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Research Article

Response Mechanism of Cotton Growth to Water and Nutrients under Drip Irrigation with Plastic Mulch in Southern Xinjiang

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The effects of water and nutrient control measures on the cotton plant height, stem diameter, biomass, seed yield, and soil moisture under an irrigated plastic mulch production system were studied. Using field experiments in the 2018 cotton-growing season, 6 fertilization treatments (30-10.5-4.5 (N-P_2O_5-K_2O), 24-8.4-3.6 (N-P_2O_5-K_2O), 20-7-3 (N-P_2O_5-K_2O), 16-5.6-2.4 (N-P_2O_5-K_2O), 10-3.5-1.5 (N-P_2O_5-K_2O), and 0-0-0 (N-P_2O_5-K_2O) kg/mu) and 6 deficit irrigation treatments (40% PET, 60% PET, and 80% PET) were established at the cotton budding and flowering stages. Analysis of variance (ANOVA) ($P < 0.05$) was used to evaluate the significant differences among the treatments. The results showed that the effects of the water and nutrient control measures were obvious. The irrigation water use efficiency (IWUE) was the highest under the 80% deficit irrigation (T7) treatment at the flowering stage (2.62 kg/m^3). Increases in cotton plant height and stem diameter were promoted by mild or moderate deficit irrigation at the flowering stage, but normal growth and development were affected by severe deficit irrigation at any growth stage. The growth indexes of cotton increased with increasing fertilization, but significant differences between each fertilization gradient were not obvious. At the same time, excessive fertilization not only had a positive effect on the LAI (leaf area index) and yield but also caused fertilizer waste and unnecessary cotton growth. The cotton seed yield and single boll yield reached their highest values (566 kg/mu) under the 1.2 times fertilizer treatment (T9), but the 0.8 times fertilizer treatment had the highest IWUE among the nutrient control treatments (1.91 kg/m^3). Therefore, it is suggested that deficit irrigation at 60~80% of the potential evapotranspiration (PET) at the flowering stage and 16-5.6-2.4 (N-P_2O_5-K_2O) fertilizer be applied as an optimal water and nutrient management strategy to maximize the seed cotton yield, IWUE, and overall growth and development of cotton.

1. Introduction

Xinjiang is the most important high-quality commodity cotton production base in China. Cotton production is completely dependent on irrigation. At present, the shortage of irrigation water resources restricts the comprehensive improvement of cotton productivity [1]. Water-deficit irrigation practices are inevitable for the sustainable development of Xinjiang's agricultural economy [2–4]. Saline-alkali land is widely distributed in Xinjiang, accounting for approximately 32% of the total area of cultivated land [5, 6]. Due to soil salinization and secondary salinization, the average annual loss of grain is 2-2.5 × 10^9 kg and of cotton is 5 × 10^8 kg [7]. In addition, due to irrational irrigation, the increase in the groundwater level and phreatic water evaporation intensify the occurrence of secondary salinization of soil [8]. Therefore, it is urgent that saline-alkali land be managed appropriately to ensure the sustainable development of land resources. Second, there is scarce rainfall and a lack of water resources in Xinjiang, and rational utilization of water resources to increase crop water and fertilizer use efficiencies are necessary. Agriculture in Xinjiang requires irrigation. To solve water shortages, we must achieve agricultural water savings to promote the healthy development of the ecological environment.

Drip irrigation under plastic film mulch has been widely used in arid or semiarid regions, such as the Tarim River Basin in the Xinjiang Uygur Autonomous Region, over the past two decades [9–11], because it incorporates the advantages of plastic film mulch and drip irrigation. In this irrigation system, the soil is covered by a plastic film to decrease evaporation and eliminate the energy exchange between the atmosphere and the soil at the same time [12]. Additionally, this method prevents soil salinization to some degree [13, 14]. Drip irrigation under plastic mulch can supply enough heat for sowing in the frigid spring (sowing season), especially for summer crops such as cotton, which are among the most important in Xinjiang's agricultural production. In addition, crops can acquire adequate water during the whole growing season despite high evaporative demands under this pattern [15, 16]. On the other hand, by avoiding water vapor waste and decreasing needless evaporation, plastic mulch drip irrigation has proven to be an economical way to change the soil-microclimate thermal environment and improve water use efficiency [17]. In this context, crop evapotranspiration changes under plastic mulch compared to that under bare soil.

The effects of water on crop growth are mainly reflected in the root system, plant height, stem diameter, leaf area index, and yield. The effects of water on crop physiology are mainly related to leaf water potential, enzyme activity, photosynthetic rate, transpiration rate, and stomatal conductance. A large number of studies have been conducted, generally focusing on the response of crops to water deficit. In terms of crop growth, Kozlowski and Winget [18] and Goldhamer and Fereres [19] showed that water stress can cause stems to shrink. Molz and Klepper [20] noted that the distribution of roots under moderate drought treatment (50%-60% of field capacity) increased significantly in the lower layer, the root biomass under the sufficient water supply treatment (80%-90% of field capacity) was mainly concentrated in the upper layer, and the total biomass of the root system was higher. Other researchers studying different crops [21–25] (cotton, pea, maize, winter wheat, etc.) showed that water deficit inhibits plant height growth, leaf area expansion, and dry matter accumulation, especially during the crop seedling stage, and that crop yield and composition are also affected because of the inhibited crop growth. In crop physiology, when moisture is insufficient, stomata may close and stomatal conductance may be reduced. On the one hand, transpiration loss through the stomata decreases. On the other hand, CO_2, which enters the blade through the stomata, decreases, resulting in a decrease in the photosynthetic rate. Generally, the transpiration rate decreases more than the photosynthesis rate. Under light-water stress, stomatal closure may increase water use efficiency. Farquhar and Sharkey [26] showed that the effect of water stress on the photosynthesis of crops was also affected by nonstomatal factors; that is, the activities of the photosynthetic organs of crops were decreased under water stress, the diffusivity and RuBP carboxylase activity of mesophyll were decreased, and the transport of electrons and phosphorylation were inhibited. The chlorophyll content decreased, resulting in a decline in the photosynthesis rate.

Similar to crop responses to water, crop responses to nutrients are mainly reflected in crop morphology, physiology, and biochemistry. Li et al. [27] stated that nitrogen fertilization was the dominant factor affecting the leaf area index and plant height in the early growth stage of spring wheat, and the combination of nitrogen and phosphorus could promote increases in plant height and leaf area of spring wheat. Bezborodov et al. [28], through cotton field experiments with drip irrigation, found that the amount of nitrogen application significantly affected the dry matter weight, nitrogen accumulation, and yield of hybrid cotton. When the amount of applied nitrogen was $450\,\mathrm{kg\,hm^{-2}}$, the frequency of nitrogen application had no significant effect on cotton growth. Cowell and Dawes [29] and Anderson and Nelson [30] studied the effects of nutrient stress on grain filling. The results showed that under nutrient stress, stress-related proteins increased significantly in the early and middle stages of grain filling, photosynthesis of grains decreased, respiration increased in the late stages, nitrogen metabolism of grains was significantly affected, and glutenin and embryo protein expression was delayed. Additionally, the synthesis of protein and fat decreased, resulting in insufficient grain filling and lower yield; the photosynthesis and respiration of rice leaves decreased significantly during grain filling; the expression of scavenging reactive oxygen species (ROS) proteins decreased; the expression of ROS-producing proteins and stress signal transduction proteins increased; the stress resistance of rice decreased; the accumulation of ROS in leaves increased; and the senescence of rice increased.

Therefore, the effects of different control measures (water and nutrient control measures) on soil-water movement and crop growth characteristics and the relationships between different control measures and soil-water availability, water consumption, crop yield, and composition were quantified. The objective of this study was to determine the optimal control measures under a drip irrigation-plastic mulch cotton production system. This study provides a reference for improving crop water and fertilizer utilization and crop yields. In addition, these findings also have important significance for guiding irrigation and fertilization, water conservation, and sustainable development of agriculture in arid saline-alkaline areas.

2. Materials and Methods

2.1. Experimental Site Description. The experiments were performed at the 31st Regiment of the Second Agricultural Division, which belongs to the Tarim Reclamation Area of the Second Agricultural Division of Xinjiang Production

Figure 1: The soil profile and experimental plot.

Table 1: Initial soil properties of experimental plots.

Layer (cm)	Clay (%)	Silt (%)	Bulk density ($g \cdot cm^{-3}$)	Wilting point ($cm^3 \cdot cm^{-3}$)	Field capacity ($cm^3 \cdot cm^{-3}$)	Saturated water content ($cm^3 \cdot cm^{-3}$)	Initial water content ($cm^3 \cdot cm^{-3}$)
0-10	4.16	46.29	1.59	0.047	0.207	0.278	0.152
10-20	4.16	46.29	1.44	0.047	0.228	0.360	0.150
20-30	3.8	52.65	1.67	0.045	0.161	0.215	0.183
30-40	3.8	52.65	1.58	0.045	0.175	0.247	0.217
40-50	3.8	47.83	1.68	0.046	0.172	0.235	0.216
50-60	3.8	47.83	1.47	0.047	0.230	0.357	0.282
60-80	4.2	46.99	1.70	0.047	0.122	0.246	0.205
80-100	4.1	46.35	1.66	0.047	0.082	0.246	0.225

and Construction Corps. The field site (86°56′E, 40°53′N) is located in the suburbs of Korla in southern Xinjiang, an autonomous region in northwestern China, which is at the foot of the Tianshan Mountain and the northeast edge of the Taklamakan Desert. This region has a typical continental arid desert climate in the north temperate zone and belongs to the Kaidu-Peacock River Basin (a tributary of the Tarim River). Large temperature fluctuations occur between day and night, and the area is also characterized by many sunshine hours, hot winters and cold summers, drought, and abundant light and heat. These climate conditions are particularly conducive to the growth of cotton. The annual and average precipitations during the cotton-growing season are approximately 34.1 mm and 30.6 mm, respectively. The mean annual potential evaporation (measured using an evaporation pan with an inside diameter equal to 20 cm) reaches 2417 mm, with 2082 mm in the cotton-growing season. In the same period, the evaporation is 50-80 times the precipitation, the annual average sunshine hours are approximately 2941.8, the annual average temperature is 10.9°C, and the annual accumulated temperature is 4218.3°C, while the frost-free period is 180-220 days. Because of the high evaporation, agriculture and forestry in the region rely entirely on irrigation. The soil textures of the experimental fields were silty loam (41.4% sand, 54.4% silt, and 4.2% clay) and sandy loam (50.2% sand, 46.0% silt, and 3.8% clay) (Figure 1). The soil bulk density of the experimental field varied from 1.44 $g\,cm^{-3}$ to 1.68 $g\,cm^{-3}$ in the 0-1 m soil profile, and the saturated water content of the soil was nearly 0.27. Before the experiment, the 0-1.0 m soil depth was divided into 5 layers, and the soil particle size distribution from each layer was analyzed by a laser particle size analyzer. The wilting point, field water capacity, and saturated water content were determined by high-speed centrifugation. The bulk density of each layer was measured by the ring knife method. The initial soil-water content was also determined before planting by the soil-drying method. The soil properties, including the saturated water content, field capacity, and wilting point in the experimental field, are listed in Table 1 [31–33]. The average depth of groundwater was approximately 1.5 m. The experimental cotton cultivar was Xinluzhong 78 (*Gossypium hirsutum* L.).

2.2. Experimental Design. The experiments were conducted during the 2018 cotton-growing seasons under drip irrigation with plastic film mulch. A planting setup of "one film, two pipes, and four rows of cotton" was used (Figure 2), that is, 10 cm + 10 cm + 10 cm + 46 cm + 10 cm + 10 cm + 10 cm, with row spacings of 10 cm, 10 cm, 10 cm, and 46 cm with the plastic film. The plant spacing with a row was 10 cm, and the planting density was 22 plants m^{-2}. A polyethylene resin-embedded thin-walled labyrinth drip tape with an inner diameter of 16 mm was used, with an emitter spacing of 30 cm and emitter discharge range of 2.4 L/h. In this pattern, two drip pipes were placed in the wide rows beneath the film mulch, so each basic planting unit was divided into three parts: a wide row, a narrow row, and bare soil (Figure 2). The plot size was 7 m ∗ 7 m. To reduce experimental error, 1 m protection lines were arranged between each plot and two replicates were set up in each experiment.

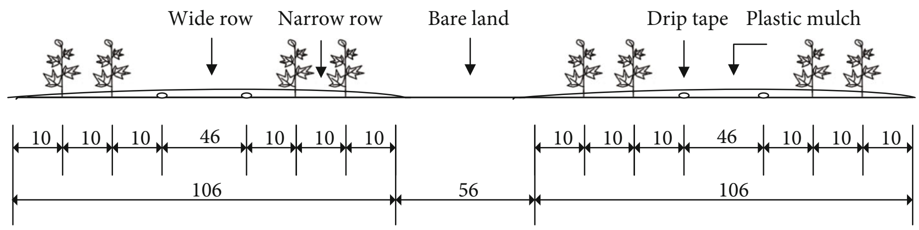

Figure 2: Drip irrigation pipe arrangement. Note: the arrows point to the soil moisture-monitoring points.

Table 2: Different irrigation treatments used in the experiment.

Treatment	Emergence	Budding	Flowering and boll development	Boll opening	Irrigation amount	Degree of deficit
T2	0	0.4 PET	PET	0	322.54	I
T3	0	0.6 PET	PET	0	298.21	II
T4	0	0.8 PET	PET	0	298.13	III
T5	0	PET	0.4 PET	0	338.28	I
T6	0	PET	0.6 PET	0	322.05	II
T7	0	PET	0.8 PET	0	321.99	III
T1	0	PET	PET	0	369.74	IV

Note: I: severe deficit; II: moderate deficit; III: mild deficit; IV: no deficit.

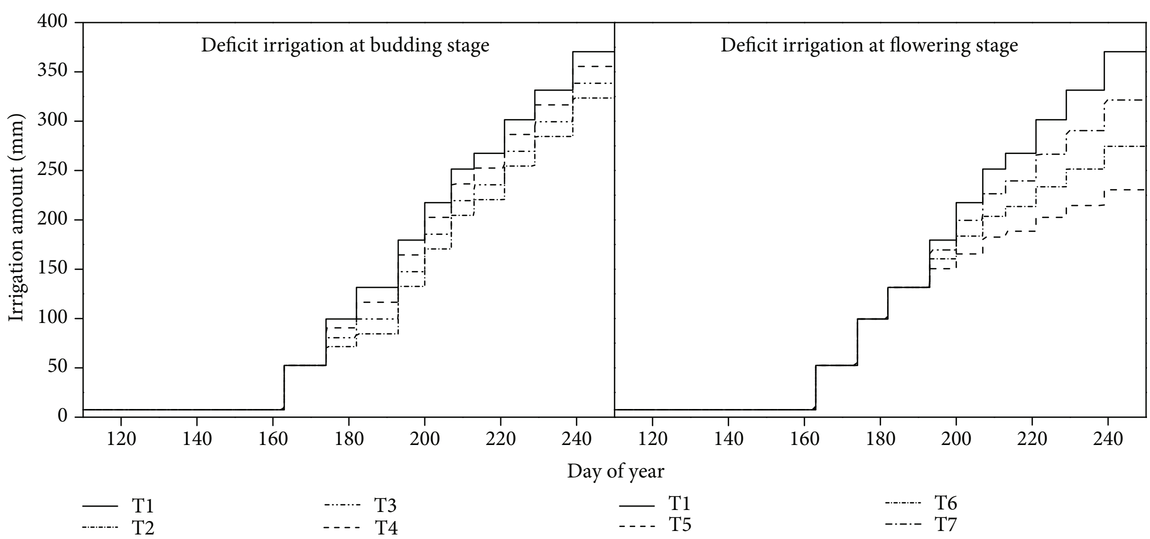

Figure 3: Irrigation during the cotton growth period.

The irrigation water mainly came from the Peacock River, with an average irrigation salinity of 0.8 g/L. To provide sufficient water and to leach salt from the soil, flood irrigation (irrigation amount of approximately 300 mm) was carried out every spring (early March). The experimental treatments were as follows.

2.2.1. Water Control Measures. When the cotton started to emerge, drip irrigation was conducted. The conventional irrigation amount in this region is approximately 500 mm based on the annual water requirement for cotton. The irrigation amounts in this experiment were calculated based on the potential evapotranspiration (PET) during the cotton growth season, which was calculated according to the meteorological data. The water control measures were mainly divided into 10 water treatments. Irrigation amounts corresponding to 0.4, 0.6, and 0.8 times the potential evapotranspiration (0.4 PET, 0.6 PET, and 0.8 PET) were applied in the budding, flowering, and boll development stages, respectively, and were designated as T2-T7. Full irrigation was designated T1 (PET). Irrigation water was from a local reservoir, and the planned irrigation period was 7~10 days in the growing season, with no irrigation during cotton emergence and boll-opening periods. A water flowmeter was used to control the water volume. Fertilization was carried out according to the local fertilization practices (20-7-3 kg/mu (N-P_2O_5-K_2O)) and adjusted according to actual local conditions. The treatment details and irrigation schedules are shown in Table 2 and Figure 3.

2.2.2. Nutrient Control Measures. Cotton was sown after plowing on 5 April. Basal fertilizers (700 kg ha^{-1} diammonium

Table 3: Fertilization treatments at different cotton growth periods.

Date	Full fertilization	Urea (g)	Diammonium phosphate (g)	Crystal potassium (g)
June 23rd	F	320	127	36
July 1st	F	320	127	36
July 12th	F	320	127	36
July 19th	2F	640	254	72
July 26th	2F	640	254	72
August 1st	F	320	127	36
August 9th	F	320	127	36
August 17th	F	320	127	36
Total	10F	3200	1270	360

phosphate with 18% N and 46% P, 75 kg ha^{-1} urea with 46% N, 75 kg ha^{-1} potassium sulfate with 45% K_2O, and 600 kg ha^{-1}compound fertilizer with 25% N, 25% K, and 25% P) were directly applied in the field before sowing, following local agronomic practices. Additional fertilizers were applied through the drip irrigation system during the cotton-growing season. Nutrient control measures were mainly aimed at the regulation of nitrogen, phosphorus, and potassium fertilizers. Urea, diammonium phosphate, and crystal potassium were used in the nitrogen, phosphorus, and potassium fertilizer treatments, respectively, mainly in the flowering and boll development stages. According to the recommended level of fertilization of 20-7-3 kg/mu (N-P_2O_5-K_2O), 6 fertilization treatments were set up on the basis of the annual growth requirements and were converted to nitrogen, phosphorus, and potassium gradients, specifically, 30-10.5-4.5 (N-P_2O_5-K_2O), 24-8.4-3.6 (N-P_2O_5-K_2O), 16-5.6-2.4 (N-P_2O_5-K_2O), 10-3.5-1.5 (N-P_2O_5-K_2O), and 0-0-0 (N-P_2O_5-K_2O) kg/mu (designated 1.5F, 1.2F, 0.8F, 0.5F, and 0F), recorded as T8, T9, T10, T11, and T12. Irrigation water also used local reservoir water, and the planned irrigation period was 7~10 days during the growth period. No irrigation was required for the cotton seedling and boll-opening periods. The irrigation amounts were based on the potential evapotranspiration (PET) and adjusted according to actual local conditions. The treatment details and fertilization schedules are shown in Table 3 and Figure 4.

2.2.3. Field Control Measures. To reflect the benefits of drip irrigation under mulch more directly (the plastic film was released on June 10th, after cotton seeding, ensuring cotton growth), an experimental plot was selected randomly for examination of the differences in soil moisture, soil temperature, and cotton growth indexes between plastic mulch and bare soil, and this was recorded as treatment 13 (T13). The irrigation and nutrient measures were the same as those of the control treatment (T1). To prevent the low temperature from affecting the emergence of cotton, the plastic film mulch was deployed on June 10th.

(1) Phenological Phases and Agronomic Measures. Phenological monitoring under the different treatments was not comprehensive, and the subtle differences between different treatments were not fully considered. However, in the second year of the experiment, the time points of agronomic measures were adjusted according to the different treatments. Main phenological phases and agronomic measures applied during the cotton-growing season are shown in Tables 4 and 5.

2.3. Data Collection and Analysis

2.3.1. Meteorological Data. Daily meteorological data were used for calculating the PET. The minimum daily data included solar radiation, maximum temperature, minimum temperature, and rainfall. Daily meteorological data were collected from a HOBOware 3.7 weather station (Onset Computer Corporation, Pocasset, USA). The daily meteorological data during the two cotton-growing seasons are shown in Figure 5.

The crop evapotranspiration (ET) was calculated by FAO56 Penman-Monteith models. According to the FAO56 Penman-Monteith method, the wind speed and relative humidity were considered in the calculation process. In Bayingolin of Xinjiang, the windy climate and sandy soils had a great impact on the cotton growth process.

FAO56 Penman-Monteith [34, 35]: solar radiation, maximum and minimum temperature, wind speed, and relative humidity

$$ET_0 = \frac{0.408\Delta(R_n - G) + r(900/(T + 273))u_2(e_s - e_a)}{\Delta + r(1 + 0.34u_2)}, \quad (1)$$

where ET_0 is the reference rate of evapotranspiration (mm day^{-1}), R_n is the net radiation on the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), T is the daily mean temperature at a 2 m height (°C), u_2 is the wind speed at a 2 m height (m/s), e_s is the saturated vapor pressure (kpa), e_a is the actual vapor pressure (kpa), $e_s - e_a$ is the saturated vapor pressure difference (kpa), Δ is the slope of the saturated vapor pressure curve, and γ is a thermometer constant (kpa/°C).

2.3.2. Determination of Soil Physical and Chemical Indexes

(1) Measurement of Soil-Water Content. Because there were multiple irrigation events during the cotton-growing season, soil was collected only before sowing, before irrigation, at harvesting, and at key cotton growth periods, and the soil-water content was also measured in the flowering and boll development periods. Two sampling points were set up in each plot, and the soil-water content was measured by the drying method (105°C, 24 h) in the same section at the wide line (below the dripper), narrow line, and middle position between the bare soil. The sampled soil layers were 0-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm.

(2) Measurement of Soil-Salt Content. A DDS-307 conductivity meter was used to determine the conductivity of the soil in a soil-water ratio of 1 : 5. The salt content in the soil was determined according to the relationship between the conductivity and the total salt content.

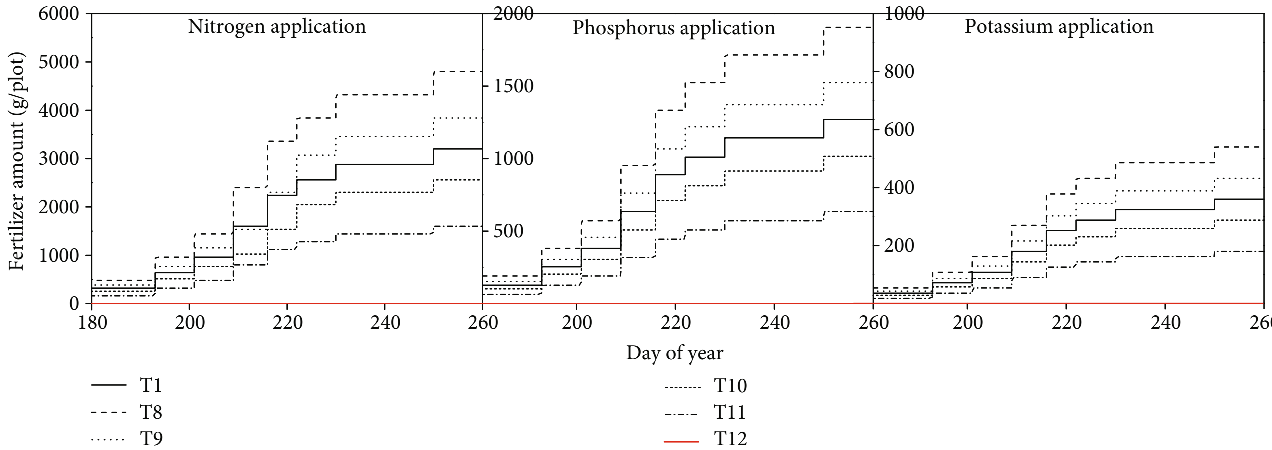

FIGURE 4: Fertilization during the cotton growth period.

TABLE 4: Main phenological phases of cotton.

	Sowing	Emergence	Trifoliate	Budding	Flowering (closure)	Boll opening
Date	April 5th	April 16th	May 10th	June 2nd	July 4th	August 21st

TABLE 5: Main agronomic measures applied during the cotton-growing season.

	Pesticide	Pesticide	Pesticide	Pesticide	Film uncovering	Topping
Date	May 13th	June 17th	July 5th	July 10th	June 10th	July 1st
Measure	DPC	DPC Acetamiprid pyridaben Emamectin benzoate	Acetamiprid pyridaben	DPC Pyridaben Boron fertilizer		

Note: DPC: mepiquat chloride.

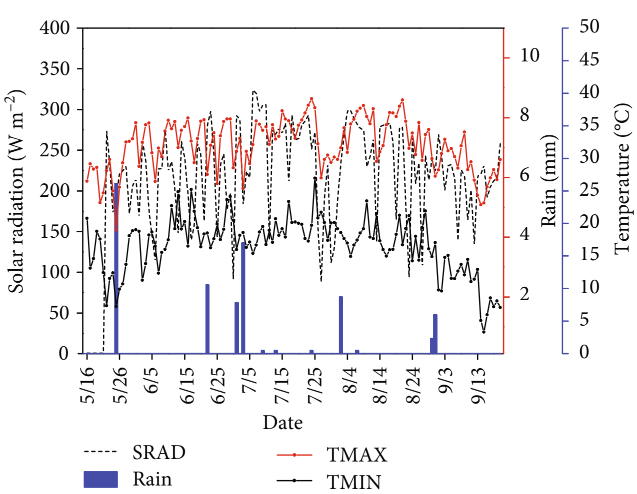

FIGURE 5: Daily maximum and minimum temperatures, rainfall, and solar radiation during two cotton-growing seasons of 2018.

(3) Soil Evaporation. Soil evaporation was measured at 20:00 each day using a homemade miniature evaporating dish (a PVC tube with an inner diameter of 12.5 cm and a height of 20 cm). Daily changes were measured at each growth stage from 8:00 to 20:00 once every 2 h.

2.3.3. Cotton Growth Measurements

(1) Emergence Rate. The emergence of cotton seedlings was observed every three days after sowing. At the end of the seedling stage, the survival rate was measured as emergence per unit area, and then the emergence rate of the whole area was estimated. The emergence rate was calculated as follows:

$$\text{Emergence rate} = \left(\frac{\text{seedling number}}{\text{number of seeds sown}}\right) * 100\%. \quad (2)$$

(2) Cotton Growth Index. Six representative cotton plants (three from the inside line and three form the outside line) with uniform growth were selected from each plot. The plant height, leaf area index, stem diameter, and effective boll number were measured at each stage of cotton growth, and additional tests were conducted at the flowering and boll development stages. The cotton yield was measured after the experiments.

Plant height: the distance between the cotyledon node and apical growing point was measured by a tape measure.

Stem diameter: the stem diameter of the cotyledon node was measured using a Vernier caliper.

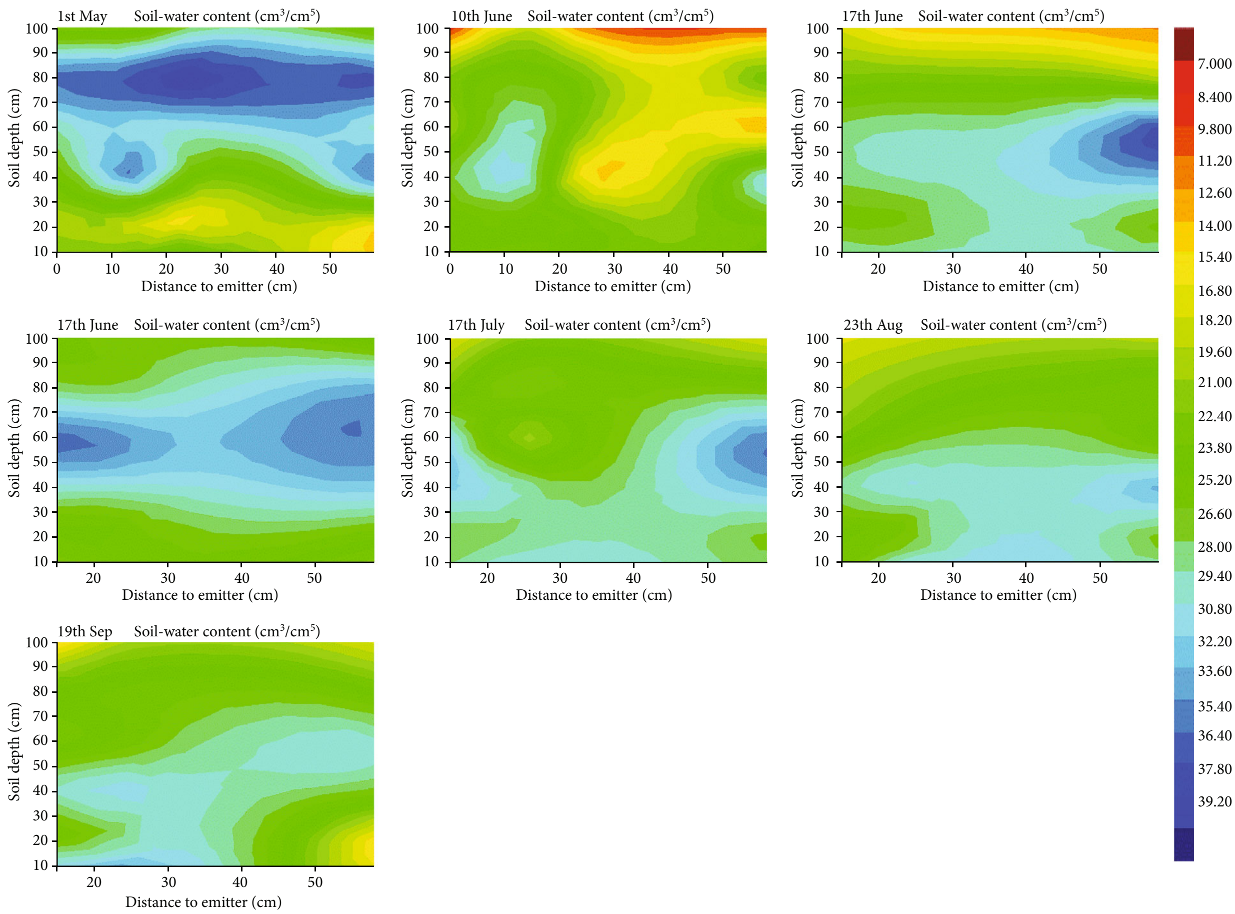

FIGURE 6: Soil-water distribution in the CK(T1) plots during different cotton growth periods (1st May, 10th June, 17th June, 27th June, 17th July, 23rd August, and 19th September).

Leaf area index: the length and width of each leaf were measured with a tape, the leaf area of the whole individual plant was then calculated, and the leaf area index was finally calculated as follows:

$$\mathrm{LAI} = \frac{\text{leaf area}}{\text{ground area}}, \quad (3)$$

where LAI is the leaf area index, a dimensionless quantity that characterizes plant canopies.

Dry matter quality: the aboveground parts of cotton plants were separated from the stem base and underground parts, and the surface dust was removed. The aboveground parts were put into an oven at 105°C for 1 hour. The sample was dried to constant weight at 75°C and then weighed after cooling.

Yield and components: at harvest, uniform and robustly growing areas of 6.67 m^2 were randomly selected from three fields from each treatment. The number of bolls larger than 2 cm in diameter was recorded. A total of 30 bolls, 40 bolls, and 30 bolls were picked from the upper, middle, and lower layers of cotton plants in each plot, respectively, to calculate the 100-boll weight.

2.3.4. Data Analysis. The data were analyzed by the SPSS statistical program, and analysis of variance (ANOVA) was conducted to evaluate the effects of the treatments on plant height, stem diameter, LAI, and biomass. Duncan's multiple range test was used to compare and rank the treatment means. Differences were declared significant at $P < 0.05$ and $P < 0.01$.

3. Results and Discussion

3.1. Soil-Water Content. Because drip irrigation is a type of partial irrigation, the area under the dripper is humid during irrigation; after irrigation, soil moisture is changed by many factors, such as the crop root system, atmospheric evaporation, self-gravity, and the influence of film mulching, which makes the conditions in the surrounding soil more complex and causes soil moisture to have both temporal and spatial distribution patterns [36]. The spatial and temporal distribution of soil moisture is not homogeneous (Figure 6).

In the 0-30 cm soil layer, the soil-water content increased gradually with increasing soil depth; when the soil depth reached 40 cm, the high soil-water content decreased slightly. The soil-water content on May 1st (initial) showed a continuous increasing trend. Because the main roots of cotton are distributed in the 0-40 cm layer, the water absorption of roots

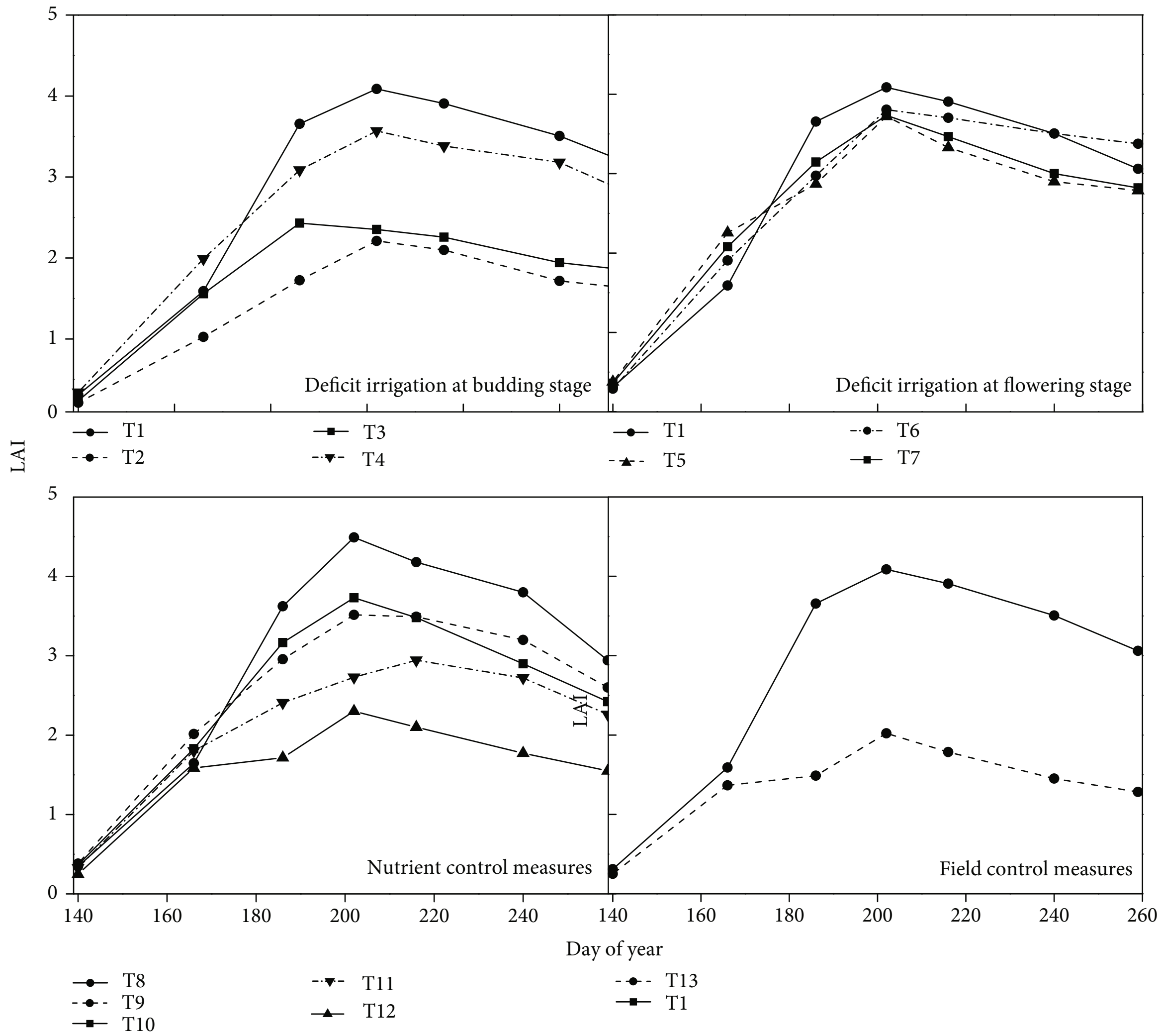

Figure 7: Changes in the LAI during the cotton growth period under different treatments.

mainly occurs in this layer. The water absorption of roots decreased gradually with increasing depth, from top to bottom. Therefore, the soil-water content increased gradually in the 0-30 cm layer, but the degree of change in this layer was not clear. In the 40-80 cm soil layer, the soil-water content was almost constant.

In addition, on May 1st, the soil-water content in the 80-100 cm soil layer was higher than that in the 60-80 cm soil layer, possibly because the average depth of the groundwater was shallow, and the groundwater recharged the upper soil. The soil-water content in other areas was higher than that at 80-100 cm, which indicates that seepage occurred at 80 cm. Root seepage should be estimated when calculating the water consumption of cotton.

The soil-water content in the wide rows was the highest in the 0-5 cm surface layer and was higher than that of the bare land and narrow rows. This is because the root distribution was more "sparse" in wide rows than narrow rows, and film mulching reduced the loss of soil moisture in the 0-5 cm surface layer. For the 5-40 cm soil layer, the soil-water content during the growth period showed the trend of bare land > wide row > narrow row. The root system was mainly distributed in the wide and narrow rows during the growth period and occupied a large proportion of the narrow rows. During cotton growth, cotton roots absorb more water from the soil of narrow rows, while the root system was less distributed in the bare land. Additionally, the cotton canopy shields the bare land from direct sunlight, so the soil-water content in the bare land was the highest, and that in the narrow rows was the lowest. For the soil layer below 40 cm, the soil-water content between the bare land, narrow rows, and wide rows was almost equal. This was mainly because the soil below 40 cm was subjected to a smaller vertical effect of cotton root water absorption and soil evaporation, and after irrigation during the growth period, the soil moisture under 40 cm was redistributed mainly by its own gravity because the time of soil extraction was one day before irrigation or two or three days after irrigation, and the soil texture was sand. The soil-water content in the soil layer below 40 cm was uniform during the growth period, and the water potential gradient between the bare land, narrow rows, and wide rows was small, so the water content in the soil layer below 40 cm showed slight differences along a horizontal gradient.

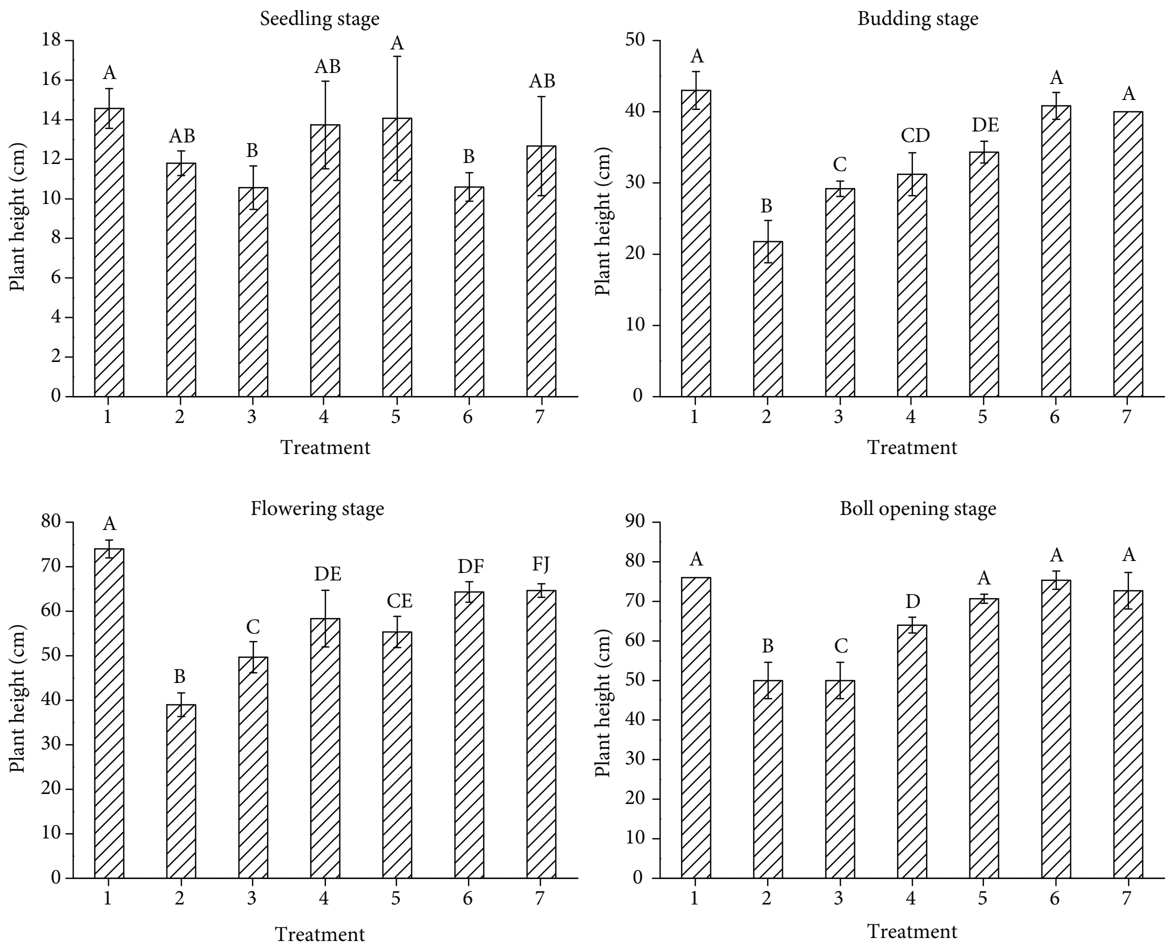

Figure 8: Changes in cotton plant height under different irrigation treatments.

3.2. Leaf Area Index (LAI). The changes in the LAI during cotton growth under each treatment are shown in Figure 7. During the cotton growth period, the LAI showed a trend of increasing at first and then decreasing with time.

In the early growth stages, the LAI increased as the fertilizer application increased under the same irrigation amount, which may be because in the early growth stage, cotton needs to absorb a large number of nutrients for vegetative growth and to increase the leaf area, thereby promoting photosynthesis and synthesis of organic compounds. Therefore, increasing the amount of fertilizer applied in the early stage can promote the growth of cotton. The LAI reached its maximum value at approximately 190-200 days in 2018, which was in the period of vigorous vegetative growth and sufficient photosynthesis of cotton. Then, with the passage of time, the growth of cotton changed from vegetative growth to reproductive growth. In this stage, the water and nutrients needed for cotton growth decreased, and those in the leaves were gradually transferred to the reproductive organs. The rate of the increase in the LAI declined, and the LAI began to decrease. At this time, the LAI increased with increasing fertilizer application, although excessive fertilizer application inhibited cotton growth to a certain extent, which led to the maximum LAI of cotton under the T9 treatment being lower than that under the T10 treatment. Since the test site had saline-alkali soil, drip irrigation resulted in the leaching of salt, enabling the cotton root system to avoid salt stress and ensuring the growth of cotton. Therefore, the LAI increased with increasing irrigation amount with the same fertilizer application conditions. At the same time, the cumulative amount of leaf area was lower in the budding stage deficit treatments (T2, T3, and T4) than in the flowering stage deficit treatments (T5, T6, and T7). This was due to the lack of irrigation in the budding stage, which limits the vegetative growth of cotton and has a greater impact than deficits in the flowering and boll development stages.

3.3. Plant Height and Stem Diameter. The effects of different irrigation and fertilizer treatments on cotton height and stem diameter are shown in Figures 8 and 9, respectively. The topping date was July 1st, which was at the flowering stage, and thus, the increase in cotton height was influenced by the topping. Before topping, the cotton plant height increased rapidly by 24.23~47.54 cm, and after topping, the height only increased by 1.79~6.00 cm. The cotton height and stem diameter during the topping period and mature period were similar, mainly because topping can control the vegetative growth of cotton, and during the mature period, the cotton height and stem diameter basically no longer increased.

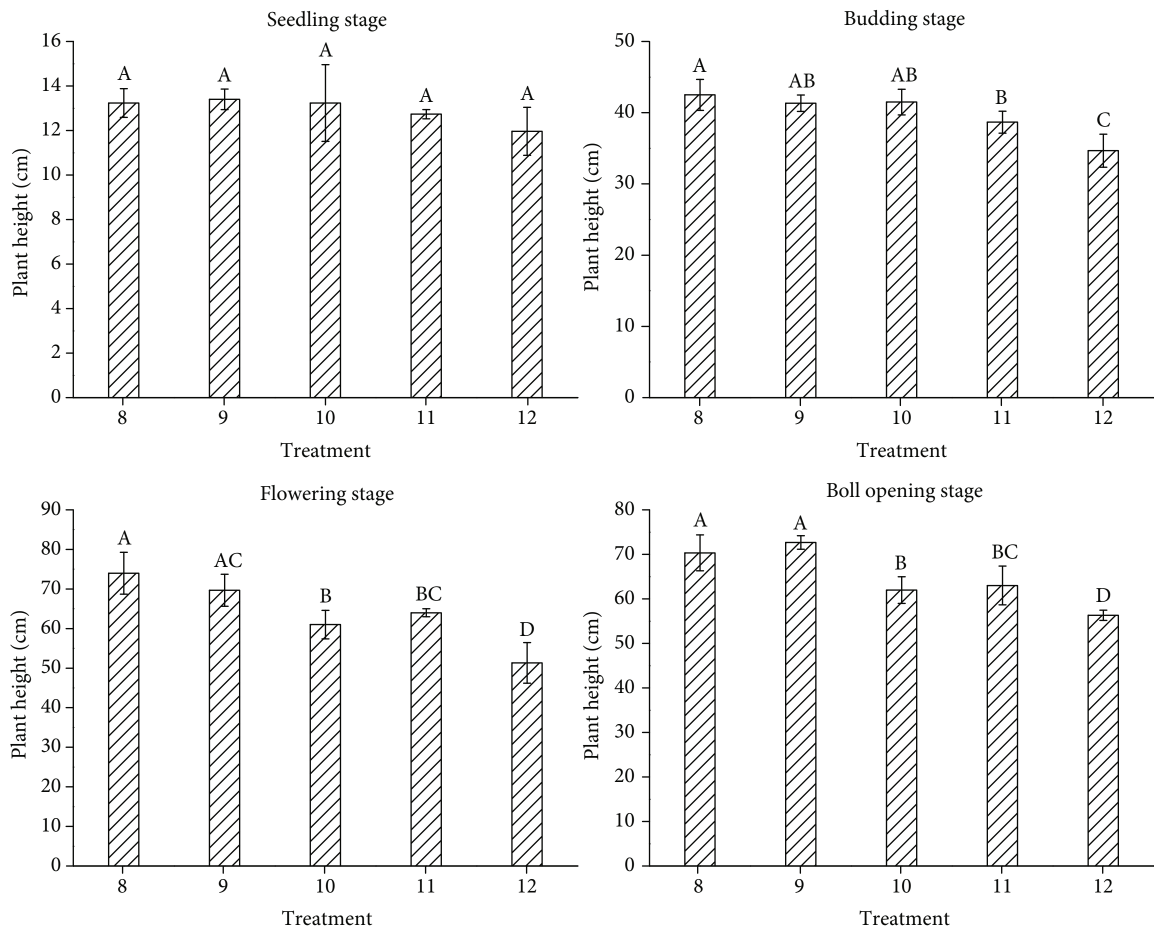

Figure 9: Changes in cotton plant height under different fertilization treatments.

With the increase in fertilizer application, the height increased at the early stage and then decreased at the later stage; specifically, the height of cotton plants increased with fertilizer application at all stages under the most severe deficit irrigation conditions (T2 and T5). Under saline soil conditions, the height of the cotton plants increased with the irrigation amount, and the average plant height under the flowering stage deficit irrigation treatments (T5, T6, and T7) was 72.92 cm, which was 36.63% and 3.03% higher than those of the budding stage deficit irrigation treatment (T2, T3, and T4) and full irrigation treatment (T1), respectively. In other words, deficit irrigation at the flowering stage has little effect on cotton height, and efficient water utilization can also be achieved by controlling the irrigation amount at this stage.

Figures 8 and 9 show that in each period of cotton growth, most of the plant heights under the different fertilization treatments were not significantly different. However, there were significant differences in plant height under different irrigation treatments. This indicated that the effect of water control measures was greater than that of nutrient control measures. Reasonable control of irrigation can ensure that the plant height of cotton is within the normal range. At the same time, we found that there were no significant differences between the moderate and mild deficit irrigation treatments in the flowering stage (T6 and T7) and the full irrigation treatment (T1).

During the growth period, the stem diameter changes over time were basically the same, increasing first and then becoming stable. Since stem diameter variations reflect the combined effects of environmental variables and plant vegetative characteristics, the maximum stem diameter had a great response to water stress under different water conditions [37].

In terms of nutrient control measures, cotton height was positively correlated with the amount of fertilizer application, and stem diameter also increased with the increase in fertilizer. For the water control measures, cotton height was inversely correlated with the amount of irrigation applied. Deficit irrigation at the budding stage had the most obvious effect on cotton height, while stem diameter decreased with increasing irrigation amount. However, the nonhomogeneous soil qualities and proximity to the bare field hindered the growth of cotton and affected the experimental results to a certain extent.

Statistical analysis indicated that different amounts of irrigation and fertilization had little effect on stem diameter (Figures 10 and 11). The difference in stem diameter between the nutrient control treatments was no more than 2 mm and no more than 4 mm between the water control treatments. Except for the significant difference in stem diameter between

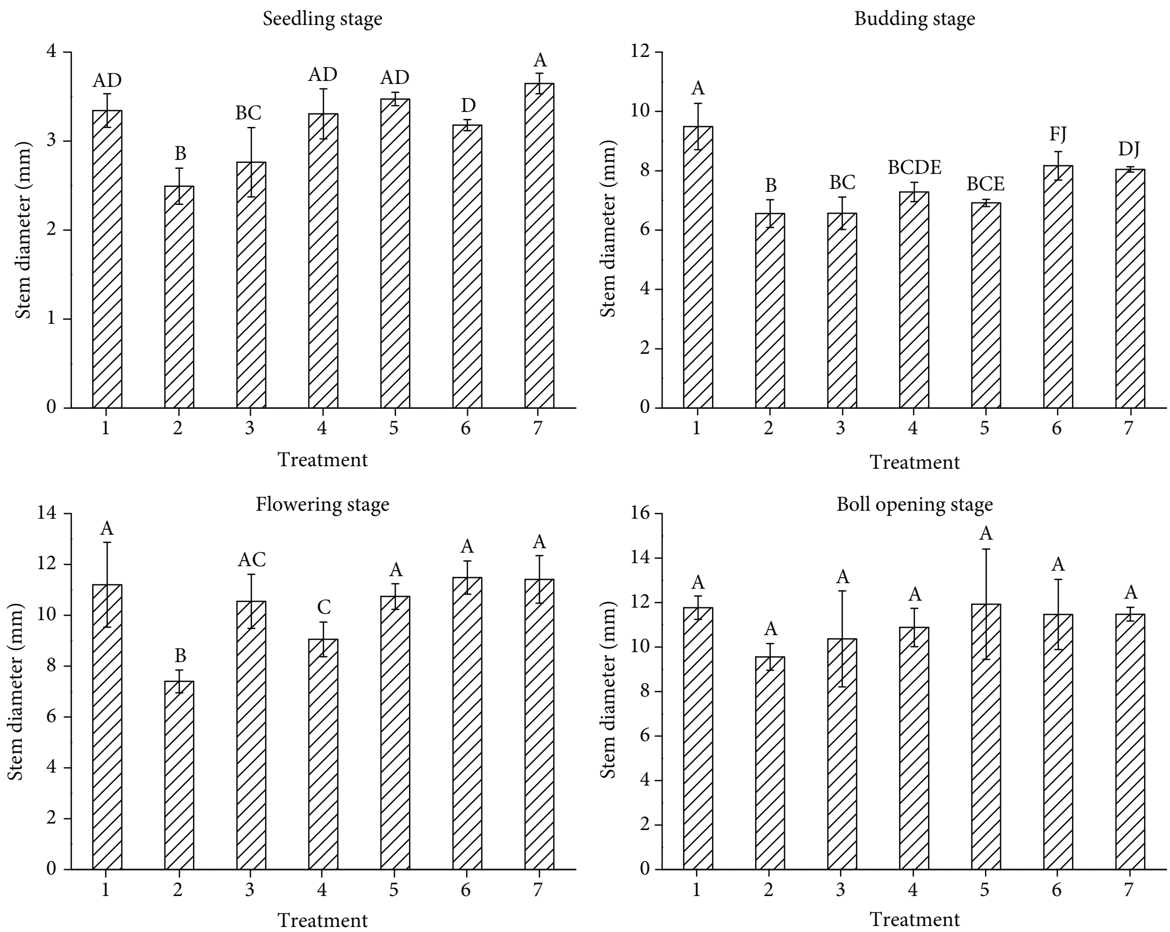

Figure 10: Changes in cotton stem diameter under different irrigation treatments.

the severe deficit irrigation in the budding stage (T2) and the full irrigation treatment (T1), the difference between treatments was not obvious. At the same time, because of errors in the measurement process, the changes in irrigation and fertilization amount had no significant effect on the stem diameter.

3.4. Biomass. Biomass is the basis for crop production. According to the local topping date, the biomass at the topping period was compared with that at the later stage. In the early stage of cotton growth, the main components of cotton biomass were stems, leaves, and other vegetative organs; in the late stage, the content of nutrients (water, nutrients, etc.) transferred from vegetative organs such as stems and leaves to reproductive organs was far lower than the change in biomass. The biomass of yield-related organs showed a trend of gradual increase with the progression of the growth period, and the most intense change was at the beginning of the boll development stage. This is because in the reproductive growth stage, roots, stems, leaves, and other vegetative organs transfer most of their nutrients to the reproductive organs, promoting the rapid development of the reproductive organs. In the later growth stage, the proportion of yield-related organs to the total biomass is considered the stem-leaf yield composition.

The proportion of biomass of cotton organs at different growth stages is shown in Figure 12. In the seedling stage, the dry matter was mainly concentrated on the leaves because of the thin stems, and leaf dry matter accounted for more than 70% of the total dry matter mass. After the seedling stage, the proportion of dry matter mass of reproductive organs among the total dry matter mass increased continuously, and the proportions at the budding, early flowering, late flowering, and boll-opening stages were 4.27~13.05%, 17.53~21.88%, 51.34~58.63%, and 51.92~59.48% under the different treatments, respectively. Under the experimental saline-alkaline soil, the dry matter of different organs of cotton increased with increasing fertilizer amount. In the boll development stage, the average total dry matter mass of T8 was 177.42 g, 41.66%, 40.6.46%, 14.19%, and 4.12% higher than those of T12, T11, T10, and T9, respectively.

3.5. Yield Components and Irrigation Water Use Efficiency (IWUE). It can be seen from Figure 13 that the cotton yield was different under the different fertilization treatments, showing a trend of 1.5F > 1.2F > F > 0.8F > 0.5F > 0F, which shows that the yearly increase in N, P, and K can effectively guarantee cotton production.

The different irrigation and fertilization treatments had extremely significant effects on the boll number (Table 6),

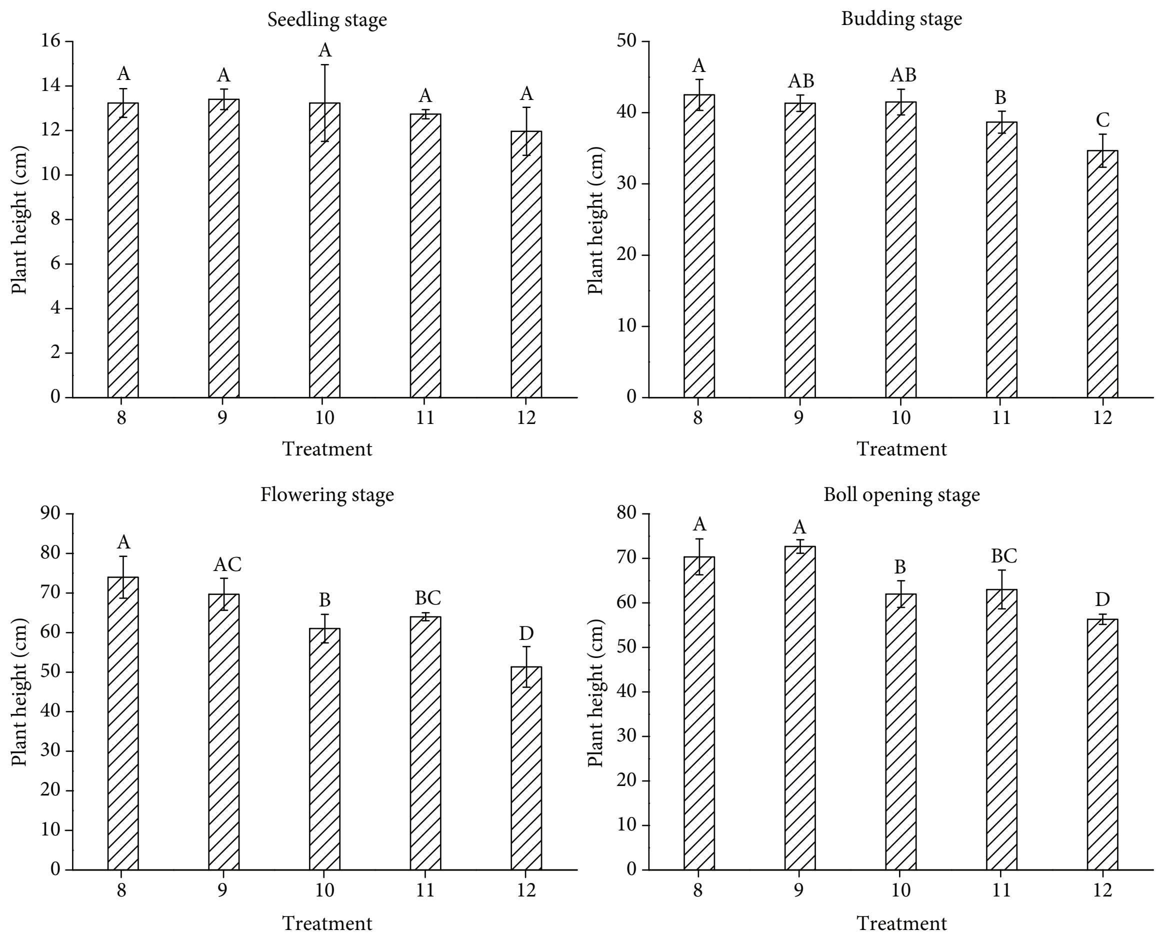

Figure 11: Changes in cotton stem diameter under different fertilization treatments.

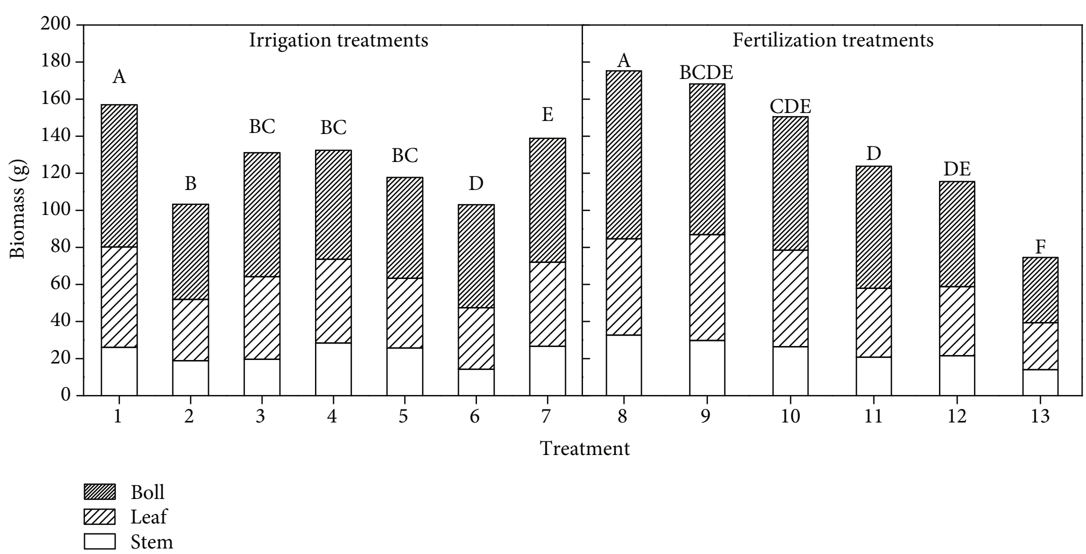

Figure 12: Changes in cotton biomass on September 16th (late growth stage).

seed cotton yield, and IWUE ($P < 0.01$) and a significant effect on the boll weight ($P < 0.05$). Under the three deficit irrigation treatments (T2-T7), the number of bolls per plant and the weight of bolls per plant increased with increasing irrigation, and the effect of deficit irrigation on the yield was less than that at the bud stage. This result shows that serious irrigation deficits have a great influence on cotton growth and yield components. Under T7, the boll number and boll weight were higher than those under T6, but the difference was not significant, which indicated that slight

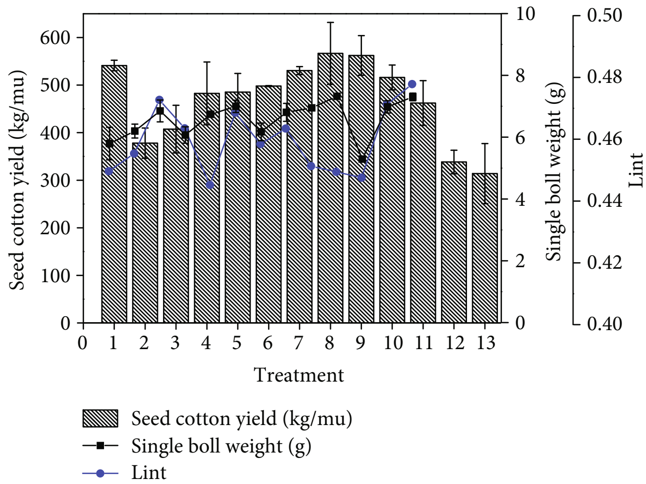

Figure 13: Seed cotton yield under different irrigation and fertilization treatments.

Table 6: Effect of irrigation and fertilization on yield and water use efficiency.

Treatment	Boll number/plant	Single boll weight (g)	Seed cotton yield (kg/mu)	IWUE (kg/m^3)
Irrigation				
T1	6.58cdef	7.32bcd	541.16g	1.77ef
T2	5.18h	6.19d	485.25k	2.18bc
T3	5.32h	6.85abcd	496.16j	2.35b
T4	6.11fg	6.07bcd	407.45h	2. 29a
T5	5.91g	6.74bcd	497.15i	1.97d
T6	6.26efg	6.99cd	490.52h	2.03cd
T7	6.47abc	6.17abcd	482.531ef	2. 62b
Bare land				
T13	4.43ab	5.32abc	313.93b	2.04cd
Fertilization				
T8	6. 76a	6.98abcd	563.66cd	1.64de
T9	6. 98bcde	7.30abcd	566.29f	1.55g
T10	6.13cdefg	7.29abc	534.05de	1.91fg
T11	6.22abcd	6.74a	462.28a	1.78ef
T12	5.13cdef	4.72ab	338.32c	1.66fg
ANOVA				
W	**	*	**	**
F	**	*	**	**

Note: different small letters in the same column indicate significant differences among treatments at the 0.05 level. ∗∗ indicates a significant difference at 1%; ∗ indicates a significant difference at 5%.

deficit irrigation could ensure the normal growth of cotton and achieve efficient water utilization at the same time. This conclusion was consistent with the study from Yazar et al. [38], who found that the boll number decreased under a decrease in the water supply.

Under the five different fertilization treatments (T8-T12) at the same irrigation level (full irrigation), the change in the boll weight formed a quadratic parabola with the increase in fertilization. The maximum value appeared under T9, and the average boll weight of T9 was 7.30 g, which was 4.58%, 1.37%, 8.31%, and 54.6% higher than that under T8, T10, T11, and T12, respectively. This result indicates that under the same irrigation level, appropriate increases in fertilization are beneficial to the boll weight, but overfertilization reduces the boll weight.

The results indicated that under drip irrigation with plastic mulch, the effect of an increasing irrigation amount on cotton seed yield was more significant than that of increasing fertilization application, especially under saline soil conditions, and appropriate irrigation promotes cotton growth (vegetative and reproductive growth). Furthermore, with appropriate irrigation, the salt can be leached from the cotton root area, providing appropriate conditions for cotton growth.

For drip irrigation without plastic mulch (T13), under sufficient irrigation and fertilization, the yield, dry matter, plant height, and stem diameter of cotton were all at the lowest level in the bare land. This also shows that in areas with large temperature differences between day and night, plastic mulch can ensure that the accumulated temperature requirements of crops are met, reduce soil evaporation, increase soil temperature, and improve the soil and water microenvironment in the root area of the crops. In this experiment, mulch release that was too early also has some influence on the test results. In future comparative tests, further quantitative analysis is needed.

The experimental site was located in southern Xinjiang, an area with an extreme lack of water resources, so improving the water use efficiency has great significance for relieving the local water resource shortage. The IWUE values under the different treatments are shown in Table 6. At the same irrigation level, the IWUE had the same trend as the seed cotton yield. The results indicated that under the same irrigation conditions, fertilization application affected the IWUE by affecting cotton seed yield. The IWUE decreased gradually with increasing irrigation amount, and the same results were found by Dağdelen et al. [39], who found that the IWUE increased as the irrigation amount decreased. Hence, under drip irrigation with plastic mulch, increasing the irrigation amount can increase the seed cotton yield; however, the IWUE decreases to a large extent at the same time.

The mechanisms by which drip irrigation under plastic mulch regulates field conditions and increases yields are unclear at present; methods to quantify the relationship between the regulatory measures and the soil-water and salt transport, water availability, water consumption, salt accumulation, and crop yield also need to be further understood. In addition, it is also worth exploring ways to modify the water and nutrient stress coefficients under the regulatory measures; moreover, methods for the prediction of field salt accumulation and crop growth should also be developed.

In summary, various water, nutrient, and field control measures under a drip irrigation-plastic mulch production system will inevitably have a certain impact on soil-salt accumulation and crop growth. Scholars have performed much research on the mechanism and model of soil-water, salt transport, and crop growth processes under various field control measures, which lay a theoretical and experimental foundation for later research in this field.

4. Conclusion

Soil moisture has a significant effect on cotton growth; when the water supply is excessive, vegetative growth is vigorous but can easily become excessive, thus increasing crop water consumption and reducing IWUE. However, if soil moisture is insufficient, vegetative growth is easily inhibited, and the distribution of water among underground and aboveground parts will further affect root growth and dry matter accumulation. Soil moisture also affects the accumulation of photosynthetic products and the yield of cotton.

In the early stage of cotton growth (vegetative growth stage), the plant height increases rapidly with the progression of the growth process; after entering the budding stage (vegetative and reproductive growth stages), this increase in plant height slows gradually; after entering the flowering stage, which is dominated by reproductive growth, and with the application of artificial topping, the rate of increase of cotton height further slows and tends to stop. Moderate water stress at the seedling stage is beneficial to cotton height, and the same degree of water deficit at the later growth stage has a less negative effect on cotton height than that at the earlier growth stage.

The cotton stem diameter trend was opposite to that of plant height in the early growth stage, but the increase in stem diameter gradually decreased and stopped in the later growth stage. Water deficit at the flowering stage resulted in a slow increase in stem diameter, while deficit irrigation at budding promoted the increase in stem diameter.

The effect of soil-water on the LAI was similar to that on plant height. The LAI decreased with the increase in the water deficit at the budding stage, but after restoring the water supply at the flowering stage, a water-deficit compensation effect appeared with this treatment. The negative effects of water stress on the LAI increased with an increasing degree of water deficit.

The effects of nutrient control measures on plant height and stem diameter were not significant, and excessive fertilization had little effect on the LAI. However, the greater the amount of fertilizer applied, the greater the biomass accumulation. At the same time, because the biomass accumulated in the later growth stage, deficit irrigation at the flowering stage had a greater effect on biomass accumulation than the same treatment at other stages.

In general, cotton irrigation practices in the study area should include mild deficits at the flowering stage (60%~80% PET), while ensuring that the water demand is met in the budding stage (full irrigation during the early period). Fertilization at 0.8 times the standard local application amount can ensure normal yields and improve the IWUE of cotton.

Data Availability

1) the nature of the data is agricultural data, 2) the data can be accessed by contect with first or corresponding author, and 3) This study was financially supported by the National Key Research and Development Program of China (No. 2017YFC0403303), and the National Key Research and Development Program of China (No. 2017YFC0403305).so there are some restrictions on data access.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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