Effects of Different Irrigation Modes on the Growth, Physiology, Farmland Microclimate Characteristics, and Yield of Cotton in an Oasis

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Abstract: In order to determine the effects of different water-saving irrigation techniques on physiological growth, farmland microclimate, and yield of cotton (Gossypium Spp.), a two-year field experiment was carried out in an oasis area of Northwest China, and three irrigation methods were tested, including on-film irrigation (T1), under-film drip irrigation (T2), and automatic irrigation (T3). The results showed that the relative humidity, plant height, leaf area, stem thick, and photosynthetic index with the T3 treatment were significantly higher than those with T2 and T1. The air and soil temperature with T3 (except seedling stage) were considerably lower than those with T2 and T1. According to the fitting and statistical analysis of each index and yield, except for air and soil temperature, the other indices were positively correlated with yield. Based on the analysis of each index, the T3 treatment had the most significant regulatory effect on cotton’s physiological growth and farmland microclimate. Compared with T1, the irrigation amounts of T2 and T3 decreased by 16.43% and 25.90%, but the yield increased by 38.96% and 46.28%, respectively. The automatic irrigation strategy showed significant advantages in water saving and yield increase, which could provide some reference for cotton drip irrigation in similarly arid areas.

Keywords: irrigation mode; Gossypium spp.; physiological growth; farmland microclimate; yield; Xinjiang

1. Introduction

Cotton fiber has ideal length, good texture, strong moisture absorption, air permeability, and dye affinity [1,2]. Therefore, cotton (Gossypium Spp.) is an important textile material, as one of the principal economic crops in China [3]. At present, cotton accounts for more than 40% of all textile raw materials, and this proportion continues to increase [4]. Xinjiang is the main region of origin of cotton in China, as a result of its unique climatic conditions and vast land resources making it very suitable for the growth of cotton [5]. Since under-film drip-irrigation technology has been widely implemented in Xinjiang, high-yield cotton cultivation techniques have gradually matured. According to the National Bureau of Statistics, as of 2019, the cotton planting area in Xinjiang was $2.54 \times 10^6$ hm² and the yield was $5.00 \times 10^6$ t, accounting for 76.08% of the national cotton planting area and 84.94% of the total cotton yield [6,7]. However, with the increase in under-film drip irrigation over time, its disadvantages of excessive consumption of soil water and soil resources have become more obvious, and the cotton yield has decreased year by year [8,9]. In recent years, in order to increase yield, cotton farmers have continuously increased irrigation water consumption, even exceeding the demand for cotton growth [10]. Problems such as
rampant plant growth, yield and quality decline, low water-use efficiency, and premature senescence of cotton have become increasingly intense, and have become prominent problems affecting the further yield increase of cotton [11,12]. Therefore, it is urgent to advance the high-yield cultivation techniques of cotton in Xinjiang to improve the utilization rate of water resources and increase the cotton yield.

Automatic irrigation control systems combine water-saving irrigation technology, computer technology, sensors, and communication technology, enabling monitoring and prediction of soil moisture in real time, depending on the characteristics of crop water demand, and can achieve on-demand irrigation and precision irrigation [13,14]. The crisis of water resources in Xinjiang is prominent, and serves as a good foundation for automatic irrigation. The Xinjiang Production and Construction Corps vigorously promote automatic drip-irrigation technology, where the eighth division’s 148 regiments oversee 45 hm² of cotton using automatic drip-irrigation technology. Automatic drip-irrigation technology mainly uses soil moisture sensors to control irrigation, which also plays a certain role in improving crop water-use efficiency and yield [15,16]. Jones [17] and Van [18] considered capacitance- or frequency-domain reflection measurement sensors to be suitable soil moisture sensors for automated irrigation systems in nursery and greenhouse production, due to ease of maintenance, low cost, and reliability. Bacci used tension gauges to detect water potential in flowerpots to adapt water supply to plants’ actual needs, reducing consumption without having a negative impact on plants [19]. Riber and Yoder used soil water sensors and a weather forecasting device to monitor soil moisture and predict crop transpiration in a real-time fuzzy control irrigation system. The system used changes in climate and soil moisture to control irrigation [20]. Devitt [21] developed an intelligent irrigation automation system based on changes in plant transpiration, and achieved good water-saving and yield-increasing effects after local practical application. Nielson [22] and Yuan [23] used different water shortage indices of crop canopy temperature as feedback indices to judge the water shortage status of crops, so as to accurately find the threshold of irrigation time and achieve more accurate irrigation. Yuan [24] designed an intelligent irrigation system based on GPRS + ZigBee wireless networking technology, which could adjust and control the amount of irrigation according to the changes in light intensity, environmental humidity, and soil temperature, so as to ensure the balance and stability of the irrigated ecological environment. Scholars have studied large-scale farmland irrigation computer control systems with multiple communication forms and remote control irrigation and fertilization, which can be commonly used in farmland, orchards, and other green spaces [25,26]. Advanced irrigation technology can improve the irrigation water-use efficiency and the yield of cotton, and achieve the efficient utilization of water resources, which is the inevitable trend of the development of high-yield cultivation techniques in Xinjiang.

It is well known that crop growth is affected not only by the soil environment, but also by the farmland microclimate environment. Farmland microclimate is derived from the balance of matter and energy between soil–crop–atmosphere systems [27]. A reasonable farmland microclimate can regulate the temperature and humidity of the environment, improve light-use efficiency, and prevent wind and sand [28]. It can also effectively regulate crop photosynthesis and material conversion, and has a positive impact on crops’ physiological growth and yield improvement [29]. As for influencing factors of the farmland microclimate, previous studies have mainly focused on crop planting density, intercropping mode, planting mode, and coating film types; however, there have been relatively few studies on irrigation methods [30,31]. Irrigation is an important part of agricultural production; it changes the soil environment and, thus, the farmland microclimate environment. Therefore, this study discusses the effects of different irrigation methods on cotton’s physiological and growth indices, yield, and farmland microclimate, thus providing valuable information to boost yields by selecting appropriate irrigation techniques in similar areas.
2. Materials and Methods

2.1. Experiment Site

A field experiment was conducted over two crop growth periods from 2018 to 2019 in the Key Laboratory of Modern Water-Saving Irrigation (85°57′49″ E, 44°19′28″ N), Shihezi, Xinjiang Province, Northwest China (Figure 1). The test station is located in the western suburbs of Shihezi, with an elevation of 452 m and an average slope of 5.6‰. The region has a temperate continental climate, with an annual average sunshine time of about 2868 h. The accumulated temperature above 10 °C is 3472.3 °C, and the accumulated temperature above 15 °C is 2958.4 °C. The average annual rainfall is 209 mm, and the average annual evaporation is 1658 mm. The soil conditions of each soil layer in the test station are shown in Table 1. The meteorological data of the experimental area during the cotton growth periods are shown in Figure 2.

![Figure 1](image1.png)

**Figure 1.** The experimental station’s location.

| Soil Depth (cm) | Soil Particle Composition (g kg⁻¹) | Texture | Bulk Density (g cm⁻³) | Water-Holding Capacity (%) | pH |
|-----------------|-----------------------------------|---------|------------------------|---------------------------|-----|
|                 | <0.002 mm 0.002–0.02 mm 0.02–2 mm |         |                        |                           |     |
| 0–20            | 113 683 212                          | Silty loam | 1.54                  | 33.91                      | 7.71 |
| 20–40           | 126 716 186                          | Silty loam | 1.69                  | 33.11                      | 7.96 |
| 40–60           | 193 581 53                           | Silty loam | 1.71                  | 33.12                      | 7.63 |
| 60–80           | 220 653 50                           | Silty loam | 1.76                  | 35.51                      | 7.18 |
| 80–100          | 207 705 51                           | Silty loam | 1.76                  | 32.21                      | 7.74 |

![Figure 2](image2.png)

**Figure 2.** Daily meteorological variation during cotton growth periods (1 April to 30 October) in 2018 and 2019.
2.2. Experimental Design

The field was established in a randomized block design with 3 replicates. The plot (92 m²) was 11.5 m long and 8 m wide. A common local cotton variety, “Nongfeng No.133”, was raised in both years. The sowing dates were 22 April 2018 and 24 April 2019, and the harvest dates were 3 October 2018 and 1 October 2019. According to the habits of local farmers when planting cotton, cotton farmers have weak water-saving awareness and engage in excessive fertilization. This generally leads to waste of water and fertilizer. To find the most suitable irrigation strategy and improve the utilization efficiency of water, three irrigation methods based on previous research and local habits were designed: On-film irrigation (T1)—ridges were made around the film, and seedling holes were opened in the film. Irrigation took place 5 times in both years, and the irrigation quota was 718 mm. The planting method of one film and four rows was adopted, and the film width was 140 cm; Under-film drip irrigation (T2)—the planting mode was one film, two tubes, and four rows, and the film width was 140 cm. In this mode, the narrow row length was 30 cm, the wide row length was 60 cm, and the plant spacing was 15 cm. There were 14 instances of irrigation and 600 mm irrigation quotas in the whole growth period, including 2 times and 25 mm at the seedling stage, 10 times and 50 mm at the budding and flowering stages, and 2 times and 25 mm at the boll-opening stage; Automatic irrigation (T3)—the planting pattern was the same as in T2. In this mode, three soil moisture sensors were buried in the center of the left and right parts of the plot, and each group of sensors was buried at 20 cm, 40 cm, and 60 cm directly below the dropper. The irrigation threshold of each growth period (the percentage of soil moisture content to soil field capacity; threshold 3%) is shown in Table 2. When the soil moisture content reached the lower limit of the set irrigation threshold, the irrigation was started, and was stopped when the irrigation threshold reached the upper limit. Each time, urea (CO(NH₂)₂) and potassium phosphate amine (KH₂PO₄) were applied at a ratio of 2:1. The chemical control, topping, spraying, weeding, and other agronomic measures of all treatments were consistent. The automatic irrigation system, automatic irrigation-decision system, soil moisture sensors, automatic fertilization devices, and field automatic irrigation controllers used in the experiment were produced by Guizhou Aerospace Smart Agriculture Co., Ltd. (Guiyang, China). The type of drip-irrigation belt was a single-wing labyrinth drip-irrigation belt (WDF16/2.6-100) produced by Xinjiang Tianye Company (Urumqi, China). The wall thickness was 0.18 mm, the inner diameter was 16 mm, the drip hole spacing was 300 mm, the rated flow was 2.6 L·h⁻¹, and the working pressure was 0.05–0.1 MPa. A schematic representation of the experimental setup is illustrated in Figure 3.

### Table 2. Irrigation thresholds of automatic drip irrigation under mulch.

| Soil Depth (cm) | Seedling Stage | Budding Stage | Flowering Stage | Boll-Opening Stage |
|-----------------|----------------|---------------|-----------------|--------------------|
| 20              | 60–65          | 65–70         | 75–80           | 65–70              |
| 40              | 60–65          | 65–70         | 75–80           | 65–70              |
| 60              | 60–65          | 65–70         | 75–80           | 65–70              |

2.3. Sampling and Measurements

2.3.1. Farmland Microclimate Indices

A metallic mercury geothermometer was used to measure the soil temperature at 5, 10, 15, 20, and 25 cm below the cotton plants in each treatment, and the average value was taken as the soil temperature at this point. The monitoring time was 08:00–20:00 at the seedling stage, budding stage, flowering stage, and boll-opening stage. Each treatment was repeated three times, and the average value was taken.

The air temperature and relative humidity at the seedling stage, budding stage, flowering stage, and boll-opening stage were measured with a handheld meteorological instrument (Kestrel5200, Berlin, Germany). The measuring positions were the lower, the
middle, the canopy and 10 cm above the canopy of the cotton. The measuring range was a cotton row with uniform growth except for the boundary. Each treatment was replicated three times.

![Diagram of the experimental design](image)

**Figure 3.** Depiction of the filed experimental design: (a) the experimental plot distribution under three irrigation methods (T1, T2, and T3), with three replicates; (b) a diagram of the T3 treatment, showing the system and its size; (c) a profile view of the cultivation pattern of the drip-irrigated cotton used in this study, with sensor locations depicted.

2.3.2. Cotton Physiological Indices

Cotton physiological indices under natural atmospheric conditions were measured every 10 days between 08:00 and 20:00 (local time) using a handheld photosynthesis apparatus (CID CI-340, San Francisco, CA, USA). These indices included net photosynthetic rate (Pn) and transpiration rate (Tr), intercellular CO₂ concentration (Ci), and stomatal conductance (Gs), as well as environmental factors such as photosynthetically active radiation (PAR), air temperature (Ta), and CO₂ concentration in the air. The basic environmental parameters during the experiment were as follows: the air temperature was 29.5–37.4 °C, the light intensity was 1695–2148 µmol·m⁻²·s⁻¹, and the CO₂ concentration was 308–710 µmol·mol⁻¹. On the basis of these measurements, WUEins was calculated as follows [32]:

\[ WUEins = \frac{P_n}{T_r} \]  

(1)

2.3.3. Cotton Growth Indices

Cotton growth indices were measured within 46–164 d after sowing, including plant height (PH), stem thickness (ST), and leaf area (LA). Three random plants per treatment were sampled at 7–10-day intervals to measure cotton growth indices during the different cotton growth stages (seedling, budding, flowering, and boll-opening stages). Plant height (height from the cotyledon node to the top leaf) was measured with a ruler. Stem thickness was measured with a Vernier caliper. The length (L) and width (W) of all green leaves were measured with a ruler, and leaf area was calculated as follows:

\[ LA = L \times W \times 0.84 \]  

(2)
### 2.3.4. Yield and Irrigation Water-Utilization Efficiency

Three 2 m × 1.4 m plots were selected for each treatment to measure the number of plants (P), number of bolls (S), weight of 30 bolls (M) and single boll weight (G). The yield-related indicators were averaged. Finally, the yield (Y) (kg·hm⁻²) was calculated as follows:

\[ G = M / 30 \]  
\[ Y = S \times G / 30 \]

The irrigation water-utilization efficiency (iWUE) (kg·m⁻³) was calculated as follows [33]:

\[ iWUE = Y / I \]

where I is the amount of irrigation water (m³·hm⁻²).

### 2.3.5. Data Normalization

The data normalization was carried out to scale the data proportionally and make them fall into a small specific interval. Data normalization can remove the unit limitations of data and convert them into dimensionless pure values, so that the indices of different units or orders of magnitude can be compared and weighted. This study used the Z-score method to standardize the data, and the transformation formula was as follows:

\[ x^* = \frac{x_i - \mu}{\sigma} \]  
\[ \sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}} \]

where \( x^* \) represents standardized values, \( \mu \) is the mean value, and \( \sigma \) is the standard deviation.

### 2.4. Statistical Analysis

The value of each indicator was subjected to the Shapiro–Wilk normality test and the homogeneity of variance test, and there were no significant differences between the two years (\( p > 0.05 \)). The value of each indicator is the average of the data for 2018 and 2019. Statistical analysis was performed using IBM SPSS Version 26.0 (IBM, San Francisco, CA, USA). All data presented are the means of three replicates. Differences between means were tested by analysis of variance (ANOVA). Duncan’s test was performed to conduct multiple comparisons to identify significant differences between the means of different treatments. Differences were considered statistically significant when \( p < 0.05 \).

### 3. Results

#### 3.1. Effects of Irrigation Methods on Farmland Microclimate

##### 3.1.1. Effects of Irrigation Methods on Air Temperature

As shown in Figure 4, the differences in air temperature at different growth stages and different locations were significant (\( p < 0.05 \)). Throughout the whole growth period, the air temperature at different locations was T1 > T2 > T3. Compared with T1, the air temperature in the lower, middle, canopy, and 10 cm above the of T2 and T3 decreased by 0.25, 0.3, 0.25, and 0.57 °C; and 0.84, 0.89, 0.37, and 0.77 °C, respectively. Within the growth period, the air temperature of each treatment showed the following trend: budding stage > seedling stage > flowering stage > boll-opening stage. The air temperature at different locations of each treatment showed the law of being high in the middle and low on both sides, which may have been due to the concentration of leaves in the middle, poor permeability, and relatively blocked heat exchange.
Figure 4. The air temperature changes at different growth stages and locations under different irrigation methods: (a) is the variation of seeding stage; (b) is the variation of budding stage; (c) is the variation of flowering stage; (d) is the variation of Boll-opening stage.

3.1.2. Effects of Irrigation Methods on Relative Air Humidity

As shown in Figure 5, the relative air humidity of T3 and T2 was significantly higher than that of T1 throughout the whole growth period, and that of T3 was significantly higher than that of T2. The relative air humidity of the surface, middle, canopy, and above in T3 was on average 2.2%, 1.9%, 3%, and 1.5% higher than that of T1, and 0.9%, 0.4%, 0.2%, 0.1% higher than that of T2. All treatments showed a decreasing trend from bottom to top, and the relative air humidity increased throughout the growth period. This was due to the continuous improvement of vegetation coverage, reducing the amount of solar radiation, and causing the relative humidity to increase. In addition, after the flowering and boll-opening stages, the air temperature decreased significantly, resulting in a decrease in atmospheric evaporation and a further increase in relative air humidity. T3 adjusted the soil moisture content to a reasonable threshold via irrigation, which promoted the good growth of crops and effectively increased the relative humidity.

3.1.3. Effects of Irrigation Methods on Soil Temperature

As shown in Table 3, the diurnal variation trend of soil temperature in each treatment throughout the whole growth period was consistent, where it began to rise slowly from 08:00 and began to decline slowly from 16:00. The soil temperature differences between the T1, T2, and T3 treatments at different growth stages were significant, and the soil temperature generally followed the trend T1 > T2 > T3. The T2 and T3 treatments significantly reduced the soil temperature, which may be attributable to differences in crop growth and soil moisture levels. The T1 treatment had poor crop growth, low vegetation coverage, high solar radiation on the soil surface, and a slow increase in soil temperature. The T2 and T3 treatments showed the opposite trend. Irrigation in the T2 and T3 treatments was more frequent, and the soil moisture content was maintained at a high level, resulting in large soil heat capacity, and a significant decrease in soil temperature, making this difference more obvious.
Figure 5. The relative humidity changes at different growth stages and locations under different irrigation methods: (a) is the variation of seeding stage; (b) is the variation of budding stage; (c) is the variation of flowering stage; (d) is the variation of Boll-opening stage.

Table 3. Effects of different irrigation methods on soil temperature.

| Treatment | Growth Stage | Time Frame          |
|-----------|--------------|---------------------|
|           |              | 08:00–10:00 | 10:00–12:00 | 12:00–16:00 | 16:00–20:00 |
| T1        | Seedling stage | 22.7 ± 0.2 Ab | 23.1 ± 0.2 BCb | 30.1 ± 0.5 Cbc | 28.8 ± 0.4 Bc |
|           | Budding stage  | 23.9 ± 0.3 Ccd | 24.1 ± 0.1 Cc  | 34.0 ± 0.7 Cd  | 32.0 ± 0.6 Bd |
|           | Flowering stage| 24.2 ± 0.2 Cd  | 26.0 ± 0.4 Cd  | 31.0 ± 0.8 Cc  | 28.0 ± 0.3 Bbc |
|           | Boll-opening stage | 18.8 ± 0.2 Ba | 20.0 ± 0.2 Ba | 24.0 ± 0.4 Ca | 21.7 ± 0.7 Ba |
|           | Seedling stage  | 23.1 ± 0.1 Ab  | 22.7 ± 0.2 Ab  | 30.0 ± 0.7 Bbc | 28.2 ± 0.2 Abc |
|           | Budding stage  | 23.7 ± 0.3 BCc  | 24.0 ± 0.5 Bc  | 33.7 ± 0.7 Bd  | 30.0 ± 0.4 Ad  |
|           | Flowering stage| 24.0 ± 0.5 Bd  | 25.1 ± 0.5 BCd | 30.8 ± 0.8 Bc  | 27.6 ± 0.5 Bbc |
|           | Boll-opening stage | 18.1 ± 0.1 Aa | 19.0 ± 0.5 Aa | 23.6 ± 0.6 Ba | 21.4 ± 0.4 Aa |
| T2        | Seedling stage  | 22.8 ± 0.2 Aabc | 23.2 ± 0.1 Cb | 29.8 ± 0.8 Abc | 28.0 ± 0.5 Ac |
|           | Budding stage  | 23.5 ± 0.1 Ac  | 23.8 ± 0.3 Acd | 33.5 ± 0.5 Ad  | 29.7 ± 0.7 Ad  |
|           | Flowering stage| 23.8 ± 0.2 Ad  | 24.0 ± 0.4 Cd  | 30.0 ± 0.6 Ac  | 27.3 ± 0.3 Abc |
|           | Boll-opening stage | 18.0 ± 0.3 Aa | 18.7 ± 0.2 Aa | 23.6 ± 0.6 Aa | 21.6 ± 0.6 Ba |

Note: different capital letters indicate significant differences between different treatments at the same growth stage; different lowercase letters indicate significant differences between different growth stages of the same treatment.

3.2. Effects of Different Irrigation Methods on Physiological Indices, Growth Indices, and Yield

3.2.1. Effects of Different Irrigation Methods on Plant Height, Stem Thickness, and Leaf Area

Throughout the growth period, the plant height, stem thickness, and leaf area of T1 were at the lowest levels, and the growth with this treatment was the worst. Compared with T1, the plant heights of T2 and T3 were 30.51% and 35.59% higher at the seedling stage, 65.52% and 68.96% higher at the budding stage, 42.62% and 56.90% higher at the flowering stage, and 39.20% and 71.21% higher at the boll-opening stage, respectively. During the boll-opening stage, the plant height of T2 and T3 began to show significant differences. This shows that the irrigation threshold set by T3 is more sensitive and frequent, allowing the soil moisture content to be maintained within a reasonable range. Throughout the whole growth period, the stem thickness of T2 and T3 was significantly different from that of T1, while there were no significant differences between T2 and T3. Compared with T1, the stem thickness of T2 and T3 was 25.00% and 30.56% higher at the seedling stage, 30.56%
and 38.29% higher at the budding stage, 44.62% and 84.61% higher at the flowering stage, and 28.12% and 46.88% higher at the boll-opening stage, respectively. It can be seen from Figure 6 that the leaf area of T1, T2, and T3 had no meaningful differences at the seedling stage. After the budding stage, the leaf area of T2 and T3 was significantly higher than that of the T1 treatment, and the difference was significant. Compared with T1, the leaf area of T2 and T3 was 23.85% and 61.28% higher at the budding stage, 144.16% and 191.35% higher at the flowering stage, and 101.94% and 162.91% higher at the boll-opening stage, respectively. T3 used real-time monitoring of soil moisture to determine irrigation, so the cotton root system maintained a suitable state of soil moisture, which ensured the safe growth of the cotton.

Figure 6. Dynamic changes in cotton plant height, stem thickness, and leaf area throughout the whole growth period.

3.2.2. Effects of Irrigation on Photosynthesis and Transpiration of Cotton

During the seedling stage, Pn was relatively low, with an average value of 13.51 μmol·m⁻²·s⁻¹ across the different treatments (Table 4), but then peaked during budding stage, reaching an average value of 27.81 μmol·m⁻²·s⁻¹ across the different treatments. Then, Pn decreased rapidly during the flowering and boll-opening stages, reaching its lowest values at the boll-opening stage, with an average of 12.81 μmol·m⁻²·s⁻¹. Patterns in Tr were similar to those in Pn across the different treatments throughout the cotton-growing season. From the seedling stage to the budding stage, Tr values increased from 3.30 μmol·m⁻²·s⁻¹ to the maximum value 4.88 μmol·m⁻²·s⁻¹. However, from the budding stage to the boll-opening stage, Tr reduced to 3.93 μmol·m⁻²·s⁻¹. WUEins at different treatments increased first, then decreased, and then rebounded slightly. In the budding stage, all treatments reached the maximum value of WUEins. The maximum value of T3 was 5.98, which was 3.46% and 10.95% higher than the maximum values of T2 and T1, respectively. With the progress of the growth period, Gs showed a downward trend, while Ci showed the opposite. From the seedling stage to the boll-opening stage, the Gs values of T1, T2, and T3 decreased by 74.77%, 68.96%, and 63.83%, respectively, while their Ci values increased by 27.90%, 22.65%, and 17.54%, respectively.

Multiple analyses showed that there were significant differences in Pn between T3 and T2, and between T3 and T1, throughout the whole growth period. However, there were no significant differences in Pn between T2 and T1 at the budding stage and the boll-opening stage. With the development of the growth period, the difference in Tr between T1, T2, and T3 gradually narrowed. There were no significant differences in Tr between T1, T2, and T3 in the boll-opening period. With the development of the growth period, the differences in WUEins values between T1, T2, and T3 gradually became obvious, and there were significant differences between the three treatments in the boll-opening period. Throughout the whole growth period, the Gs and Ci of the T1, T2, and T3 treatments showed significant differences.
Table 4. Effects of different irrigation methods on net photosynthetic rate (Pn), transpiration rate (Tr), intercellular CO₂ concentration (Ci), stomatal conductance (Gs), and WUEins.

| Growth Stage   | Treatment | T1                | T2                | T3                | Average |
|----------------|-----------|-------------------|-------------------|-------------------|---------|
|                | T1        | T2                | T3                |       |
| Seedling stage | Pn        | 11.36 ± 0.31 a    | 13.53 ± 0.19 b    | 15.65 ± 0.53 c    | 13.51   |
|                | Tr        | 2.87 ± 0.18 a     | 3.22 ± 0.26 a     | 3.81 ± 0.27 b     | 3.30    |
|                | WUEins    | 3.62 ± 0.28 a     | 3.91 ± 0.27 a     | 3.85 ± 0.19 a     | 3.79    |
|                | Gs        | 362.11 ± 3.79 a   | 386.37 ± 5.17 b   | 480.21 ± 5.42 c   | 409.56  |
|                | Ci        | 286.74 ± 3.62 a   | 311.51 ± 5.30 b   | 368.17 ± 4.79 c   | 322.14  |
|                | Pn        | 23.59 ± 0.77 a    | 27.88 ± 0.80 a    | 31.95 ± 0.68 c    | 27.81   |
|                | Tr        | 4.38 ± 0.30 a     | 4.88 ± 0.59 ab    | 5.38 ± 0.51 b     | 4.88    |
| Budding stage  | WUEins    | 5.39 ± 0.19 a     | 5.78 ± 0.87 a     | 5.98 ± 0.70 a     | 5.72    |
|                | Gs        | 343.61 ± 4.61 a   | 377.56 ± 4.22 b   | 432.11 ± 5.63 c   | 384.43  |
|                | Ci        | 322.91 ± 6.11 a   | 355.91 ± 5.93 b   | 402.97 ± 6.33 c   | 360.60  |
|                | Pn        | 13.44 ± 0.24 a    | 17.43 ± 0.13 b    | 21.44 ± 0.20 c    | 17.44   |
|                | Tr        | 3.98 ± 0.30 a     | 4.31 ± 0.31 a     | 4.98 ± 0.36 b     | 4.42    |
| Flowering stage| WUEins    | 3.39 ± 0.20 a     | 4.06 ± 0.26 bc    | 4.36 ± 0.36 c     | 2.60    |
|                | Gs        | 256.99 ± 5.77 a   | 289.77 ± 6.97 b   | 352.88 ± 5.66 c   | 299.88  |
|                | Ci        | 332.17 ± 7.17 a   | 356.77 ± 6.17 b   | 417.77 ± 8.35 c   | 368.90  |
|                | Pn        | 11.91 ± 0.44 a    | 12.19 ± 0.39 a    | 14.34 ± 0.52 b    | 12.81   |
|                | Tr        | 3.67 ± 0.50 a     | 4.01 ± 0.30 a     | 4.12 ± 0.40 a     | 3.93    |
| Boll-opening stage | WUEins | 3.19 ± 0.30 b     | 3.06 ± 0.33 a     | 3.52 ± 0.46 c     | 3.26    |
|                | Gs        | 207.19 ± 8.76 a   | 228.67 ± 5.37 b   | 293.12 ± 1.42 c   | 242.99  |
|                | Ci        | 366.71 ± 6.63 a   | 382.07 ± 7.77 b   | 432.76 ± 8.96 c   | 393.85  |

Note: different lowercase letters indicate significant differences between different treatments at the same growth stage.

3.3. Cotton Yield Components

Table 5 shows the yield components of cotton. The numbers of plants between T2 and T1, and between T3 and T1, were significantly different, but there were no significant differences between T2 and T3. This indicates that T2 and T3 met the requirements of plant survival, while T1 reduced the plant survival rate due to low water-use efficiency. The number bolls, weight of 30 bolls, yield, and iWUE of T1, T2, and T3 showed significant differences. The yield and iWUE of T3 were significantly higher than those of T1 and T2. T3 had obvious advantages in water saving and yield increase.

Table 5. Cotton yield components under different irrigation methods.

| Treatment | Number of Plants | Number of Bolls | Weight of 30 Bolls | Yield | iWUE  |
|-----------|------------------|-----------------|-------------------|-------|-------|
| T1        | 38 ± 3.6 a       | 183 ± 6.03 a    | 149.05 ± 7.01 a   | 3489.75 ± 91.80 a | 0.49 ± 0.02 a |
| T2        | 46 ± 1.5 b       | 264 ± 12.59 b   | 183.23 ± 5.38 b   | 5717.40 ± 77.25 b | 0.95 ± 0.01 b |
| T3        | 48 ± 2.5 b       | 282 ± 15.1 c    | 196.58 ± 5.53 c   | 6496.70 ± 101.40 c | 1.22 ± 0.02 c |

Note: different lowercase letters indicate significant differences among different treatments of the same indicator.

In order to understand the effect of each index on yield, the factors of yield improvement had to be made clear. The farmland microclimate index was fitted and analyzed with the crop yield and crop growth physiological indices (Table 6). Air temperature, stem diameter, net photosynthetic rate, transpiration rate, stomatal conductance, and yield have specific functional relationships. The relative humidity, plant height, leaf area, and yield had a high degree of fitting. This shows that the farmland microclimate and cotton growth index have great influence on cotton yield. The correlation between soil temperature and yield was weak, and the fitting degree was only 0.32. Other than air temperature and soil temperature, other indices were positively correlated with yield.

The physiological growth and development of plants and the microclimate characteristics of the farmland throughout the whole growth period of each treatment were standardized, and the heat change map was constructed. From the heat map, the dif-
ferences between each treatment could be seen more intuitively. It can be observed in Figure 7 that according to the chromatographic stratification standard, the overall effect of the T3 treatment is significantly better than that of T2 and T1 in the two indicators of crop relative humidity and air temperature. In other words, the T3 treatment maintained a lower temperature and higher relative humidity throughout the whole growth period, compared with T2 and T1. This is more conducive to cotton growth. In terms of physiological growth indices of crops, the indices of the T3 treatment were significantly better than those of the T2 and T1 treatments, and the indices of the T2 treatment were also better than those of T1. As a whole, the T3 treatment was preferable to the other two treatments for regulating the farmland microclimate and promoting cotton growth and development.

Table 6. Fitting analysis of physiological growth indices and farmland microclimate indices with yield.

| Index               | Fitting Equation                  | R²   | p Value |
|---------------------|-----------------------------------|------|---------|
| Air temperature     | $y = -210.38x + 6972.90$         | 0.80 | <0.01   |
| Relative humidity   | $y = 28.89x - 795.33$            | 0.87 | <0.01   |
| Soil temperature    | $y = -89.57x + 6993.10$          | 0.32 | <0.05   |
| Plant height        | $y = 8.36x - 65.55$              | 0.86 | <0.01   |
| Leaf area           | $y = 0.26x + 126.26$             | 0.84 | <0.01   |
| Stem thick          | $y = 531.50x - 47.07$            | 0.64 | <0.01   |
| $Pn$                | $y = 28.57x - 121.20$            | 0.76 | <0.01   |
| $Tr$                | $y = 166.58x - 401.36$           | 0.70 | <0.01   |
| $Gs$                | $y = 1.74x - 204.78$             | 0.76 | <0.01   |
| $Ci$                | $y = 1.90x - 380.81$             | 0.72 | <0.01   |

Figure 7. Thermal map of variation of parameters related to different irrigation methods.
4. Discussion

Plant height, leaf area, and stem thickness are important traits of crop growth and important indicators for evaluating crop growth [34,35]. Cotton plant height directly affects cotton density and light utilization. Cotton stem thickness has an important impact on crop nutrient absorption and migration [36]. The effect of cotton leaf area on green leaf coverage and light-use efficiency is significant, and it is also one of the important indices to measure early onset of cotton [37]. With the rapid decrease in water supply and the increase in crop water demand, people are more and more interested in precise irrigation technology to improve water productivity [38,39]. Wang [40] pointed out that a reasonable irrigation threshold can improve the growth of cotton, which is similar to the conclusion of this study. The soil environment and climate are constantly changing, and irrigation systems that can meet crops’ water demand should also be available, and more accurate information irrigation is needed to achieve this purpose. Automatic drip irrigation as a technology to obtain irrigation information is more precise than the general artificial irrigation technology, and the differences in each growth index between the three treatments were most obvious in the flowering stage. The flowering period is a sensitive period for cotton with respect to watering [41]. The amount of irrigation must be kept within a reasonable range. Insufficient irrigation will lead to the decrease in the number of cotton bolls and a decrease in cotton yield. Excessive irrigation will also lead to delays to the cotton growth period, and the cotton bolls will not produce cotton, which will also reduce its yield [42]. This study showed that the plant height, leaf area, and stem diameter of T3 at the flowering and boll-opening stages were significantly higher than those of the T2 and T1 treatments due to advanced water and fertilizer management techniques, and the cotton yield was significantly increased. It can be seen that automatic drip irrigation under mulch can make reasonable irrigation decisions in the irrigation-sensitive period of cotton by collecting information on the soil and atmospheric environment, so as to improve crop growth and yield.

The photosynthesis, growth, and development of crops depend on their genetic characteristics to a large extent, but the external environment also has a significant impact on them [43]. The construction of a reasonable farmland microclimate environment can promote the growth of crops and the improvement of photosynthetic capacity [44], which is also one of the important factors for the improvement of cotton yield. Academics [45,46] found that the fertilizer level of rice was inversely proportional to the air temperature within the population, but positively associated with the relative humidity. This is consistent with the results of this study. The air temperature of the T3 treatment was significantly lower than that of the T2 and T1 treatments (p < 0.05), while the relative humidity of the T3 treatment was significantly higher than that of the T2 and T1 treatments (p < 0.05). After the seedling stage, the soil temperature and air temperature were both negatively correlated with yield, although relative humidity was not. This demonstrates that the technology of automatic drip irrigation under mulch can provide a colder and wetter environment for crops. Under automatic irrigation, the growth and the vegetation coverage rate of crops are better than those attained when using on-film irrigation or under-film drip irrigation. Thus, the automatic irrigation method has a good shielding effect against the light radiation, which not only improves the light-utilization efficiency, but also protects the soil from direct light. In addition, with frequent irrigation at the beginning of the flowering period, the soil moisture content is always higher, the soil heat capacity is increased, and the soil temperature is noticeably decreased. In this study, the on-film irrigation had the lowest planting density and the worst growth potential. Although the planting density of the under-film drip irrigation was the same as that with automation, the growth potential was not as good as that of automation. Therefore, different irrigation technologies regulate the farmland microclimate through their planting density, and affect the growth potential of crops. This shows that the physiological growth of crops and the microclimate of farmland are mutually connected.
Photosynthesis is the basis of all life activities of crops, and the improvement of cotton yield is also based on the improvement of photosynthetic products. The strength of photosynthetic capacity is affected by the external climatic conditions and the growth conditions of crops [47]; suitable growth environment and conditions can improve the photosynthetic capacity of crops [48]. The results showed that the net photosynthetic rate, transpiration rate, stomatal conductance, and intercellular CO$_2$ concentration of drip irrigation were significantly higher than those of the other two treatments ($p < 0.05$). The physiological indices of each treatment were positively correlated with the yield. This study further shows that farmland microclimate, crop physiological growth characteristics, and yield are mutually connected, and that these factors are affected by factors such as fertility, irrigation, and soil. This experiment further highlighted that the effect of T3 on these factors was significantly better than that of T2 and T1.

The crop yield is the point of greatest concern for farmers. If we take the increase in yield as the main basis of our evaluation, the yield-increasing effect of T3 was the most obvious. In arid areas such as Xinjiang, water resources are very scarce [49]. When increasing cotton production, the shortage of water resources in northern Xinjiang should also be considered. Therefore, it is necessary to consider irrigation strategies more comprehensively. This study found that the yield and iWUE of T3 were significantly higher than those of T1 and T2. T3 is the optimal irrigation strategy to achieve water savings and yield increase.

In order to save water and optimize agronomic factors, international modifications have been introduced that improve the production of perennial tropical crops [50]. Today, for the irrigation of cotton, bananas, and other crops, farmers mainly use sprinklers (under foliage) and drip irrigation; with respect to the latter, there are crops such as bananas that grow in an inconsistent and random way, deviating from the original planting line, and after several years the plants will no longer be aligned with the drip line, reducing the irrigation efficiency. Additionally, drip irrigation in tropical territories has been found to be a method that saves water and reduces runoff, allowing water to trickle slowly towards plant roots, and improving productivity under certain physical or morphological soil properties [51,52].

Today, the global water crisis has seriously affected the development of agriculture [53]. Drip irrigation is recognized as the most advanced irrigation technology in the world, and has a very wide range of application—especially in Xinjiang, China, where water resources are seriously short, and the drip-irrigation area has reached $3.53 \times 10^6$ hm$^2$ [54]. This provides basic conditions for the implementation of automatic drip irrigation. In addition, the rapid development of the Internet, computer technology, and automation has further promoted the development of smart agriculture and agricultural informatization [55,56]. Combined with the findings of this study, automatic drip irrigation has obvious advantages in water saving and yield increase, and is an important measure to achieve the sustainable development of agriculture, with very optimistic prospects for future development.

5. Conclusions

(1) Automatic drip irrigation technology significantly increased relative humidity, and reduced soil and air temperature, providing a good farmland microclimate environment for crop growth.

(2) The growth and photosynthetic capacity of cotton under automatic drip-irrigation technology were significantly higher than under the other two treatments, improving the yield of cotton. The yield of automatic drip irrigation was 5.8% and 73.2% higher than that of drip irrigation and film irrigation, respectively.

(3) The physiological growth indices of cotton under different irrigation methods, along with the farmland microclimate indices, were positively correlated with cotton yield, except for soil and air temperature. Based on the analysis of each index, automatic drip irrigation under mulch is the optimal way to regulate physiological and farmland microclimate indices of cotton growth.
(4) Continuous implementation of automatic irrigation in drip-irrigation application areas is an important measure to achieve water saving and yield increase, and has very broad development prospects.

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