient cultivation of quinoa in the arid regions of northwestern China, but also offers new insights into and technical support for agricultural water resource management in the region, contributing to the sustainable development of agriculture in arid areas.

Keywords: quinoa; irrigation quota; water consumption; yield; dry matter accumulation



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1. Introduction

In recent years, extreme weather events, such as high temperatures, heavy rainfall, flooding, and drought, have been occurring frequently worldwide [1,2], causing significant impacts on agricultural production [3]. Drought, in particular, is a major climate disaster in arid regions that severely limits agricultural productivity [4]. Due to water scarcity, efficient water-saving measures have become crucial, and researchers have been focusing on the optimization of irrigation systems for different crops to cope with the lack of water resources [5,6]. Quinoa, a drought-tolerant, cold-resistant, nutrient-rich crop [7–9], is considered a preferred solution for food security [10,11], especially in arid regions [12,13]. Its cultivation area and market demand have been expanding globally [14–16], attracting research interest in many countries [17,18]. In China, quinoa cultivation originated in Tibet [19,20] and was first successfully grown in high-altitude areas in Shanxi [21]. Currently, research on quinoa is being conducted nationwide, with the goal of making it a staple crop in the future [18,22]. Quinoa is renowned for its strong drought resistance [23–25], and traditional cultivation methods rely on natural precipitation, even in arid and semi-arid regions [26]. Scientists have conducted studies on the growth and development of quinoa using deficit irrigation methods [27,28]. Geerts et al. [13,27,28] revealed the potential to significantly increase quinoa yield through deficit irrigation (DI). Additionally,

practical experiments carried out by Hirich et al. [8,11] in the arid regions of Chile positively validated the application of DI in quinoa cultivation. Furthermore, given quinoa's unique growth characteristics and low tolerance to humid conditions, DI not only optimizes the growing environment but also enhances yield and quality by reducing the incidence of downy mildew [12]. A study by Garcia et al. [23] further elaborated this point by carrying out precise analyses of the water requirements of quinoa at different growth stages to significantly improve its water use efficiency (WUE) and ensure adequate water supply during the most sensitive stages while achieving higher yields. In modern agricultural production practices, proper water management and its impact on crop yield and quality cannot be overlooked. In their 2008 research, Geerts et al. [27,28] indicated that when quinoa receives sufficient water supply during its critical growth stages, such as germination, flowering, and grain filling, its water use efficiency is significantly enhanced. This finding reveals that, even if drought occurs during the vegetative growth stage, its impact on the final yield is relatively limited.

Mulei County, as a primary cultivation region for wheat, also serves as a significant base for the introduction of quinoa. The region primarily practices rain-fed agriculture, flood irrigation, and drip irrigation. Therefore, it is crucial to understand the differences in water requirements for quinoa under these various cultivation conditions, as well as how different irrigation systems impact the accumulation of dry matter and the formation of grain yield in quinoa. In this study, we conducted field experiments in Mulei County using different irrigation quotas. The aim of this study was to analyze their effects on the growth characteristics, dry matter accumulation, and yield of quinoa. The overarching goal was to evaluate the cultivation suitability and the water demand and sensitivity of quinoa in the arid northwestern region in China, providing a theoretical basis for food security production in this area.

2. Materials and Methods

2.1. Climatic Conditions

This study was conducted at the Mulei County Experimental Station in Xinjiang (43°52' N, 90°16' E; 1191 m a s l) in 2019 and 2020 (Figure 1). The region experiences a temperate continental arid climate characterized by average annual temperatures of 5–6 °C and accumulated temperatures above 10 °C ranging from 2567 to 3100 °C. The annual precipitation in the area is approximately 343.5 mm, with a total sunshine duration of 3013.8 h and a frost-free period lasting 136–157 days [29]. The meteorological data collected by the agricultural automatic weather stations installed at the experimental site reveal that the highest temperature recorded in the period from 1 April to 1 October 2019 was 35.60 °C (on 3 August), the lowest temperature was −1.50 °C (on 9 April), and the average temperature was 18.14 °C. In 2020, the highest temperature recorded was 34.90 °C (on 18 July), the lowest temperature was −1.10 °C (on 1 April), and the average temperature was 18.08 °C. The total rainfall amounts during the growth period were 83.5 mm in 2019 and 131.4 mm in 2020. The topsoil in the experimental area is classified as gray desert soil and consists of clay loam with a thickness of approximately one meter with coarse sandy loam underneath it (Figure 1). Preliminary data on the soil properties, as shown in Table 1, indicate that the organic matter content decreases with soil depth, dropping from 17.48 g·kg^{−1} in the topsoil to 4.90 g·kg^{−1} in the deeper layers. Soil pH levels are relatively stable across different layers, and the total salt content also decreases with depth, from 0.65 mg·g^{−1} in the topsoil to 0.21 mg·g^{−1} in the deeper layers. Additional data are displayed in Table 1. Additionally, the groundwater is located at a depth of over 30 m.

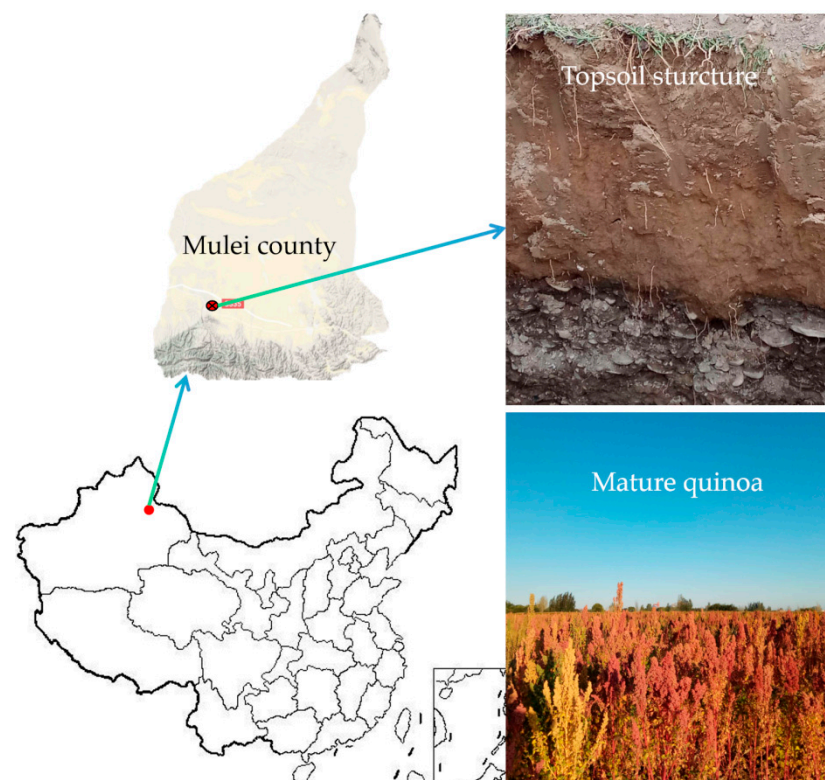


Figure 1. Overview of the experimental area.

Table 1. Initial soil properties of the test area (post-organic fertilizer application).

Topsoil, cm	Organic Matter, g·kg ⁻¹	Available Nitrogen, mg·kg ⁻¹	Available Phosphorus, mg·kg ⁻¹	Available Potassium, mg·kg ⁻¹	PH	Total Salts, mg·g ⁻¹	Field Capacity, %	Wilting Point, %	Soil Bulk Density, g·cm ⁻³
0–20	17.48	69.50	45.25	384.00	7.84	0.65	21.73	10.12	1.64
20–40	12.80	52.75	14.55	269.15	7.78	0.50	21.34	9.76	1.62
40–60	7.00	36.25	6.85	151.30	7.15	0.31	21.12	9.54	1.59
60–80	4.90	25.38	4.80	105.91	5.01	0.21	20.75	9.21	1.58

2.2. Experiments

JL-1 quinoa was used as the trial variety during field trials conducted in 2019 and 2020. Planting was carried out in a 0.67 ha trial area, and a combination of mechanical and manual seeding methods was used. Utilizing drip irrigation without film, the irrigation system was designed as “one pipe with two rows”. with a row spacing of 0.5 m, a drip head flow rate of 1.8 L·h⁻¹, and a drip head spacing of 0.3 m to ensure a uniform water distribution. The drip irrigation tape, crafted from recycled PE material, had a diameter of 16 mm. The quinoa plants were spaced 0.40 and 0.50 m apart. One week before sowing quinoa each year, organic fertilizer treatment was applied, with 1600 kg·ha⁻¹ of composted cow and sheep manure used to increase the soil organic matter content, improve the soil properties, enhance the soil structure, and promote soil permeability and aeration. Over the course of two years, a total of eight treatments were set up under non-membrane drip irrigation conditions. In 2019, there were four treatments: M91, M92, M93, and CK. In 2020, there were also four treatments: M01, M02, M03, and CK. Each treatment had three replicates. All the treatments were sown simultaneously on 24 April, and irrigation trials commenced on 29 June, with a 14-day watering cycle. Water was stopped on 24 August, and harvesting took place on 15 September. Our goal was to determine the irrigation quota based on local water resource conditions and the growth characteristics of quinoa. In 2019,

the irrigation quotas for treatments M91, M92, and M93 were $2250 \text{ m}^3 \cdot \text{ha}^{-1}$, $2625 \text{ m}^3 \cdot \text{ha}^{-1}$, and $3000 \text{ m}^3 \cdot \text{ha}^{-1}$, respectively (Table 2 and Figure 2). No irrigation was conducted for 66 days after sowing to demonstrate the quinoa's drought resistance during the dry season. A control group (CK) was also included and was watered twice during the seedling stage at $150 \text{ m}^3 \cdot \text{ha}^{-1}$, with a final irrigation quota of $3675 \text{ m}^3 \cdot \text{ha}^{-1}$ (Table 2). The 2020 experiment built upon the 2019 study by investigating the impact of different irrigation quotas on quinoa growth. Three different irrigation quotas, M01, M02, and M03, were set at $2550 \text{ m}^3 \cdot \text{ha}^{-1}$, $2925 \text{ m}^3 \cdot \text{ha}^{-1}$, and $3300 \text{ m}^3 \cdot \text{ha}^{-1}$, respectively (Table 2). Unlike in 2019, all treatments received two watering sessions during the seedling stage at $150 \text{ m}^3 \cdot \text{ha}^{-1}$ each. The field trial layout was the same as in 2019 (Figure 2). A control group (CK), with an irrigation quota of $3675 \text{ m}^3 \cdot \text{ha}^{-1}$, was included to determine the most suitable irrigation level for quinoa growth, as shown in Table 2 and Figure 2.

Table 2. Irrigation quotas during quinoa growth stage ($\text{m}^3 \cdot \text{ha}^{-1}$). M91: treatment with irrigation quota of $2250 \text{ m}^3 \cdot \text{ha}^{-1}$; M92: treatment with irrigation quota of $2625 \text{ m}^3 \cdot \text{ha}^{-1}$; M93: treatment with irrigation quota of $3000 \text{ m}^3 \cdot \text{ha}^{-1}$; M01: treatment with irrigation quota of $2550 \text{ m}^3 \cdot \text{ha}^{-1}$; M02: treatment with irrigation quota of $2925 \text{ m}^3 \cdot \text{ha}^{-1}$; M03: treatment with irrigation quota of $3300 \text{ m}^3 \cdot \text{ha}^{-1}$; CK: treatment with irrigation quota of $3675 \text{ m}^3 \cdot \text{ha}^{-1}$.

Growth Stages	Date	Days of Growth	2019				2020			
			M91	M92	M93	CK	M01	M02	M03	CK
Germination	24 April–2 May	9	0	0	0	0	0	0	0	0
Seedling	3 May–25 May	23	0	0	0	300	300	300	300	300
Branching	26 May–19 June	25	0	0	0	0	0	0	0	0
Bud	20 June–6 July	19	450	525	600	675	450	525	600	675
Flowering	7 July–22 July	15	450	525	600	675	450	525	600	675
Fruiting	23 July–3 September	42	1350	1575	1800	2025	1350	1575	1800	2025
Ripening	4 September–15 September	12	0	0	0	0	0	0	0	0
Irrigation quota		145	2250	2625	3000	3675	2550	2925	3300	3675

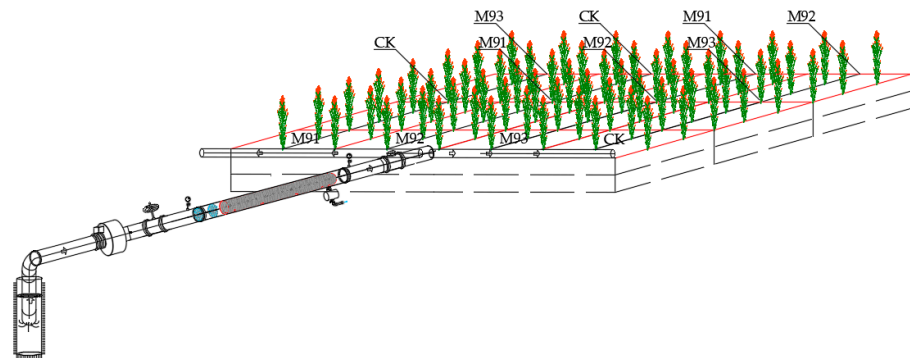


Figure 2. Field trial layout in 2019. M91: treatment with irrigation quota of $2250 \text{ m}^3 \cdot \text{ha}^{-1}$; M92: treatment with irrigation quota of $2625 \text{ m}^3 \cdot \text{ha}^{-1}$; M93: treatment with irrigation quota of $3000 \text{ m}^3 \cdot \text{ha}^{-1}$; CK: treatment with irrigation quota of $3675 \text{ m}^3 \cdot \text{ha}^{-1}$.

2.3. Data Collection

Calculation of reference crop evapotranspiration [30]: the reference crop evapotranspiration (ET_0) in the experimental area was calculated using the Penman–Monteith formula as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where

ET_0 is the reference crop evapotranspiration ($\text{mm} \cdot \text{day}^{-1}$);

Δ is the slope of the saturation vapor pressure curve ($\text{kPa} \cdot ^\circ\text{C}^{-1}$);

R_n is the radiation ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$);
 G is the soil heat flux density ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$);
 T is the mean daily air temperature ($^{\circ}\text{C}$);
 U_2 is the wind speed at a 2 m height ($\text{m}\cdot\text{s}^{-1}$);
 e_a is the saturation vapor pressure (kPa);
 e_d is the actual vapor pressure (kPa);
 γ is the psychrometric constant ($\text{kPa}\cdot^{\circ}\text{C}^{-1}$).

Crop water consumption in each growth stage: this is usually calculated based on the principle of water balance in actual production [31]. It is expressed as shown in Equation (2):

$$ET_{c1-2} = 10 \sum_{i=1}^n \gamma_i H_i (W_{i1} - W_{i2}) + M + P + K + C \quad (2)$$

where

ET_{c1-2} is the evapotranspiration during the stage ($\text{mm}\cdot\text{day}^{-1}$);
 n is the total number of soil layers;
 γ_i is the bulk density of the i th soil layer ($\text{g}\cdot\text{cm}^{-3}$);
 H_i is the thickness of the i th soil layer (cm);
 W_{i1} is the moisture content at the beginning of the period in the i th soil layer (percentage of dry soil weight);
 W_{i2} is the moisture content at the end of the period in the i th soil layer (percentage of dry soil weight);
 M is the irrigation amount during the period (mm);
 P is the precipitation amount during the period (mm);
 K is the groundwater recharge amount during the period (mm);
 C is the drainage amount during the period (sum of surface- and lower-layer drainage; mm).

Due to the groundwater level being below 30 m in the experimental area, groundwater recharge was not considered ($K = 0$). Based on observations of quinoa root distribution, over 90% of the roots were within a soil depth of 40 cm. In this study, when analyzing soil moisture throughout the entire growth period of quinoa, we assumed a constant planned wetting depth of 80 cm. As all the irrigation water was assumed to infiltrate into the soil without deep percolation for micro-irrigation, C was not considered.

Crop coefficient: the crop coefficient, denoted by K_c , refers to the ratio of actual water consumption to reference crop evapotranspiration, as shown in Formula (3):

$$K_c = ET_c / ET_0 \quad (3)$$

where

ET_0 is the reference crop evapotranspiration ($\text{mm}\cdot\text{day}^{-1}$);
 ET_c is the crop water consumption in each growth stage ($\text{mm}\cdot\text{day}^{-1}$);
 K_c is related to factors such as crop type, variety, crop population, and leaf area index.
 Dry matter: three quinoa plants were sampled in their seedling, branching, bud, flowering, grain-filling, and maturity stages. The leaves, bolting parts, and stems were sampled, dried at 105°C , oven-dried at 80°C to constant weight, and weighed, and the average values were calculated. This process yielded the dry matter accumulation per plant, which was converted to dry matter accumulation per unit area. The water use efficiency (WUE) of quinoa crops can be calculated using Formula (4).

$$\text{WUE} = \text{Dry matter accumulation} / \text{Water consumption during the growth stage} \quad (4)$$

Yield collection method: during the maturity stage, 9 plants were sampled for each treatment to analyze the average weight of a thousand grains. Subsequently, the yield per plant for each treatment was converted to yield per unit area. The harvest index (HI) of quinoa can be calculated using Formula (5), and the seed grain water efficiency (GWUE) can be calculated using Formula (6).

$$\text{HI} = \text{Yield} / \text{Dry matter accumulation (excluding roots)} \quad (5)$$

$$\text{GWUE} = \text{Yield} / \text{Water consumption during the growth stage} \quad (6)$$

2.4. Data Processing and Analysis

In this study, we meticulously organized meteorological data, quinoa yield-related data, and dry matter accumulation using WPS Office 12.1.0 software and calculated important parameters such as reference crop evapotranspiration, quinoa water consumption, crop coefficients, and water use efficiency. Additionally, we conducted Duncan's variance analysis on quinoa data under different treatment conditions using SPSS 19.0 software. We also employed Pearson correlation coefficient analysis to examine the relationship between quinoa water consumption, yield-related factors, and growth indicators.

3. Results

3.1. Reference Crop Evapotranspiration (ET_0)

After having meticulously organized and analyzed the meteorological parameters such as maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$), rainfall, radiation (R_n), and wind speed (WS) collected by automatic weather stations during the two growing seasons of 2019 and 2020 (Figure 3), we calculated the reference crop evapotranspiration (ET_0), as shown in Figure 3. Through this analysis, we observed that during the entire growth period of quinoa in 2019, evaporation generally exceeded precipitation. Specifically, the cumulative precipitation for that growing season was only 83.5 mm, while ET_0 was 657.37 mm. In 2020, the data showed an increase in cumulative precipitation during the growth period, reaching 131.4 mm, with a corresponding increase in ET_0 to 666.23 mm, a higher figure compared with the previous year. This change could be attributed to variations in climatic conditions and soil moisture content in the experimental area for that year. According to the comparison of the data from these two years, it is evident that, in overcast conditions, an increase in rainfall can increase air humidity, thereby reducing the reference crop evapotranspiration; on the other hand, under clear and hot weather conditions, the transpiration of crops and evaporation from the ground surface are enhanced. Therefore, we infer that, in the same experimental area, whether in the first or second growing season, an increase in rainfall and overcast weather conditions relatively decreases the reference crop evapotranspiration, while under conditions of less rainfall, higher temperatures, and clear weather, the ET_0 value increases.

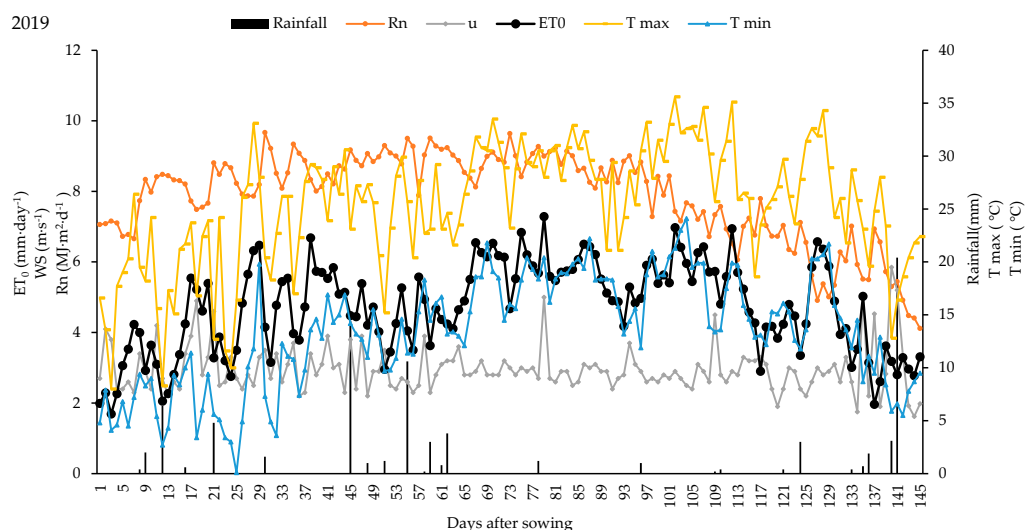


Figure 3. Cont.

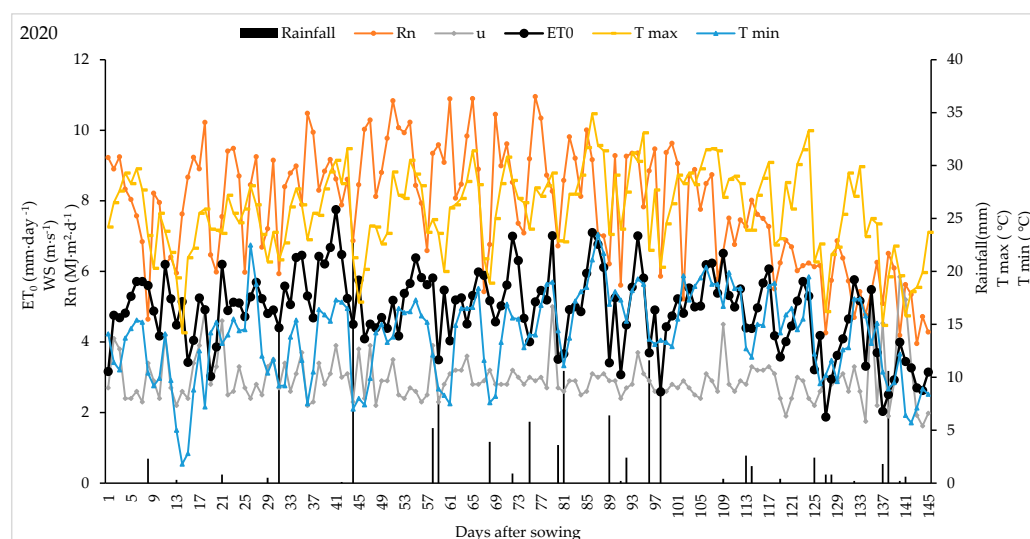


Figure 3. ET_0 and rainfall during the growing season ($\text{mm} \cdot \text{day}^{-1}$). T max: maximum temperature ($^{\circ}\text{C}$); T min: minimum temperature ($^{\circ}\text{C}$); Rn: radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$); WS: wind speed ($\text{m} \cdot \text{s}^{-1}$).

3.2. Changes in Water Consumption during the Growth Stages of Quinoa

The data analysis based on Table 3 indicates that, in 2019, under conditions without initial irrigation, the water consumption of quinoa in various growth stages in a water-deficient environment was significantly lower than that of the conventional irrigation control group. During the seedling stage, water consumption ranged between 22.80 and 52.80 mm with treatments M91, M92, and M93, showing a 57% reduction in water consumption compared with the control group, indicating a significant difference ($p < 0.05$). This trend of reduced water consumption continued into the branching stage, with a 5% reduction. The reduction in water consumption was even more significant during the visibility stage, with decreases of 25%, 17%, and 9% with M91, M92, and M93, respectively. Similar trends were observed during the flowering and grain-filling stages, with reductions of 27%, 17%, and 8%, and 25%, 17%, and 8%, respectively, compared with the control group, with the first two treatments showing significant differences. In the maturity stage, the reductions in water consumption were 14%, 12%, and 5%, respectively, demonstrating certain water-saving effects. These results indicate that under water-deficient conditions, quinoa effectively reduced water consumption during its growth period and that there were significant differences among different treatments.

The 2020 trial results regarding the characteristics of quinoa's water consumption in different growth stages were similar to those of 2019, showing the highest water consumption during the grain-filling stage, followed by the flowering, visibility, branching, maturity, and seedling stages. Water consumption during the seedling stage was slightly reduced, but the difference was not significant. The reductions in water consumption during the visibility and flowering stages were more significant, especially during the grain-filling stage, indicating potential water-saving benefits in water management. Although reduced, water consumption in the maturity stage did not show significant differences between some treatment groups and the control group. These data further confirm quinoa's potential for water saving under water-deficient conditions and its water consumption characteristics in different growth stages.

Table 3. Water consumption in different quinoa growth stages (mm). M91: treatment with irrigation quota of $2250 \text{ m}^3 \cdot \text{ha}^{-1}$; M92: treatment with irrigation quota of $2625 \text{ m}^3 \cdot \text{ha}^{-1}$; M93: treatment with irrigation quota of $3000 \text{ m}^3 \cdot \text{ha}^{-1}$; M01: treatment with irrigation quota of $2550 \text{ m}^3 \cdot \text{ha}^{-1}$; M02: treatment with irrigation quota of $2925 \text{ m}^3 \cdot \text{ha}^{-1}$; M03: treatment with irrigation quota of $3300 \text{ m}^3 \cdot \text{ha}^{-1}$; CK: treatment with irrigation quota of $3675 \text{ m}^3 \cdot \text{ha}^{-1}$. Tables show different letters (a, b, c, d) indicating significant differences among treatments ($p < 0.05$).

Year	Treatments	Growth Stages						ET_c
		Seedling	Branching	Bud	Flowering	Fruiting	Ripening	
2019	M91	22.80 b	47.03 b	61.72 c	64.06 d	184.40 c	26.93 c	406.94 c
	M92	22.80 b	47.03 b	68.52 bc	73.20 c	205.80 b	27.81 bc	445.16 bc
	M93	22.80 b	47.03 b	75.20 b	81.03 b	226.42 a	29.96 ab	482.43 b
	CK	52.80 a	53.44 a	82.28 a	88.30 a	246.50 a	31.43 a	554.75 a
2020	M01	50.11 a	60.58 a	64.95 c	74.73 c	193.73 d	22.01 b	466.10 c
	M02	50.98 a	60.23 a	73.14 b	82.57 bc	216.21 c	25.69 a	508.81 bc
	M03	50.28 a	59.29 a	79.37 b	90.27 ab	241.44 b	25.78 a	546.43 ab
	CK	51.24 a	60.92 a	87.04 a	97.60 a	264.31 a	27.36 a	588.45 a

3.3. Quinoa Crop Coefficient (K_c)

Based on the analysis of the data in Figure 4, we can observe that, under drip irrigation, the crop coefficient of quinoa during its entire growth period exhibited significant stage-specific characteristics, showing an initially increasing trend, with the highest values being found in the central stages, and later decreasing trend. In the early stages of growth, due to the small size of quinoa plants that did not cover the soil extensively, the crop coefficient was relatively low, approximately 0.4 (K_c ini). As the plants entered the rapid growth stage, the increase in leaf area enhanced transpiration, causing the crop coefficient to rise to about 1.10 (K_c mid) during the mid-growth period. As the plants matured, the growth rate slowed, and some leaves started to senesce, leading to a decrease in the crop coefficient, with values of about 0.5 (K_c end) during this period. Finally, during the harvest period, as the crop's transpiration demand was at its lowest, the crop coefficient dropped to the lowest value during the entire growth period. These changes reflect the differences in the water requirements of quinoa in different growth stages, which is of significant importance for guiding irrigation management.

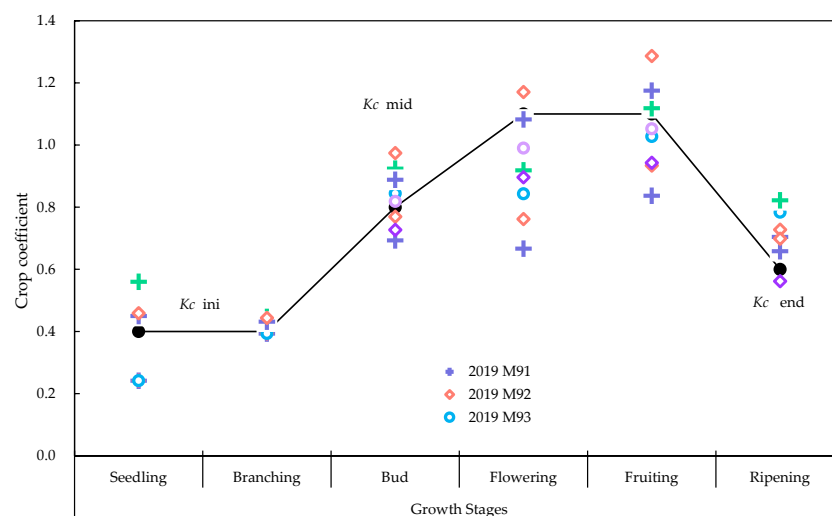


Figure 4. Crop coefficients for quinoa growth stages. M91: treatment with irrigation quota of $2250 \text{ m}^3 \cdot \text{ha}^{-1}$; M92: treatment with irrigation quota of $2625 \text{ m}^3 \cdot \text{ha}^{-1}$; M93: treatment with irrigation quota of $3000 \text{ m}^3 \cdot \text{ha}^{-1}$; M01: treatment with irrigation quota of $2550 \text{ m}^3 \cdot \text{ha}^{-1}$; M02: treatment with irrigation quota of $2925 \text{ m}^3 \cdot \text{ha}^{-1}$; M03: treatment with irrigation quota of $3300 \text{ m}^3 \cdot \text{ha}^{-1}$; CK: treatment with irrigation quota of $3675 \text{ m}^3 \cdot \text{ha}^{-1}$.

3.4. Dry Matter in Different Growth Stages of Quinoa

Table 4 shows the impact of different water treatments on dry matter accumulation in quinoa plants under drip irrigation without mulch in the two growing seasons. During the seedling stage, the dry matter accumulation per plant ranged from 0.500 to 0.980 g·plant in 2019 and from 1.009 to 1.040 g·plant in 2020. Variations were observed between 2019 and the control group (CK), with average values of all the treatments in 2019 being 0.627 g·plant and 1.028 g·plant in 2020, indicating a 1.641-fold increase in dry matter accumulation in 2020 compared to 2019. Regarding the branching stage, despite no irrigation being performed in either growing season, watering during the seedling stage in the second growing season led to significantly higher dry matter accumulation than in the first season, with average values of 8.645 g·plant in 2019 and 18.070 g·plant in 2020, showing a 2.09-fold increase. During the bud stage in both seasons, quinoa plants were irrigated with varying amounts of water, resulting in rapid growth and dry matter accumulation ranging from 24.91 to 56.07 g·plant in 2019 and from 56.08 to 70.22 g·plant in 2020, showing significant differences compared with the CK treatment ($p < 0.05$). In the grain-filling stage, dry matter accumulation per plant ranged from 240.677 to 349.87 g·plant in 2019 and from 275.080 to 384.850 g·plant in 2020, with significant differences compared with the CK treatment ($p < 0.05$). At maturity, dry matter accumulation per plant ranged from 262.168 to 370.46 g·plant in 2019 and from 285.290 to 400 g·plant in 2020, also showing significant differences compared with the CK treatment ($p < 0.05$). These results demonstrate the significant impact of different water treatments on dry matter accumulation in quinoa under drip irrigation without mulch, which was especially evident in different growth stages.

Table 4. Changes in quinoa dry matter in different growth stages (g·plant). M91: treatment with irrigation quota of 2250 m³·ha^{−1}; M92: treatment with irrigation quota of 2625 m³·ha^{−1}; M93: treatment with irrigation quota of 3000 m³·ha^{−1}; M01: treatment with irrigation quota of 2550 m³·ha^{−1}; M02: treatment with irrigation quota of 2925 m³·ha^{−1}; M03: treatment with irrigation quota of 3300 m³·ha^{−1}; CK: treatment with irrigation quota of 3675 m³·ha^{−1}. Tables show different letters (a, b, c, d) indicating significant differences among treatments ($p < 0.05$).

Year	Treatments	Growth Stages					
		Seedling	Branching	Bud	Flowering	Fruiting	Ripening
2019	M91	0.500 b	5.820 b	24.910 c	78.571 c	240.677 c	262.168 c
	M92	0.512 b	5.840 b	29.540 b	87.424 bc	283.909 b	285.077 c
	M93	0.515 b	5.910 b	32.200 b	95.050 b	304.624 b	332.360 b
	CK	0.980 a	17.010 a	56.070 a	153.540 a	349.870 a	370.460 a
2020	M01	1.009 a	17.980 a	56.080 c	107.550 d	275.080 c	285.290 d
	M02	1.032 a	18.140 a	61.360 bc	127.950 c	308.000 b	318.830 c
	M03	1.032 a	18.010 a	66.520 ab	151.740 b	358.740 a	367.428 b
	CK	1.040 a	18.150 a	70.220 a	166.346 a	384.850 a	400.340 a

3.5. Relationship between Growth Indicators of Quinoa and Water Consumption during Different Growth Stages

During the two growing seasons in 2019 and 2020, the Pearson correlation coefficients between the growth indicators of quinoa under drip irrigation without film and the water consumption throughout the entire growth period indicated a positive correlation relationship, as shown in Table 5. Specifically, in the second growing season, there was a significant positive correlation (0.586, $p < 0.05$) between the leaf area of quinoa and water consumption during the seedling stage, while a stronger and highly significant positive correlation was observed during the rest of the growth period.

Table 5. Pearson correlation coefficients between growth indicators of quinoa and water consumption during different growth stages. * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

Year	Growth Parameters	Growth Stages					
		Seedling	Branching	Bud	Flowering	Fruiting	Ripening
2019	Plant height	0.969 **	0.890 **	0.825 **	0.973 **	0.989 **	0.911 **
	Stem diameter	0.997 **	0.972 **	0.958 **	0.859 **	0.932 **	0.856 **
	Leaf area	0.724 **	0.855 **	0.909 **	0.849 **	0.991 **	0.934 **
	Root dry mass	0.997 **	0.932 **	0.827 **	0.822 **	0.975 **	0.917 **
	Stem dry mass	0.967 **	0.941 **	0.938 **	0.936 **	0.997 **	0.973 **
	Leaf dry mass	0.999 **	0.939 **	0.817 **	0.780 **	0.979 **	0.883 **
	Fruit dry mass			0.803 **	0.836 **	0.966 **	0.942 **
	Dry mass accumulation	0.999 **	0.939 **	0.874 **	0.854 **	0.990 **	0.956 **
2020	Plant height	0.952 **	0.950 **	0.932 **	0.996 **	0.966 **	0.955 **
	Stem diameter	0.942 **	0.980 **	0.991 **	0.984 **	0.956 **	0.978 **
	Leaf area	0.586 *	0.888 **	0.947 **	0.941 **	0.987 **	0.795 **
	Root dry mass	0.750 **	0.968 **	0.951 **	0.972 **	0.902 **	0.969 **
	Stem dry mass	0.937 **	0.971 **	0.988 **	0.989 **	0.986 **	0.831 **
	Leaf dry mass	0.926 **	0.977 **	0.992 **	0.987 **	0.977 **	0.884 **
	Fruit dry mass			0.937 **	0.972 **	0.979 **	0.884 **
	Dry mass accumulation	0.918 **	0.976 **	0.992 **	0.987 **	0.995 **	0.896 **

Furthermore, both in the first and second growing seasons, the plant height and stem thickness of quinoa maintained a highly significant positive correlation with water consumption in different growth stages. Dry matter accumulation in stems, roots, and leaves showed a highly significant positive correlation with water consumption from the seedling stage to maturity, and that in stems from the elongation stage to maturity also exhibited a highly significant correlation; the dry matter accumulation per plant similarly showed a consistent highly significant positive correlation trend from the seedling stage to maturity. These data emphasize the importance of effective water resource management in quinoa production.

3.6. Changes in the Factors Affecting Quinoa Yield under Different Irrigation Levels

As shown in Table 6, in the two growing seasons, the yield composition factors of quinoa under drip irrigation without film were significantly affected by the amount of water. With the increase in water volume, the yield of quinoa also increased. In 2019, the yields of various treatment groups ranged from 994.859 to 1436.128 kg·ha^{−1}. Compared with the control group (CK), the yields of treatment groups M91, M92, and M93 decreased by 31%, 25%, and 7%, respectively. The differences between the first two treatments and CK were significant ($p < 0.05$). The individual plant yield ranged from 49.718 to 71.771 g, showing a similar trend to the overall yield. The changes in thousand-grain weight ranged from 1.945 g to 2.270 g. Although the same seed variety was used for the different treatments, the amount of water during the reproductive growth stage determined the plumpness of the quinoa grains. The CK treatment resulted in the greatest grain plumpness, with treatments M91, M92, and M93 decreasing the thousand-grain weight by 14%, 6%, and 5% compared with CK, with a significant difference between M91 and CK. Quinoa showed different water use efficiencies under different treatment conditions. The research data indicate that the crop water use efficiency (WUE) ranged from 1.281 kg/m³ to 1.379 kg/m³, with the M93 treatment group showing the highest efficiency. Additionally, the grain water use efficiency (GWUE) ranged from 0.241 kg/m³ to 0.278 kg/m³, with the M93 treatment group also standing out. However, the difference in GWUE between the M93 treatment and the control group (CK) was not significant.

Table 6. Changes in factors affecting quinoa yield under different irrigation levels. M91: treatment with irrigation quota of 2250 m³·ha^{−1}; M92: treatment with irrigation quota of 2625 m³·ha^{−1}; M93: treatment with irrigation quota of 3000 m³·ha^{−1}; M01: treatment with irrigation quota of 2550 m³·ha^{−1}; M02: treatment with irrigation quota of 2925 m³·ha^{−1}; M03: treatment with irrigation quota of 3300 m³·ha^{−1}; CK: treatment with irrigation quota of 3675 m³·ha^{−1}; TGW: thousand-grain weight; HI: harvest index; WUE: crop water use efficiency; GWUE: grain water use efficiency. Tables show different letters (a, b, c) indicating significant differences among treatments ($p < 0.05$).

Year	Treatments	TGW, g	Yield per Plant, g	Yield, kg·ha ^{−1}	HI	WUE, kg·m ^{−3}	GWUE, kg·m ^{−3}
2019	M91	1.945 b	49.718 b	994.859 b	0.213 a	1.289 a	0.244 b
	M92	2.140 ab	53.704 b	1074.622 b	0.215 a	1.281 a	0.241 b
	M93	2.162 a	66.978 a	1340.234 a	0.228 a	1.379 a	0.278 a
	CK	2.270 a	71.771 a	1436.128 a	0.220 a	1.336 a	0.259 ab
2020	M01	2.204 a	57.417 c	1232.211 c	0.224 b	1.314 b	0.264 b
	M02	2.320 a	66.879 b	1435.264 b	0.240 ab	1.345 ab	0.282 b
	M03	2.436 a	83.670 a	1795.618 a	0.257 a	1.443 ab	0.328 a
	CK	2.297 a	88.364 a	1896.364 a	0.248 ab	1.460 a	0.322 a

In 2020, all treatment groups were watered twice during the seedling stage, with no difference in water volume (15 mm) among treatments. However, in the flowering stage, there were differences in water volume among different treatment groups. Yet, the data for that year showed that the change in thousand-grain weight was not significant ($p > 0.05$), indicating a limited impact of water volume on thousand-grain weight. The yield variation among treatments ranged from 1232.211 to 1896.364 kg·ha^{−1}, with treatments M01, M02, and M03 decreasing by 35%, 24%, and 5%, respectively, compared with the CK group; there were significant differences between the first two treatments and CK ($p < 0.05$). The individual plant yield ranged from 57.417 to 88.364 g, with the individual grain yield of CK in the second growing season increasing by 16.594 g/pearl compared with CK in the first growing season, indicating that the yield of quinoa is influenced not only by the watering but also by the water consumption during the growing season. This emphasizes the importance of appropriate irrigation in increasing quinoa yield. The values of WUE and GWUE ranged from 1.314 to 1.460 kg·m^{−3} and 0.264 to 0.328 kg·m^{−3}, respectively, with the M03 and CK treatments performing the best, although there is no significant difference between them.

3.7. Relationship between Yield, Water Consumption, and Water Use Efficiency

In the management of crop production, crop water use efficiency (WUE) and grain water use efficiency (GWUE) are important indicators for measuring the efficiency of crop water management. These indicators reflect the relationship between the water consumption of crops throughout the entire growth period and the biomass and grain yield. By conducting a systematic analysis of water consumption, biomass, and grain yield during the crop growth period, we can gain a deeper understanding of how water affects the growth and yield of crops. The research results in Table 7 show significant correlations among quinoa yield, water consumption during the growth period (0.932 **), water consumption from flowering to maturity (0.886 **), GWUE (0.949 **), and WUE (0.955 **). The correlation coefficient between water consumption and yield during the entire growth period was as high as 0.932 **, and during the flowering and ripening stages, this correlation remained significant, with a coefficient of 0.886 **. These findings emphasize the importance of water management throughout the entire growth period of quinoa, especially in the later stages of growth, where effective water management significantly influences crop yield and water use efficiency. Therefore, appropriate water supply during the filling stage is crucial to improving quinoa yield and water use efficiency. The significant correlation between crop water use efficiency and grain water use efficiency

indicates that these two indicators can effectively reflect the overall efficiency of water use in quinoa, providing a reliable evaluation measure for crop water management.

Table 7. Pearson correlation coefficients of components of water use efficiency. WUE: crop water use efficiency; GWUE: grain water use efficiency. * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

Parameters	Yield	ET_c	ET_c from Flowering to Ripening	GWUE	WUE
Yield	1				
ET_c	0.932 **	1			
ET_c from flowering to ripening	0.886 **	0.955 **	1		
GWUE	0.949 **	0.775 *	0.728 *	1	
WUE	0.955 **	0.818 *	0.825 *	0.971 **	1

4. Discussion

Water is crucial for the growth of crops, as it participates in physiological and biochemical processes and serves as a medium for energy conversion and material exchange throughout the various stages of the crop growth cycle [32]. In this experiment, in quinoa grown under different treatments, water consumption increased with the irrigation amount, which is consistent with the findings obtained by Kaya et al. [33]. In field experiments conducted in Adana and Tarsus, the impact of different irrigation quotas on the water consumption pattern of quinoa was examined. The results from Adana showed that total water consumption and stage-specific water consumption increased with the irrigation amount for three different irrigation quotas (140, 100, and 60 mm) within a year. By comparing water consumption in quinoa during different growth stages in this study, it was found that water consumption was the highest during the flowering and grain-filling stages. This aligns with research by Algosaibi et al. [34], where studies in eastern Saudi Arabia indicated that, under different irrigation frequencies, the water consumption intensity in quinoa peaked between 50 and 90 days after sowing at a rate of $4.1 \text{ mm} \cdot \text{d}^{-1}$. The variations in water use efficiency and harvest index related to water consumption were closely linked to irrigation amounts among different treatments. This study found that, during the first growing season, the grain water use efficiency (GWUE) ranged from 0.241 to $0.278 \text{ kg} \cdot \text{m}^{-3}$, and the crop water use efficiency (WUE) ranged from 1.281 to $1.379 \text{ kg} \cdot \text{m}^{-3}$. The highest values were observed in the M93 treatment with an irrigation quota of $3000 \text{ m}^3/\text{ha}$. During the second growing season, the values of WUE and GWUE varied between 1.314 and $1.460 \text{ kg} \cdot \text{m}^{-3}$ and 0.264 and $0.328 \text{ kg} \cdot \text{m}^{-3}$, respectively, with the M03 and CK treatments performing the best, although there was no significant difference between them. These findings are consistent with those of Geerts et al. [27], who conducted deficit irrigation trials on quinoa in the Bolivian highlands. In the regions of Irpani (2005–2006, with an effective rainfall of 385 mm) and Mejillones (2006–2007, with an effective rainfall of 107 mm), deficit irrigation was applied during the pre-blooming to grain-filling stages. In Irpani, the total water use efficiency (TWUE) values for rainfed and deficit irrigation were $0.50 \text{ kg} \cdot \text{m}^{-3}$ and $0.52 \text{ kg} \cdot \text{m}^{-3}$, respectively, while in Mejillones, the results were reversed at $0.32 \text{ kg} \cdot \text{m}^{-3}$ and $0.28 \text{ kg} \cdot \text{m}^{-3}$. The impacts of soil quality, rainfall, and climatic conditions on quinoa's WUE varied significantly across regions. Drought stress from pre-blooming to early grain-filling stages notably reduced the water use efficiency, although these results are not absolute. The experiment highlighted that larger irrigation amounts during critical water-demanding periods, especially during flowering and grain-filling stages, contributed to enhancing the reproductive growth and seed development of quinoa. This is consistent with the results obtained by Kaya and Yazar [33], who found that when irrigation accounted for 50% of water demand, the WP (water productivity) value could reach 0.78, while under full irrigation, the WP value was 0.52. This insight holds practical significance for cultivating quinoa

in arid regions with limited water resources. In a study on potatoes in a northwestern region [35], it was observed that moderate deficit irrigation during key growth stages led to higher yields compared with normal irrigation, with water use efficiency increasing to 41.48%. Employing deficit irrigation during critical growth stages is a solution to enhancing WUE, emphasizing the critical roles of irrigation timing and water management.

Our experimental results show that under different irrigation regimes, quinoa's yield and dry matter accumulation exhibit significant differences in growth indicators. These differences are primarily influenced by water supply conditions. This aligns with Jensen et al.'s [26] findings, indicating that in arid regions, quinoa faces water stress and may lose biomass or yield to adapt to the dry climate. However, under deficit irrigation conditions, quinoa's yield increases. Conversely, excessive watering may affect quinoa's root development and nutrient absorption, thereby impacting its biomass. Therefore, determining the appropriate irrigation amount through experiments in different regions is crucial for robust crop growth. Pulvento et al. [36] discovered, in a Mediterranean region with an average annual rainfall of 805 mm, that well-irrigated quinoa had lower dry matter accumulation ($5530 \text{ kg} \cdot \text{ha}^{-1}$) compared with 50%-deficit-irrigated quinoa ($5670 \text{ kg} \cdot \text{ha}^{-1}$). In contrast, quinoa planted in an area 70 km southwest of Marrakech in the Mediterranean region showed higher dry matter accumulation under full irrigation ($8300 \text{ kg} \cdot \text{ha}^{-1}$) than under 50% deficit irrigation ($6400 \text{ kg} \cdot \text{ha}^{-1}$) [37]. In this experiment, the maximum yield in the first growing season reached $1436.128 \text{ kg} \cdot \text{ha}^{-1}$. This is consistent with González et al.'s [38] findings, where quinoa's yield under deficit irrigation in arid and semi-arid regions exceeded that under rain-fed conditions. In our study, in the second growing season, with two additional irrigation operations, quinoa's emergence rate and vigorous seedling growth were ensured, leading to increased yield compared with the first season. This is in line with Geerts et al.'s [13] report, which highlighted the importance of soil moisture before sowing and during the seedling stage for establishing quinoa seedlings and early root development in arid regions. Malili et al. [39] conducted an experimental study on deficit irrigation in the mixed cropping system of quinoa and hairy vetch in the cold desert area of China's Qinghai. The study aimed to explore the effects of varying water regulation levels on crop yield and water use efficiency. Three irrigation treatments were established: moderate deficit irrigation (45–55% field capacity), mild deficit irrigation (55–65% field capacity), and full irrigation (65–75% field capacity). The findings indicated that, under mild deficit irrigation, the combined yield of quinoa and hairy vetch reached 11,030.48 kg per hectare, with a water use efficiency of 0.56. Similar phenomena occur in the cultivation of other crops. Jia Yaoyu et al. [40] found, in their research in a northwestern region in China, that planting cotton under deficit irrigation reduced yield compared with full irrigation but that using the dry sowing and wet emergence method improved cotton survival rates, thus affecting cotton yield. Duan Weina et al. [41] also noted that deficit irrigation from the seedling to tasseling stages of maize contributed to increased yield. In regions with limited rainfall, such as northwestern arid areas, increasing crop biomass with full irrigation is impractical due to limited water sources, leading to insufficient water supply for crops throughout the entire growth period. Therefore, altering irrigation regimes, especially adopting deficit irrigation moderately, shows better results in grain yield formation. In this experiment, quinoa's dry matter accumulation increased with the increase in irrigation volume. This corresponds to research results from Bolivia [27,28], Morocco [42], Iran [43], China [39], and other regions, indicating that quinoa's biomass and yield are influenced by environmental factors, including rainfall, irrigation amount, soil type, geographical location, and climatic conditions.

Different varieties of quinoa have different thousand-grain weights, which also vary under different environmental conditions, water levels, and nutrient levels. In this experiment, the thousand-grain weight of quinoa ranged from 1.76 g to 2.36 g. Although the differences among treatments were not significant, the result confirmed the influence of irrigation on the thousand-grain weight of quinoa. Specifically, different irrigation levels can cause variations in the timing of flowering and branching in individual quinoa plants,

which affects the uniformity of maturity. This inconsistency in maturity can lead to the removal of underdeveloped grains during the harvest cleaning process, thereby affecting the final yield. During the flowering to grain-filling stages, an appropriate amount of water can significantly enhance grain plumpness, which is crucial not only for yield but also for the market quality of quinoa. Similar phenomena were observed in the studies by Kaya et al. and Geerts et al. In Kaya et al. [33]’s study, the thousand-grain weight under different irrigation levels ranged from 2.5 g to 3.1 g. In Geerts et al.’s [28] study, the thousand-grain weights under rain-fed, deficit irrigation, and full irrigation conditions were 4.2 g, 5.5 g, and 5.6 g, respectively. These research results indicate that under specific environmental conditions, appropriate irrigation strategies have a certain impact on seed size in quinoa, which can affect both the yield and quality of this crop.

5. Conclusions

In the quinoa introduction trials conducted in Mulei County, we analyzed the effects of different irrigation quotas on quinoa’s water consumption, yield, biomass, and related parameters over two growing seasons (2019 and 2020). Using a drip irrigation system without a film, the irrigation quota in 2019 was set between 2250 and 3675 m³·ha^{−1}, while in 2020, it included two additional irrigation times during the seedling stage (each watering 150 m³·ha^{−1}), with irrigation quotas ranging from 2550 to 3675 m³·ha^{−1}. The results indicated that appropriate irrigation significantly enhances quinoa yield, biomass, GWUE, and WUE, all of which are crucial for agricultural production in the arid regions of northwestern China. These areas experience scant rainfall and high evaporation rates, making deficit irrigation vital not only for quinoa growth but also for maintaining stable yields under limited water resources. It is especially critical to ensure sufficient irrigation in quinoa from the flowering to the maturity stages. The results of the second growing season further confirmed this point, showing that the quinoa yield in the region increased with increased water application. Specifically, under a 14-day irrigation cycle and an irrigation quota of 3675 m³·ha^{−1} in the control group (CK), the highest yield was achieved over the two growing seasons at 1896.36 kg·ha^{−1}, with a grain water use efficiency of 0.322 kg/m³. Additionally, while the harvest index and thousand-grain weight showed minimal changes under different irrigation quotas, the increase in the harvest index reflects the positive effect of increased irrigation on yield enhancement. Lastly, in the second growing season, all treatments effectively improved quinoa germination and emergence rates by adding two irrigations during the seedling stage, with each irrigation of 150 m³·ha^{−1} providing crucial cultivation support for quinoa production.

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