Potato Growth, Photosynthesis, Yield, and Quality Response to Regulated Deficit Drip Irrigation under Film Mulching in A Cold and Arid Environment

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Abstract

The effects of the amount and timing of regulated deficit drip irrigation under plastic film on potato ('Qingshu 168') growth, photosynthesis, yield, water use efficiency, and quality were examined from 2017 to 2019 in cold and arid northwestern China. A two-factor randomized design was used with two levels of regulated deficit irrigation (mild, moderate) applied in four stages of potato growth (seedling, tuber initiation, tuber bulking, starch accumulation). Growth and photosynthetic parameters were determined in each growth stage, and yield and quality were measured after harvest. The net photosynthetic rate, stomatal conductance, and transpiration rate decreased significantly under water deficit in the tuber formation and starch accumulation stages, and the decreases were greater with moderate than mild water deficit. Although water deficit reduced potato yields, potato subjected to mild water deficit in the seedling stage had the highest yield at 43,961.91 kg·ha^{-1}, followed by those subjected to mild water deficit in the starch accumulation stage at 42,262.25 kg·ha^{-1}, which were decreases of only 4.50% and 8.19%, respectively, compared with potato under full irrigation. The highest water use efficiency was in potatoes subjected to mild water deficit in the seedling stage (8.67 kg·m^{-3}), with the second highest in those subjected to moderate water deficit in the seedling stage (8.28 kg·m^{-3}), which were significant improvements by 10.87% and 5.84%, respectively, compared with full irrigation. The highest overall quality was in potatoes subjected to mild and moderate water deficit in the seedling stage. The starch content in potatoes with mild water deficit in the seedling stage increased by 3.34% compared with that under full irrigation. In addition, the protein and vitamin C contents in potatoes under moderate water deficit increased significantly by 0.77% and 21.59%, respectively, compared with the contents under full irrigation. Principal component analysis identified mild water stress in the seedling stage as the optimum regulated deficit irrigation regime for potato. Thus, the relative soil water content should be maintained at 55% to 65% of field capacity in the seedling stage but at 65% to 75% in the other growth stages. The results of this study provide theoretical and technical references for efficient water-saving cultivation and industrialization of potato in cold and arid northwestern China.

Introduction

Solanum tuberosum L. is also known as the white or Irish potato and is rich in nutrients and starch. It is a popular food with the reputation of being a "lost treasure", with medicinal and health care properties that include neutralizing the stomach, tonifying the spleen and qi, detoxifying, and relieving inflammation. In recent years in the Hexi Corridor Oasis Irrigation Area in the Hexi Oasis, potato has been a popular crop because of its strong adaptability, simple cultivation, suitability for storage, ease of transportation, and long supply period. However, with scaled-up cultivation, irrigation systems that use water inefficiently have led to a continuous increase in demand for irrigation water. Therefore, the design of irrigation systems that increase irrigation water use efficiency is an important approach to optimize water use. Regulated deficit irrigation is an advanced irrigation technology that was first proposed and practically implemented by the Australian Sustainable Irrigation Agricultural Research Institute when studying methods to improve the productivity of densely planted orchards (mainly those with peach trees) in the 1970s[1]. With this technology, a crop experiences a regulated water deficit at different amounts according to the characteristics of water consumption for that crop, thereby saving water and increasing water use efficiency. Regulated deficit irrigation has been widely applied, including with corn[2,3], tomatoes[4], wheat[5], onions[6,7], Isatis tinctoria[8,9], grapes[10,11], persimmons[12], cherries[13,14], garlic[15], watermelons[16], and peppers[17]. The technology is effective at increasing yields and water conservation. In potato, *Xue* et al.[18] studied the effects of regulated deficit irrigation with film in different growth stages on yield and water use efficiency in a desert oasis. They found that the highest indices of potato water sensitivity were in the starch accumulation stage, followed the tuber enlargement stage, with lower indices in the seedling and tuber formation stages. Thus, regulated deficit irrigation increased water use efficiency at the seedling and tuber formation stages while stabilizing yield. By comparison, the decrease in output caused by regulated deficit irrigation was from 28.30–44.32% in the starch accumulation stage and from 20.13–27.92% in the tuber enlargement stage. *Martínez-Romero* et al.[19] found that a timely and moderate irrigation quota deficit improved potato yield, potato commodity rate, and water use efficiency in an experiment with regulated deficit irrigation in Basque, Spain. In addition, *Zhang* and *Li*[20], *Li* et al.[21], and *Du* et al.[22] further developed the technology of regulated deficit drip irrigation under film for potato in arid areas by examining water use, growth, yield, and quality.

Various modifications of regulated deficit drip irrigation under film for potato in arid inland oases have been proposed in previous studies, which are highly instructive for the development of potato cultivation and water conservation. Current research primarily focuses on the effects of regulated deficit drip irrigation under film on potato yield and water use efficiency. However, less attention is paid to the effects on photosynthesis in potatoes, and reports on the effects on potato quality are rare. Soil and climatic conditions in different regions can affect the application of irrigation and cultivation technologies. Therefore, research to improve the cultivation system of regulated deficit drip irrigation under film in arid oasis areas is a long-term task. In this study, in the light loam soil of the Hexi Oasis, the effects of regulated deficit drip irrigation under film on potato growth, photosynthetic properties, quality, output, and water use efficiency were examined in a field experiment. The study aimed to improve the potato cultivation system in the Hexi Oasis by producing high yields, maintaining stable production, and increasing water use efficiency.

Materials And Methods

Experimental site description.

The experiment was conducted at the Yimin Irrigation Experimental Station (38°39'N, 100°43'E, approximately 1,970 m) of the Hongshui River Administrative Office, Minle County, Gansu Province, China, from March to September in 2017, 2018, and 2019. The area has a typical continental arid climate, with abundant sunshine and large differences between day and night temperatures, which are conditions conducive to photosynthesis, nutrient accumulation, and yield formation in crops. The average annual temperature is 6.0 °C. The accumulated temperature exceeding 0 °C is 3,500 °C, whereas the effective accumulated temperature over 10 °C is 2,985 °C. The average annual sunshine time is 3,000 hours, and the average frost-free period is 136 days. According to meteorological data from 2000 to 2018, the average annual rainfall in the area is 328 mm, and the evaporation is 1,900 mm. Soil in the experimental site is light loam with medium fertility and a pH of 7.22. The field water retention capacity of tilled soil is 24.0%, and the soil bulk density is 1.48 t/m^3. The 0 to 20 cm of topsoil contained 12.8 g/kg organic matter, 63.5 mg/kg alkali-hydrolyzable nitrogen, 13.1 mg/kg available phosphorus, and 192.7 mg/kg available potassium. The salinization effect was mild because of the deep source of groundwater. The rainfall and temperature for three potato seasons are shown in (Fig. 1). The total seasonal rainfall was 219.25 mm in 2017, 222.2 mm in 2018, and 305.13 mm in 2019. In 2017, 2018, and 2019, the highest precipitation was from May to September. In all years, the highest precipitation was from May to September.

Experimental design.

The potato variety 'Qingshu 168' was provided by the Qinghai Agricultural Science Research Institute of China Qinghai Agricultural Research Institute. In 2017, potatoes were sown on April 17 and harvested on September 27; in 2018, they were sown on April 11 and harvested on September 28; and in 2019, they were sown on April 14 and harvested on October 9. The row spacing was 40 cm, and the plant spacing was 20 cm (Fig. 2). A white plastic film (140 cm wide, 0.01 mm-thick; China Dongguan Shuotai Industrial Co., Ltd.) covered two rows of potatoes with a planting density of 77,000 plants/ha. Drip irrigation was applied under the film with the irrigation pipe placed between two rows. Each section covered 33.6 m2 (7 m × 4.8 m). There were two levels of water deficit: mild with soil moisture at 55–65% of field capacity and moderate with soil moisture at 45–55% of field capacity. The soil moisture with conventional irrigation (CK) was 65–75% of field capacity. Each level of deficit was applied in each of four growth stages of potato: seedling, tuber initiation, tuber bulking, and starch accumulation stages. Thus, there were eight total treatments: WD1: mild, seedling; WD2: mild, tuber initiation; WD3: mild, tuber bulking; WD4: mild, starch accumulation; WD5: moderate, seedling; WD6: moderate, tuber initiation; WD7: tuber bulking; WD8: starch accumulation (Table 1).

Table 1
Soil water content (% field capacity) in conventional irrigation and regulated deficit drip irrigation treatments during potato growth. The treatments were two levels of water deficit that occurred in each of four growth stages.

Treatment	Deficit	Seedling	Tuber initiation	Tuber bulking	Starch accumulation
WD1	Slight	55–65%	65–75%	65–75%	65–75%
WD2	Slight	65–75%	55–65%	65–75%	65–75%
WD3	Slight	65–75%	65–75%	55–65%	65–75%
WD4	Slight	65–75%	65–75%	65–75%	55–65%
WD5	Medium	45–55%	65–75%	65–75%	65–75%
WD6	Medium	65–75%	45–55%	65–75%	65–75%
WD7	Medium	65–75%	65–75%	45–55%	65–75%
WD8	Medium	65–75%	65–75%	65–75%	45–55%
CK	Conventional	65–75%	65–75%	65–75%	65–75%

Field management.

To ensure crop yield, the experimental section was tilled to 30 cm ten days before sowing. Weeds were cleared manually. Diammonium phosphate (18% nitrogen and 46% P_2O_5) at 400 kg/ha and western compound fertilizer (15% nitrogen, 15% P_2O_5, and 15% K_2O) at 750 kg/ha were applied as base fertilizers one time at sowing.

Measurements And Calculations

Potato growth indices.

After potatoes entered the mature stage, 20 potato plants were randomly selected from each section. Plant height was measured with a ruler that was accurate to 0.1 cm, and stem diameter was measured with vernier calipers that were accurate to 0.01 mm.

Physiological indices.

In each growth stage, the experimental variables were measured on the 5th day after the regulated deficit treatment. The central part of the 3rd or 4th unfolding leaf was selected for testing. At 10:30 AM, a LI-6400 portable photosynthesis system (LI-COR, USA) was used to measure the net photosynthetic rate (Pn), stomatal conductance (Gs), and transpiration rate (Tr). Ten plants were measured in each section. Three stable readings were obtained with each leaf. The average value was determined for each treatment.

Yield and tuber morphological properties.

After potatoes ripened, the potatoes in each section were harvested and measured. There were three plots in each experiment, and the average value of the three plots was taken for analysis in each experiment. In other words, the average value of three replicate plots was the output of each treatment. An electronic scale (accuracy to 0.01 g) was used to weigh the potatoes, and the yield was converted to kg/ha. In addition, 20 potato plants were harvested separately in each section, and the tubers were cut off and washed. The transverse and longitudinal diameters of the tubers were measured with vernier calipers that were accurate to 0.01 mm. The average value of each treatment was determined.

Water use efficiency and irrigation water use efficiency. Water use efficiency (WUE) and irrigation water use efficiency (IWUE) were calculated using the following formulas[48]:

$$WUE = Y/ETa$$

$$IWUE = Y/I$$

where WUE (kg/m^3) and IWUE (kg/m^3) are the water use efficiency and the irrigated water use efficiency, respectively, in all growth stages; Y (kg/ha) is the yield per unit area; ETa (m^3/ha) is the actual water consumption per unit area in all growth stages; and I (m^3/ha) is the irrigation amount per unit area in all growth stages.

Quality.

The Coomassie Brilliant Blue G-250 method was used to determine protein content, and anthrone colorimetry was used to determine total sugar content. The content of starch was determined by enzymatic hydrolysis, vitamin C by 2, 6-dichloroindophenol titration, potassium by the potassium tetraphenylborate gravimetric method, and calcium by the gravimetric titration method.

Statistical analyses.

Excel 2017 (Microsoft 365) was used to perform calculations, and Duncan's multiple comparison method in SPASS 19.0 (Stanford University) software was used to determine significant differences between means. Origin 8.0 (Origin lab) was used prepare the diagrams of average values. All analyses were performed using three-year averages.

Results And Analysis

Effects of regulated deficit drip irrigation under film on the growth indices and tuber characteristics of potato.

Irrigation with different levels of regulated deficit in different growth stages significantly affected the biological characteristics of potato (Table 2). Compared with that in CK, plant height in the treatments decreased, although the decrease in mild regulated deficit treatments (WD1, WD2, WD3, and WD4) was not significant ($P > 0.05$). In the moderate deficit treatments WD6 and WD7, plant height decreased significantly ($P < 0.05$). Stem diameter decreased in all treatments to various degrees but the smallest decrease was in WD1 and WD5 with the water deficit in the seedling stage. Compared with that in CK, the diameter decreased by 3.37% in WD1 and by 5.62% in WD5. However, when the deficit occurred in the tuber initiation and tuber bulking stages, the diameter decreased by 3.93–8.99% and by 6.74–10.64%, respectively, indicating that a water deficit in those two stages reduced potato stem growth.

Compared with CK, all treatments caused the leaf area index to decrease to varying degrees, ranging from 4.14–22.07%. The greatest decreases in leaf area index were in WD6 and WD8, with significant decreases of 11.72% and 22.07%, respectively. The leaf area index was least affected in WD5, with a decrease of only 4.14%. This result showed that mild water deficit at the seedling stage did not significantly affect leaf growth. By contrast, water deficit in the other stages hindered leaf growth. Both the longitudinal and transverse lengths of the potato tubers decreased, to different degrees. The greatest effect was in WD8, with significant decreases ranging from 11.51–14.28%. In WD1, WD2, WD5, and WD6, the decreases in both diameters were slight and not significant.

Table 2
Indices of potato growth in conventional irrigation (CK) and regulated deficit drip irrigation treatments in three years and averaged across years. Diameters are those of tubers.

Year	Treatment	Plant height	Stem diameter	Leaf area index	Longitudinal diameter	Cross diameter
		(cm)	(cm)		(mm)	(mm)
2017	CK	141.62a	1.74a	1.25a	83.89a	65.62ab
	WD1	139.55ab	1.69ab	1.19ab	82.55ab	65.74a
	WD2	137.54ab	1.62b	1.12bc	81.77ab	63.88ab
	WD3	139.39ab	1.58bc	1.07c	80.96ab	63.57ab
	WD4	140.85ab	1.48 cd	0.98d	80.06ab	61.34bc
	WD5	136.01ab	1.61bc	1.13b	82.03ab	64.12ab
	WD6	130.15b	1.53c	1.09bc	81.01ab	62.69ab
	WD7	135.36ab	1.36d	1.02 cd	78.58b	61.66b
	WD8	137.52ab	1.28e	0.72e	78.05bc	57.62c
2018	CK	144.3a	1.93a	1.76ab	83.31a	65.54a
	WD1	140.5ab	1.84ab	1.66bc	80.54ab	63.81ab
	WD2	136.3ab	1.86ab	1.51c	79.86ab	61.95ab
	WD3	134.6ab	1.88ab	1.61bc	78.55ab	59.47bc
	WD4	134b	1.85ab	1.84ab	75.14bc	57.18bc
	WD5	133bc	1.78b	1.85a	81.22ab	61.88ab
	WD6	126bc	1.74bc	1.76ab	80.07ab	60.35b
	WD7	136ab	1.81ab	1.69b	76.43b	58.74bc
	WD8	139.5ab	1.86ab	1.67bc	72.69bc	54.38c
2019	CK	146.40a	1.67a	1.34a	88.53a	68.87a
	WD1	145.10ab	1.63ab	1.29ab	87.17ab	68.09ab
	WD2	143.80ab	1.64ab	1.251b	86.59ab	67.91ab
	WD3	145.67ab	1.53b	1.24bc	87.41ab	64.38b
	WD4	145.70ab	1.60ab	1.18c	84.26ab	62.93bc
	WD5	140.37ab	1.64ab	1.19bc	87.04ab	67.44ab
	WD6	133.07bc	1.59ab	0.99de	85.59ab	66.39ab
	WD7	135.73b	1.60ab	1.23bc	82.76b	65.52ab
	WD8	139.30ab	1.45c	1.01d	75.54c	59.48c
Average	CK	144.11a	1.78a	1.45a	85.24a	66.68a
	WD1	141.72ab	1.72ab	1.38ab	83.42ab	65.88ab
	WD2	139.21ab	1.71ab	1.29b	82.74ab	64.58ab
	WD3	139.89ab	1.66b	1.31bc	82.31ab	62.47ab
	WD4	140.25ab	1.64bc	1.33 cd	79.82ab	60.48bc
	WD5	136.46ab	1.68ab	1.39bc	83.43ab	64.48ab
	WD6	129.74bc	1.62b	1.28d	82.22ab	63.14ab
	WD7	135.7b	1.59c	1.31c	79.26b	61.97b

Note: Different lowercase letters within a column for a year or the average indicate significant differences among treatments ($P < 0.05$). The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

WD8	138.77ab	1.53d	1.13e	75.43bc	57.16c

Note: Different lowercase letters within a column for a year or the average indicate significant differences among treatments (P< 0.05). The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

Potato Leaf Photosynthetic Characteristics

Net photosynthetic rate.

The net photosynthetic rate (Pn) of potato leaf from seedling to starch accumulation stage increased first and then decreased, showing a single-peak in CK and all treatments (Fig. 3). Mild regulated deficit treatments did not significantly affect the rate in the seedling stage. In the moderate deficit treatment WD5, the Pn decreased by 13.14% compared that with in CK, although the decrease was not significant. In the tuber initiation stage, the rate decreased significantly to 0.410 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in WD2 (mild deficit) and to 0.337 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in WD6 (moderate deficit), decreases of 19.28% (WD2) and 33.70% (WD6) compared with that in CK. The Pn was not significantly affected in the other treatments in this stage.

In the tuber bulking stage, the Pn decreased by 8.31% in WD3 (mild deficit) and by 29.37% in WD7 (moderate deficit), compared with that in CK. The compensation effect in WD2 after rehydration was greater than that in WD6, but neither rate was significantly different from that in CK. The Pn did not decrease from the tuber initiation stage to the tuber expansion stage, and the mean value in the bulking stage was between 0.323 and 0.463 $\mu mol \cdot m^{-2} \cdot s^{-1}$. In the starch accumulation stage, the absolute value of the Pn was lower than that at tuber initiation and expansion stages, with a mean value between 0.227 and 0.348 $\mu mol \cdot m^{-2} \cdot s^{-1}$. However, the Pn was significantly higher than that in the seedling stage. The Pn decreased by 15.12% in WD4 (mild deficit) and by 33.46% in WD8 (moderate deficit), compared with that in CK, indicating that a regulated deficit at the starch accumulation stage negatively affected the net photosynthetic rate.

Stomatal conductance.

Throughout the growth period, the stomatal conductance (Gs) increased successively from the seedling stage to the tuber initiation stage and then tuber bulking stage; however, the Gs decreased at the starch accumulation stage. There were differences in the range of decrease among the treatments (Fig. 4). The lowest Gs was in the seedling stage, ranging from 5.96 to 6.71 $mol.m^{-2}.s^{-1}$. In WD1 (mild deficit) and WD5 (moderate deficit), Gs decreased significantly by 7.29% and 11.09%, respectively, compared with that in CK. The Gs in the seedling stage was not affected in the other treatments. The Gs increased in the tuber initiation stage in all treatments except WD2 and WD6, with values increasing to between 12.68 and 14.70 mol $m^{-2}.s^{-1}$. The Gs in WD2 decreased by 13.70% and that in WD6 decreased by 14.83%. In the tuber bulking stage, Gs increased to the highest levels of the entire growth period, ranging from 14.73 to 17.00 mmol m − 2 s − 1, although it was lower in regulated deficit treatments than in CK. Compared with that in CK, the Gs decreased significantly in WD3 by 8.96% and in WD7 by 13.34%, which showed that regulated deficit in the tuber initiation and expansion stages did not favor stomatal opening. The Gs decreased significantly from the tuber bulking stage to the starch accumulation stage. With sufficient irrigation in this period, Gs was not significantly different from that in CK, whereas in WD4 (mild deficit) and WD8 (moderate deficit), it decreased significantly by 17.22% and 25.05%, respectively. This result demonstrated that regulated deficit during starch accumulation affected stomatal conductance.

Transpiration Rate.

In all treatments, the transpiration rate (Tr) first increased as growth progressed and then decreased, with a peak at the tuber expansion stage (Fig. 5). In the seedling stage, the Tr decreased by 13.01% in WD1 (mild deficit) and by 22.29% in WD5 (moderate deficit), compared with that in CK. In the tuber initiation stage, the Tr was 5.45 $\mu mol\ mol^{-1}\ s^{-1}$ in WD2 (mild deficit) and 4.84 $\mu mol\ mol^{-1}\ s^{-1}$ in WD6 (moderate deficit), decreasing by 10.68% in WD2 and by 20.63% in WD6 compared with that in CK.

In the tuber bulking stage, the Tr in WD1, WD2, WD5, and WD6 was not significantly different from that in CK after rehydration, showing evidence of a compensation effect. Compared with the tuber initiation stage, the Tr showed a large increase in all treatments. The Tr in WD7 (moderate deficit) decreased significantly by 10.28% compared with that in CK, whereas in WD3 (mild deficit), the Tr decreased by 5.25%, but it was not significantly different from that in CK. In the tuber initiation and tuber bulking stages, the Tr was higher than that in the seedling stage. In the starch accumulation stage, the Tr was 4.59 $\mu mol\ mol^{-1}\ s^{-1}$ in WD4 (mild deficit) and 4.53 $\mu mol\ mol^{-1}\ s^{-1}$ in WD8 (moderate deficit), decreasing by 15.58% in WD4 and by 16.64% in WD8 compared with that in CK, although the decreases were not significant. After rehydration, the Tr in WD3 and WD7 decreased, but it was not significantly different from that in CK.

Effect of regulated deficit drip irrigation under film on potato quality.

Regulated deficit treatment had different effects on the characteristics of potato quality (Table 3). Compared with that in CK, deficient irrigation in the seedling stage did not significantly affect total sugar content in potato. However, in the other growth stages, regulated deficit reduced sugar content by 6.55–44.64%, and the greatest reduction was in WD8 with the deficit at starch accumulation. With the deficit in the seedling stage, the protein content in WD5 (moderate deficit) was 2.18 mg·g^{-1}, an increase of 0.77% compared with that in CK. The protein contents decreased by 4.46–32.46% in the other treatments. The greatest reductions compared with the protein content in CK were in WD3 (18.31%), WD7 (21.85%), and WD8 (32.46%). With the deficit in the seedling stage, the starch content reached 36.06% in WD1 (mild deficit), a 3.34% increase compared with that in CK. In the other mild deficit treatments, although the starch content decreased, it was not significantly different from that in CK. In the moderate deficit treatments, the starch content decreased significantly by 10.66% in WD6, by 20.41% in WD7, and by 27.55% in WD8. With the deficit in the seedling stage, vitamin C and calcium contents decreased significantly by 9.21% in WD1 (mild deficit), compared with the contents in CK. However, the vitamin C content increased in the other mild and moderate deficit treatments, with the values increasing by 11.55–55.35% compared with that in CK. In addition, the vitamin C content tended to increase with the delay in deficit treatment, and the greatest increase was in WD8, with the content increasing significantly by 55.35% compared with that in CK.

Table 3
Indices of potato quality at harvest in conventional irrigation (CK) and regulated deficit drip irrigation treatments in three years and averaged across years.

Year	Treatment	Total sugar (%)	Protein ($mg \cdot g^{-1}$)	Starch (%)	Vitamin C ($mg \cdot 100\ g^{-1}$)
2017	CK	0.62a	2.31b	41.42ab	15.77de
	WD1	0.59ab	2.29bc	43.01a	14.26e
	WD2	0.54bc	2.14bc	40.95ab	17.02d
	WD3	0.43de	1.88c	38.36bc	18.53 cd
	WD4	0.48 cd	2.17bc	37.79bc	20.15bc
	WD5	0.57b	2.54a	38.54b	19.07c
	WD6	0.51c	2.27bc	36.05bc	21.53b
	WD7	0.44d	1.72d	30.26c	21.97ab
	WD8	0.36e	1.54e	27.93 cd	23.49a
2018	CK	0.32b	1.93ab	19.33ab	12.14e
	WD1	0.37a	1.99a	19.4a	11.57ef
	WD2	0.22d	1.9ab	18.92ab	13.35d
	WD3	0.31bc	1.68bc	18.18bc	14.05 cd
	WD4	0.3c	1.91ab	19.02ab	14.92c
	WD5	0.29 cd	1.59c	18.37b	13.31de
	WD6	0.21de	1.46d	18.15bc	16.97b
	WD7	0.3c	1.71b	19.3ab	15.63bc
	WD8	0.17e	1.38e	17.5bc	19.38a
2019	CK	0.68a	2.29ab	42.68ab	15.01e
	WD1	0.68a	2.26b	44.39a	13.35f
	WD2	0.59b	2.16bc	41.87ab	16.84d
	WD3	0.48c	1.82c	39.79bc	18.41 cd
	WD4	0.47 cd	2.1bc	38.91bc	19.79bc
	WD5	0.64ab	2.48a	39.87b	18.97c
	WD6	0.56bc	2.2bc	37.69bc	21.06b
	WD7	0.48c	1.69 cd	32.01c	21.72ab
	WD8	0.38d	1.51d	29.17d	23.05a
Average	CK	0.56ab	2.17ab	34.89ab	14.05d
	WD1	0.58a	2.17ab	36.06a	12.76e
	WD2	0.47c	2.07ab	34.22ab	15.67 cd
	WD3	0.42d	1.77c	32.59bc	16.95 cd

Note: Different lowercase letters within a column for a year or the average indicate significant differences among treatments ($P < 0.05$). The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

	WD4	0.41de	2.03ab	32.28bc	18.17bc
	WD5	0.52b	2.18a	32.7b	17.08c
	WD6	0.44 cd	1.95b	31.17bc	19.69b
	WD7	0.42de	1.69 cd	27.77c	19.69bc
	WD8	0.31e	1.46d	25.28 cd	21.83a

Note: Different lowercase letters within a column for a year or the average indicate significant differences among treatments ($P < 0.05$). The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

Tuber yield and its components.

Regulated deficit in all growth stages significantly affected water consumption, yield, water use efficiency, and irrigation water use efficiency (Table 4). Water deficit in all growth stages significantly decreased water consumption by potato. Compared with 5,837.20 m^3 ha^{-1} in CK, water consumption decreased to 4,977.10 m^3 ha^{-1} in WD3, 4,952.03 m^3 ha^{-1} in WD5, 4,769.13 m^3 ha^{-1} in WD6, and 4,723.63 m^3 ha^{-1} in WD8, which were decreases of 14.73% (WD3), 15.16% (WD5), 18.30% (WD6), and 19.08% (WD8) compared with that in CK. In WD2 (mild deficit) and WD7 (moderate deficit), the decrease was slight. The regulated deficit treatments caused decreases in potato yield to different degrees. The water deficit in the seedling stage in WD1 caused the smallest decrease in yield to 43,961.91 kg ha^{-1}, a decrease of only 4.50% compared with that in CK. Water deficit in the tuber bulking stage in WD7 (moderate deficit) caused the greatest decrease in yield to 33,834.86 kg ha^{-1}, a decrease of 26.50% compared with that in CK. The decreases in yield under moderate regulated deficit treatment were greater than those under mild treatment, indicating that the larger decrease in irrigation had a greater negative effect on potato yield. Affected by yield, the output values showed similar trends by treatment. Output value per cubic water was the lowest in WD7 (moderate deficit), decreasing by 15.56% compared with that in CK. By contrast, the values increased in the other treatments by 0.07–50.93%, compared with that in CK.

Table 4
Potato yield, output value, and water use in conventional irrigation (CK) and regulated water deficit drip irrigation treatments in three years and averaged across years.

Years	Treatment	Rainfall	Irrigation volume	Water consumption	Yield	Output value	Unilateral aquatic product value	Water use efficiency	Irrigation water use efficiency
		($m^3 \cdot ha^{-1}$)	($m^3 \cdot ha^{-1}$)	($m^3 \cdot ha^{-1}$)	($kg \cdot ha^{-1}$)	($yuan \cdot ha^{-1}$)	($yuan \cdot m^{-3}$)	($kg \cdot m^{-3}$)	($kg \cdot m^{-3}$)
2017	CK	3017.5	2574.50	6462.20	58160.00	75608.03	29.37	9.00	22.59
	WD1	3017.5	1829.40	4883.70	50400.20	65520.25	35.81	10.32	27.55
	WD2	3017.5	2074.50	5096.00	45099.90	58629.90	28.26	8.85	21.74
	WD3	3017.5	1741.70	4761.50	40234.40	52304.71	30.03	8.45	23.10
	WD4	3017.5	1895.70	4912.10	49858.30	64815.73	34.19	10.15	26.30
	WD5	3017.5	1479.60	4495.20	48548.10	63112.49	42.65	10.80	32.81
	WD6	3017.5	1884.90	4904.00	42223.50	54890.52	29.12	8.61	22.40
	WD7	3017.5	2484.30	5502.70	35327.20	45925.33	18.49	6.42	14.22
	WD8	3017.5	1371.30	3682.30	38590.70	50167.92	36.58	10.48	28.14
2018	CK	1974	2805.24	5520.10	35317.71	45913.02	16.37	6.39	12.59
	WD1	1974	2540.72	4859.10	31913.54	41487.60	16.33	6.57	12.56
	WD2	1974	2530.99	4465.80	34852.08	45307.70	17.90	7.80	13.77
	WD3	1974	2753.43	4807.40	29747.92	38672.30	14.05	6.18	10.80
	WD4	1974	2730.44	5252.72	33619.79	43705.73	16.01	6.40	12.31
	WD5	1974	2321.73	5010.40	32508.33	42260.83	18.20	6.49	14.00
	WD6	1974	2108.91	4110.80	32879.17	42742.92	20.27	7.99	15.59
	WD7	1974	2072.00	4227.90	28633.33	37223.33	17.96	6.77	13.82
	WD8	1974	2460.65	5224.00	34050.00	44265.00	17.99	6.52	13.84
2019	CK	3051.3	2337.70	5529.30	44621.97	58008.57	33.70	8.07	19.09
	WD1	3051.3	2128.90	5438.40	49572.00	64443.60	30.27	9.12	23.29
	WD2	3051.3	2042.90	5463.00	43098.02	56027.42	49.63	7.89	21.10
	WD3	3051.3	1807.80	5362.40	39309.81	51102.75	35.42	7.33	21.74
	WD4	3051.3	1972.10	5422.50	43308.67	56301.27	69.70	7.99	21.96
	WD5	3051.3	1695.30	5350.50	40364.17	52473.42	38.24	7.54	23.81
	WD6	3051.3	1793.80	5292.60	37281.21	48465.57	44.25	7.04	20.78
	WD7	3051.3	1983.30	5188.30	37544.06	48807.28	30.62	7.24	18.93
	WD8	3051.3	1521.50	5264.60	40158.12	52205.56	44.12	7.63	26.39
Average	CK	2680.93	2572.48	5837.20	46033.23	59843.21	26.48	7.82	18.09
	WD1	2680.93	2166.34	5060.40	43961.91	57150.48	27.47	8.67	21.13
	WD2	2680.93	2216.13	5008.27	41016.67	53321.67	31.93	8.18	18.87
	WD3	2680.93	2100.98	4977.10	36430.71	47359.92	26.50	7.32	18.55
	WD4	2680.93	2199.41	5195.77	42262.25	54940.91	39.97	8.18	20.19
	WD5	2680.93	1832.21	4952.03	40473.53	52615.58	33.03	8.28	23.54
	WD6	2680.93	1929.20	4769.13	37461.29	48699.67	31.21	7.88	19.59

Note: The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

	WD7	2680.93	2179.87	4972.97	33834.86	43985.31	22.36	6.81	15.66
	WD8	2680.93	1784.48	4723.63	37599.61	48879.49	32.90	8.21	22.79

Note: The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

Water use efficiency and irrigation water use efficiency.

With water deficit in the starch accumulation stage, it increased most significantly in WD4 by 13.49 yuan m^{-3}, an increase of 50.93% compared with that in CK. Water use efficiency was the highest in WD1 at 8.67 $kg \cdot m^{-3}$, followed by WD5, WD4, and WD8, representing increases of 10.87% (WD1), 5.84% (WD5), 4.60% (WD4), and 4.99% (WD8) compared with that in CK. By contrast, WUE decreased by 6.39% in WD3 and by 12.92% in WD7 (6.81 $kg \cdot m^{-3}$) compared with that in CK. The lowest IWUE was in WD7 at only 15.66 $kg \cdot m^{-3}$, a decrease of 13.45% compared with that in CK. By contrast, IWUE increased in the other treatments by 2.52–30.13%. The highest IWUE was in WD5 at 23.54 $kg \cdot m^{-3}$, followed by WD8 at 22.79 $kg \cdot m^{-3}$, increases of 30.13% and 25.98%, respectively, compared with that in CK.

Comprehensive evaluation of different irrigation deficit methods.

We calculated the correlation matrix of 11 beneficial evaluation indices of the regulated deficit irrigation methods in the Hexi Oasis (Tables 5 and 6). Feature analysis of the matrix showed that the first five major components (comprehensive indices) had an accumulated contribution of 99.57% to the evaluation equation. Thus, we established the comprehensive formulas based on the first five indices, namely, yield, WUE, IWUE, output value per cubic water, and output value:

$$Y1 = 0.3465X1'+0.238X2'+0.0638X3'+0.0621X4'+0.3465X5'+0.3202X6'+0.3131X7'+0.3501X8'-0.341X9'+0.3611X10'-0.3542X11'=0.00007X1 + 0.27026X2 + 0.01084X3 + 0.00813X4 + 0.00005X5 + 3.04111X6 + 0.99172X7 + 0.07054X8 - 0.10740X9 + 0.00246X10 - 0.02884X11 + 22.38355$$

$$Y2 = 0.0717X1'+0.362X2'+0.6094X3'+0.61X4'+0.0717X5'-0.2455X6'+0.0025X7'-0.1024X8'+0.2X9'-0.0627X10'+0.0229X11'=0.00001X1 + 0.41107X2 + 0.10355X3 + 0.07989X4 + 0.00001X5 - 2.33164X6 + 0.00792X7 - 0.02063X8 + 0.06299X9 - 0.00043X10 + 0.00186X11 + 7.765402$$

$$Y3 = -0.2953X1'-0.4626X2'+0.2021X3'+0.2009X4'-0.2953X5'+0.2318X6'+0.6051X7'+0.2362X8'+0.2301X9'+0.0246X10'-0.0354X11'=-0.00006X1 - 0.52530X2 + 0.03434X3 + 0.02631X4 - 0.00004X5 + 2.20152X6 + 1.91661X7 + 0.04759X8 + 0.07247X9 + 0.00017X10 - 0.00288X11 + 1.32316$$

$$Y4 = 0.2945X1'+0.1369X2'-0.0846X3'-0.0831X4'+0.2945X5'+0.4041X6'+0.3817X7'-0.3322X8'+0.2156X9'-0.3331X10'+0.4657X11'=0.000006X1 + 0.15546X2 - 0.01437X3 - 0.01088X4 + 0.00004X5 + 3.83795X6 + 1.20901X7 - 0.06693X8 + 0.06790X9 - 0.00227X10 + 0.03792X11 + 1.515379$$

$$Y5 = 0.3889X1'-0.6895X2'+0.144X3'+0.1437X4'+0.3889X5'-0.2128X6'-0.1677X7'+0.1894X8'-0.1358X9'-0.1427X10'+0.1806X11'=0.00008X1 - 0.78296X2 + 0.02447X3 + 0.01882X4 + 0.00006X5 - 2.02107X6 - 0.53118X7 + 0.03816X8 - 0.04277X9 - 0.00097X10 + 0.01471X11 - 3.484436$$

According to the principal component analysis, the principal component values of deficit irrigation at different growth stages were ranked as WD1 > CK > WD5 > WD4 > WD2 > WD3 > WD6 > WD8 > WD7. In conclusion, WD1 was optimal in the valuation.

Table 5
Indices used to evaluate potato in conventional irrigation (CK) and regulated deficit drip irrigation treatments.

Treatment	Yield	Water use efficiency	Irrigation water use efficiency	Output value	Unilateral aquatic product value	Total sugar	Protein	Starch	Vitamin C	Potassium	Calcium
	(kg·ha^{-1})	(kg·m^{-3})	(kg·m^{-3})	(yuan·ha^{-1})	(yuan·m^{-3})	(%)	(mg·g^{-1})	(%)	(mg·100 g^{-1})	(mg·kg^{-1})	(mg·kg^{-1})
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
CK	46033.23	7.82	18.09	59843.21	26.48	0.58	2.17	36.06	12.76	5065.17	93.12
WD1	43961.91	8.67	21.13	57150.48	27.47	0.47	2.07	34.22	15.67	5106.18	87.26
WD2	41016.67	8.18	18.87	53321.67	31.93	0.42	1.77	32.59	16.95	5021.78	94.92
WD3	36430.71	7.32	18.55	47359.92	26.50	0.41	2.03	32.28	18.17	4968.96	96.24
WD4	42262.25	8.18	20.19	54940.91	39.97	0.52	2.18	32.7	17.08	4900.08	102.9
WD5	40473.53	8.28	23.54	52615.58	33.03	0.44	1.95	31.17	19.69	5016.32	95.12
WD6	37461.29	7.88	19.59	48699.67	31.21	0.42	1.69	27.77	19.69	4833.46	109.7
WD7	33834.86	6.81	15.66	43985.31	22.36	0.31	1.46	25.28	21.83	4695.38	123.29
WD8	37599.61	8.21	22.79	48879.49	32.90	0.58	2.17	36.06	12.76	4728.83	118.35

Note: The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

Table 6
Comprehensive index values and evaluation coefficients of potato in conventional irrigation (CK) and regulated deficit drip irrigation treatments.

Treatment	Y_1	Y_2	Y_3	Y_4	Y_5	Overall rating
CK	2.90995	−1.28064	−0.48612	0.60484	0.62713	1.60239
WD1	3.60267	−0.76356	−0.93734	0.01499	−0.42728	2.09771
WD2	1.18469	−0.01058	0.46858	−0.57993	0.14227	0.77424
WD3	−0.78786	−0.89969	0.00027	−1.43324	−0.04555	−0.77183
WD4	0.44446	3.01387	0.15027	−0.02647	0.73174	1.00346
WD5	1.55440	0.63227	0.86751	0.42978	−0.80347	1.20040
WD6	−1.27528	−0.17980	1.17898	0.37273	−0.07906	−0.78804
WD7	−4.14625	−2.19086	0.00953	0.43179	0.26601	−3.16771
WD8	−3.48678	1.67900	−1.25170	0.18551	−0.41179	−1.95061

Note: The positive and negative values in the table indicate their position only relative to the average. The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

Discussion

Regulated deficit irrigation abides by crop water-demand laws in each growth stage to induce water stress in different degrees, leading crop growth conditions to change so as to stabilize yield, save water, and adjust quality[23–26]. *Deng* et al.[27]found that regulated deficit drip irrigation under film changes the hydrothermal environment of farmland soil, further affecting crop growth.In this study, the amount of water irrigated in drip irrigation affected the indices of plant height, stem diameter, tuber transverse diameter, tuber longitudinal diameter, and leaf area of potato. These indices all tended to decrease, and regulated deficit irrigation had a greater effect in the late growth stage than in the early growth stage. The explanation might be that the root system in the seedling stage was small and required less water. In addition, slight regulated deficit had a mild influence on potato growth. By contrast, the late growth stage is essential for nutrient production in potato and requires more water. Water stress inhibited the natural growth and development of potato, hindering tuber formation.

Photosynthesis is highly sensitive to water stress. Water deficit may hinder CO_2 from entering leaves or affect the CO_2 carboxylation ability of mesophyll cells, thereby inhibiting photosynthesis[28–30]. According to *Reddy* et al.[31], water deficit can close the stomata in crop leaves; further reducing Gs and then Pn. In this study, in WD2 and WD6 and WD4 and WD8, the Pn decreased significantly in the tuber formation and starch accumulation stages. The decrease increased as the regulated deficit amount increased. *Chai* et al.[32] found that as the regulated deficit degree gradually increases, the Gs decreases significantly, thereby lowering the Pn. This result is consistent with the conclusion of this study. A similar conclusion was also reached in a study of regulated deficit drip irrigation under film with Isatis indigotica in an oasis environment[33]. The result in this study might be explained by water deficit inhibiting the aboveground growth of potato, and as a result, both leaf area index and the transpiration rate decreased. In addition, with water deficit in soil, the partial or complete closure of stomata decreases the transpiration rate, thus leading to an overall decrease in net photosynthetic rate[34–36]. In this study, moderate water deficit led to a greater decrease in Gs, likely because the increase in water stress increased stomatal closure, which further reduced the transpiration rate.

In this study, regulated deficit irrigation decreased potato yield and output values to different extents, ranging from 4.50–26.50%, which reduced production benefits. *Enciso* et al.[37] found that moderate regulated deficit in the seedling and the mature stages can increase crop yields and economic benefits. The result is in contrast to those in this study, which may because of differences in regulated deficit amount, test conditions, and potato varieties. In this experiment, compared with the output in CK, mild (WD3) and moderate (WD7) regulated deficits in the tuber enlargement stage significantly decreased the output by 20.86% and 26.50%, respectively. Consistent with this study, *Mustafa Ünlü* et al.[38], *Hassan* et al.[39], *Nagaz* et al.[40], and *Im* et al.[41] also found that water deficit at the tuber enlargement stage reduces production by approximately 20% compared with that with a sufficient water supply. As tubers begin to divide and expand in the tuber enlargement stage, potatoes transition from the reproductive stage to the vegetative growth stage. Water deficit decreases potato transpiration and photosynthesis, and compensation and recovery with rehydration are difficult. As a result, yield is severely reduced, decreasing economic benefits. Compared with the output of potatoes in CK, the output with mild regulated deficit in the seedling stage (WD1) decreased by only 4.50%, likely because root activity and absorption were low in the early growth stage. During the seedling stage, the water deficit likely promoted deep root penetration. With the irrigation deficit in the seedling stage, potato had a longer time to recover following the subsequent rehydration, and thus, water deficit had little effect on yield and economic benefits.

The highest WUE was in WD1, followed by that in WD5, WD4, and WD8, which increased by 10.87% (WD1), 5.84% (WD5), 4.60% (WD4), and 4.99% (WD8) compared with that in CK. The lowest WUE was in WD7 at only 6.81 $kg\cdot m^{-3}$, which was a decrease of 12.92% compared with that in CK. The highest IWUE was in WD5, reaching 23.54 $kg\cdot m^{-3}$, followed by that in WD8 (22.79 $kg\cdot m^{-3}$), which increased by 30.13% and 25.98%, respectively, compared with that in CK. The lowest IWUE was in WD7 (15.66 $kg\cdot m^{-3}$), which was a decrease of 13.45% compared with that in CK. The IWUE of the other treatments increased to different degrees, with an increases ranging from 2.52–30.13%. Therefore, moderate water deficit at the seedling and starch accumulation stages helped to improve the WUE and IWUE of potato, consistent with the findings of *Li* et al.[42] and *Liuyang* et al.[43]. However, unreasonable water deficit can cause significant yield reduction and thus reduce output and benefits.

While maintaining yield, timely and moderate water deficit can increase WUE and the quality of products[44–46]. In this study, moderate regulated deficit increased protein, starch, vitamin C, potassium, and calcium contents in potato. Mild regulated deficit in the seedling stage increased starch and potassium contents without reducing total sugar content. By comparison, moderate regulated deficit increased protein, vitamin C, and calcium contents. Regulated deficit irrigation in the other growth stages did not lead to the accumulation of total sugar, protein, starch, and potassium. *Guizani* et al.[47] found that water deficit in the seedling stage can improve potato quality, which is consistent with the conclusion in this study. However, *Zhang*[48] found that regulated deficit has no significant effect on starch content during potato growth stages. However, the results in this study showed that regulated deficit significantly reduced potato starch content. The inconsistency between studies might be due to differences in factors such as soil type and potato variety. Because there are few comprehensive reports on how the amount of regulated deficit and the stages in which the deficit occurs affect potato yield and quality, additional experiments are needed to explore the effects of regulated deficit irrigation on yield and quality with different varieties and in different regions.

Conclusions

1. Regulated deficit irrigation in different growth stages inhibited potato growth and development and reduced the biological indices of plant height, stem diameter, and tuber longitudinal and transverse diameters to various degrees. However, mild regulated deficit irrigation in the early growth stage had no significant effects.
2. Regulated deficit irrigation in different growth stages led to decreases in the net photosynthetic rate, stomatal conductance, and transpiration rate of potato leaves. The extent of decrease was related to the degree of water deficit and the stage of growth. Specifically, water deficit in the tuber formation and starch accumulation stages caused the greatest reductions in the net photosynthetic rate, stomatal conductance, and transpiration rate of potato leaves. At the higher degree of deficit, the decrease was greater.
3. Mild deficit irrigation in the seedling and starch accumulation stages increased the WUE and IWUE while stabilizing production. Both mild and moderate deficit irrigation in the tuber formation and enlargement stages reduced potato yield and WUE.
4. Regulated deficit irrigation improved potato quality. With the higher degree of deficit, the vitamin C content increased and the total sugar, protein, and starch contents decreased. Specifically, regulated deficit in the seedling stage produced the highest quality potatoes.

Indices such as yield, water production efficiency, output value, and fruit quality were all considered. A principal component analysis was used to conduct a comprehensive evaluation. The analysis showed that the best water regulation scheme was mild water stress in the seedling stage. Therefore, the relative water content in soil should be maintained between 55% and 65% in the seedling stage, whereas in the other growth stages, it should range from 65–75%. The irrigation method proposed in this study can simultaneously stabilize output and maintain good quality, which is significant for yield improvement, water conservation, quality adjustment, and industrialization of potatoes cultivated in the Hexi Corridor Oasis Irrigation Area.

Declarations

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Author contributions

FQ.L., HJ.Z., and HL.D conceived and designed the experiments. FQ.L., and YC.W. performed the experiments. FQ.L., XT.C., X.L and LT.L. analyzed the data. FQ.L., HJ.Z., and HL.D wrote and revised the paper. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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Figures

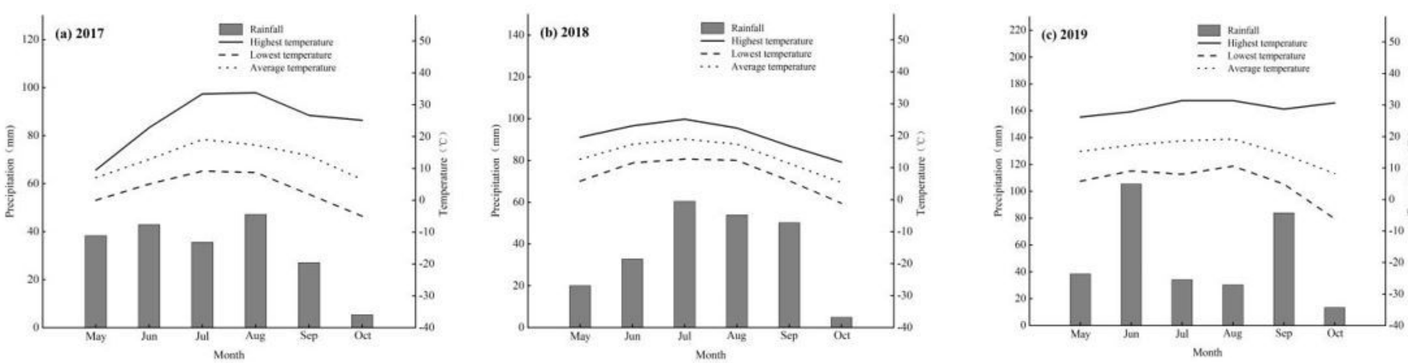

Figure 1

Rainfall and temperature in three potato seasons (2017, 2018, 2019) at the Yimin Irrigation Experimental Station, Hongshui River Administrative Office, Minle County, Gansu Province, China.

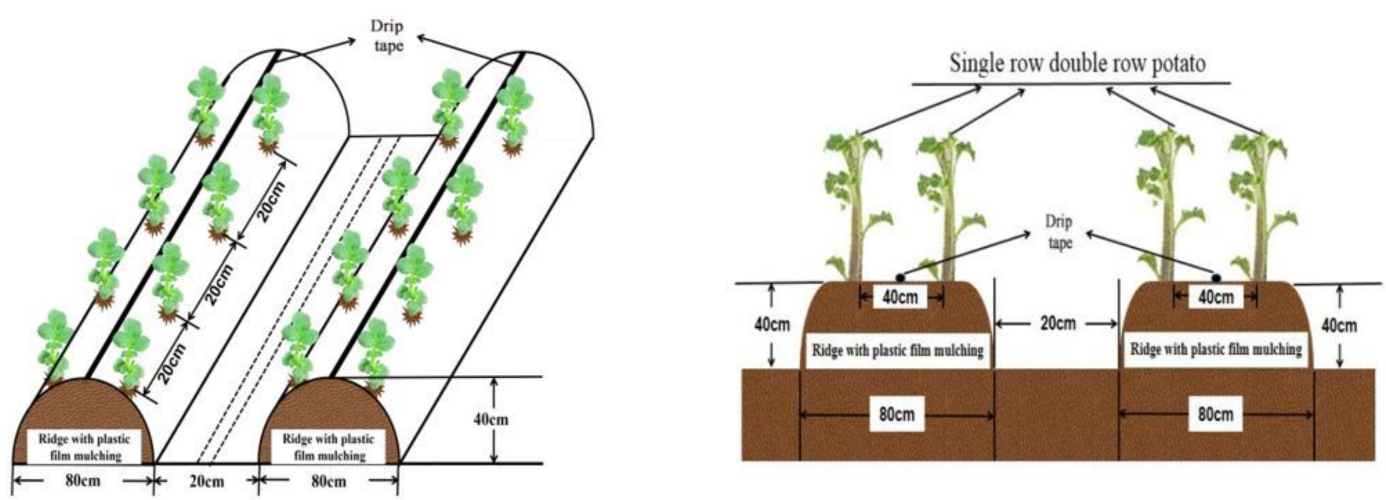

Figure 2

Cultivation of potatoes with regulated deficit drip irrigation on ridges under plastic film mulching.

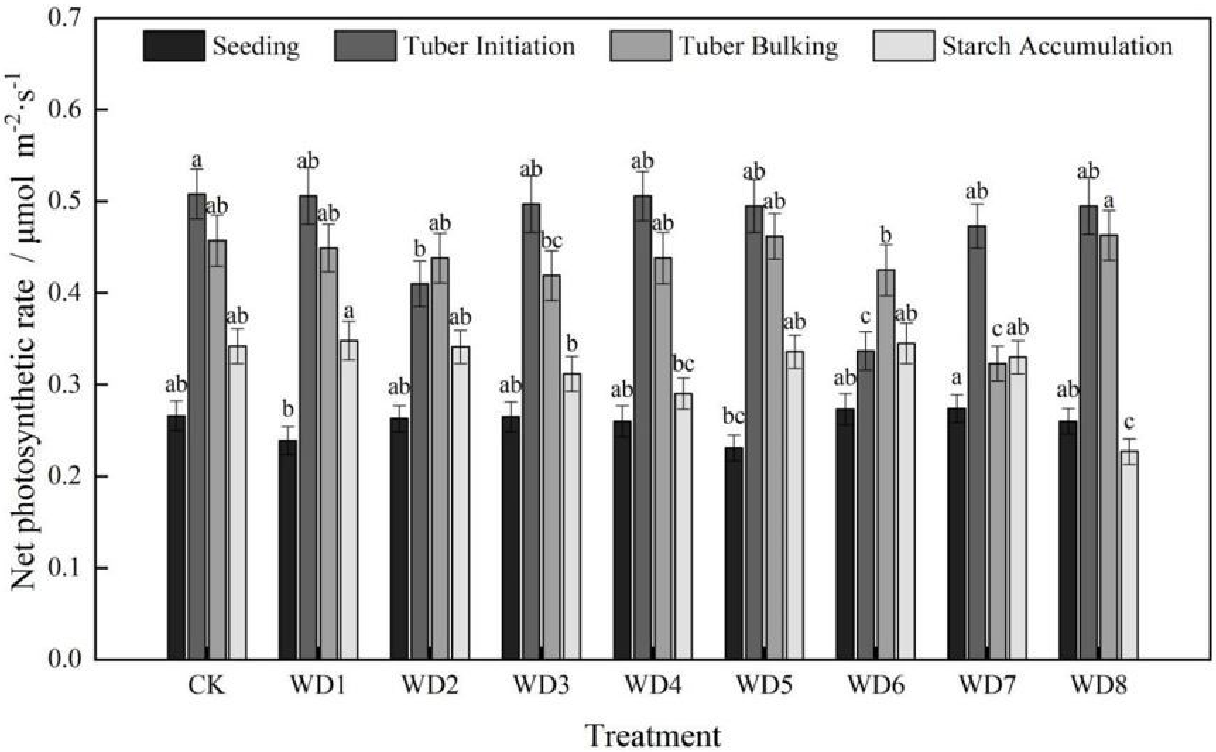

Figure 3

Effect of regulated deficit drip irrigation under film on net photosynthetic rate (μmol m−2 s−1) of potato leaf. The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

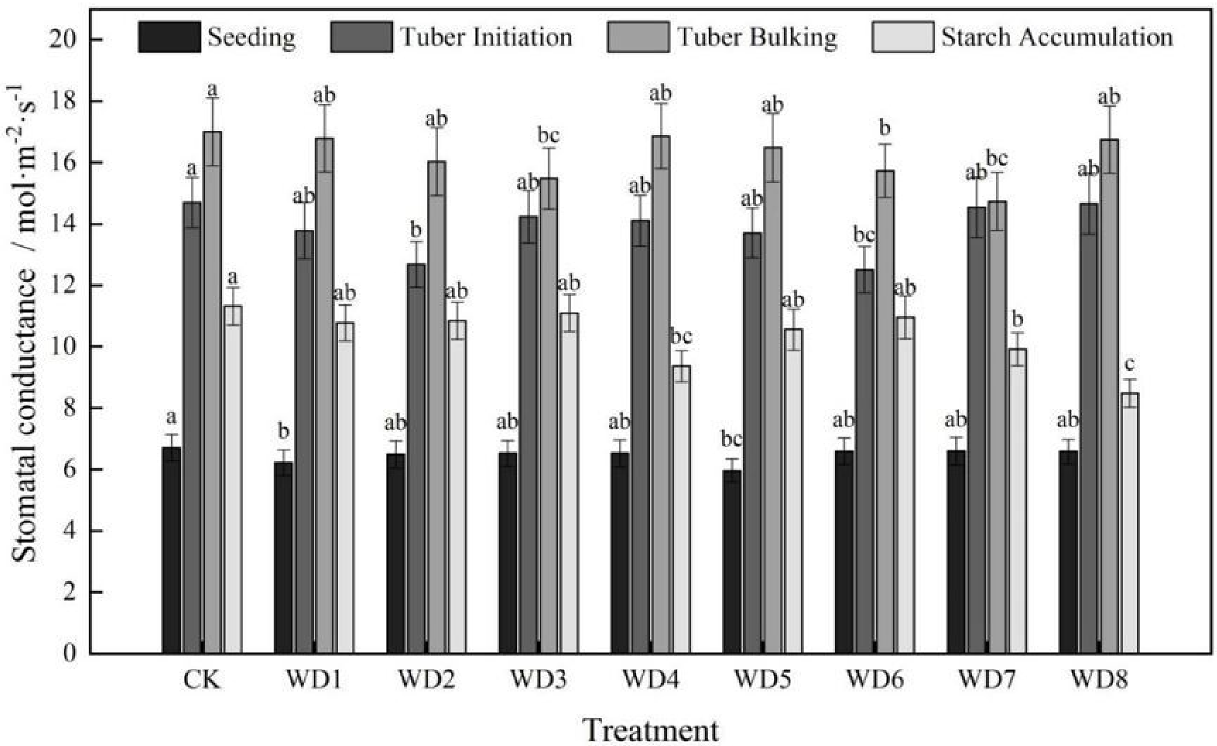

Figure 4

Effect of regulated deficit drip irrigation under film on stomatal conductance (mol m−2 s−1) of potato leaf. The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).

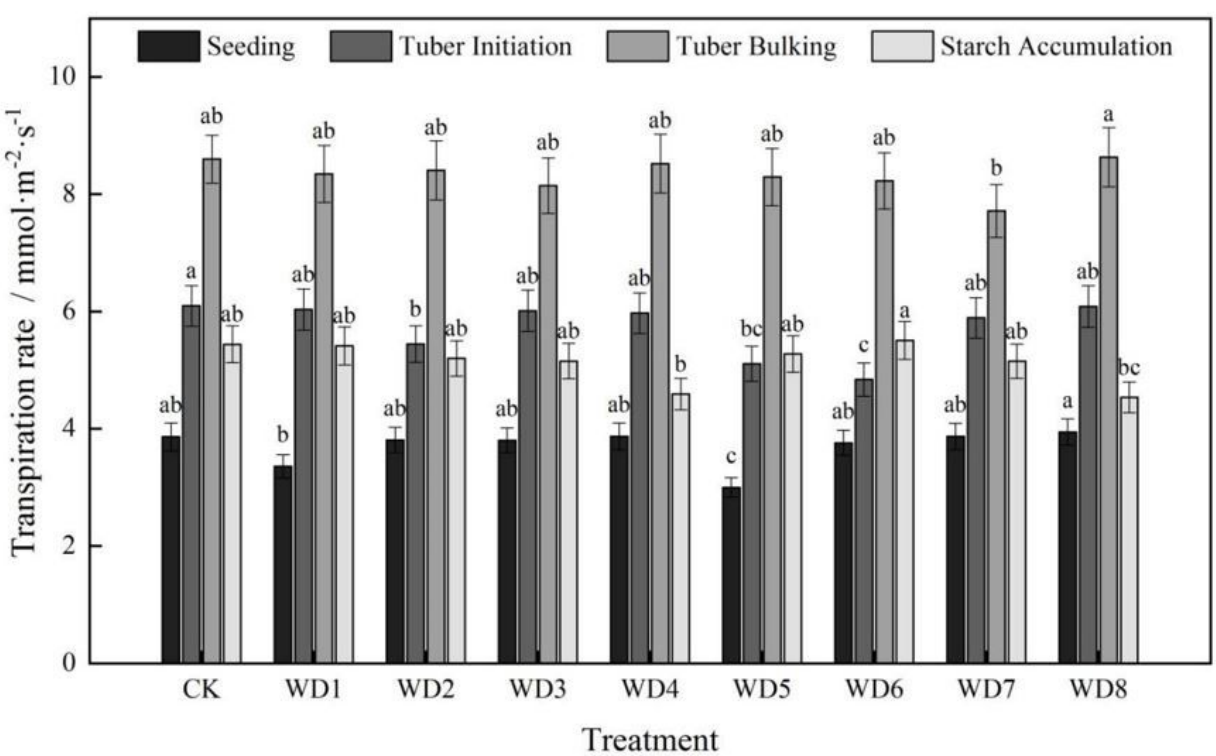

Figure 5

Effect of regulated deficit drip irrigation under film on transpiration rate (mmol m^{-2} s^{-1}) of potato leaf. The irrigation treatments were conventional irrigation (CK) and mild or moderate water deficit during each of four stages of potato growth. Mild deficit was in treatments WD1 (seedling), WD2 (tuber initiation), WD3 (tuber bulking), and WD4 (starch accumulation); moderate deficit was in treatments WD5 (seedling), WD6 (tuber initiation), WD7 (tuber bulking), and WD8 (starch accumulation).