Optimizing water and nitrogen thresholds for drip-irrigated cotton under mulch in Xinjiang based on water-nitrogen synergy

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Abstract: To optimize irrigation and nitrogen management for mulched drip-irrigated cotton in Xinjiang, a field experiment investigated varying irrigation amounts, nitrogen application rates, and fertilization frequencies on cotton growth, yield, water and nitrogen use efficiency, and fiber quality. The experiment involved three factors: irrigation amount (360 and 450 mm, denoted as W_1 and W_2), nitrogen application rate (420 and 560 kg/hm^2, denoted as N_1 and N_2), and fertilization frequency (5 and 8 times, denoted as F_1 and F_2). A control treatment ($W_1N_0F_0$) without nitrogen application was also included. Nine treatments with three replications were established. Different treatment significantly affected cotton growth traits, yield, water and nitrogen use efficiency, and fiber quality. Compared with $W_1N_0F_0$, the $W_1N_1F_1$ treatment demonstrated particularly strong performance. Plant height, stem diameter, and fiber elongation increased significantly by 16.83%, 20.63%, and 11.11%, respectively (p<0.01). In addition, water use efficiency was 23.64% higher than that of $W_1N_0F_0$, and nitrogen fertilizer productivity reached 42.86 kg/kg, indicating relatively optimal levels. For yield maximization alone, the $W_1N_1F_2$ treatment increased yield by 36.86% over $W_1N_0F_0$. It also significantly increased boll weight and number. However, its water use efficiency and nitrogen fertilizer productivity were lower than in $W_1N_1F_1$. Principal component analysis comprehensively evaluated cotton growth traits, yield components, water and nitrogen use efficiency, and fiber quality. The $W_1N_1F_1$ treatment received the highest comprehensive score. This treatment balanced high yield with efficient resource use, achieving synergistic improvements in yield, efficiency, and fiber quality. Therefore, under these conditions, the $W_1N_1F_1$ treatment (irrigation amount of 360 mm, nitrogen application of 420 kg/hm^2, and fertilization frequency of five times) is recommended as optimal for high yield and quality in mulched drip-irrigated cotton in Xinjiang. This optimization model not only ensures the efficiency of water utilization and nutrient balance, but also provides key technical references for cotton production in Xinjiang and similar ecological regions.

Keywords: water-nitrogen coupling, cotton, yield, water and nitrogen use efficiency
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1 Introduction

Cotton (*Gossypium hirsutum* L.) is a vital cash crop in China. The unique climatic conditions of Xinjiang, characterized by abundant sunlight, suitable temperatures, and low humidity, foster the growth of high-quality cotton. As one of the largest cotton-producing regions in the world, cotton serves as a primary economic resource for local farmers[1]. Against the backdrop of adjustments in agricultural planting structures, the cotton cultivation area in Xinjiang expanded to 2.25×10^6 hm^2 in 2023, with a yield of 2157.6 kg/hm^2, accounting for 90.99% of China's total cotton production. The region represents a typical irrigated agricultural area, featuring high temperatures, low precipitation, and long sunshine hours[2]. However, rapid socio-economic and industrial development has exacerbated the shortage of agricultural water resources, which is particularly critical for cotton production in Xinjiang due to its reliance on irrigation. To address water constraints, drip irrigation integrated with water and fertilizer management has been widely adopted.

Crop growth fundamentally depends on nitrogen availability, which is often limited in arid soils[3]. During various growth stages of cotton, the balance between vegetative and reproductive growth, as well as soil water-nitrogen retention, is significantly influenced by irrigation and fertilization practices. Water and nitrogen are key determinants of crop physiology and yield, and their interaction, rather than their individual effects, is crucial for achieving high

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yield and efficient resource use[4].

However, previous studies on mulch-integrated drip-irrigated cotton have largely focused on optimizing irrigation or nitrogen strategies in isolation, often overlooking their synergistic effects and lacking comprehensive analysis of multiple response variables such as growth, yield components, resource use efficiency, and fiber quality. Optimal synergy between water and nitrogen elements can significantly enhance the potential for yield[5]. Elevated irrigation levels improve nitrogen retention within the root zone[6], thereby increasing crop water use efficiency[7], while nitrogen enhances photosynthetic efficiency by modulating thermal accumulation and leaf expansion rates[8]. Conversely, insufficient water and nitrogen reduce aboveground biomass[9], while excessive nitrogen application induces excessive vegetative growth, prolongs the reproductive cycle[10], and can lead to yield reduction even when slightly oversupplied[11]. Soil moisture variations directly affect physiological performance; moderate water stress can enhance photosynthetic efficiency and increase the translocation rates of assimilates and nitrogen to reproductive organs[12], improving both yield and nitrogen utilization efficiency[13]. In contrast, excessive irrigation or fertilization delays cotton maturation and compromises fiber quality[14]. Therefore, under different irrigation scenarios, investigating the water-nitrogen coupling effect by adjusting the amount and frequency of fertilization holds dual benefits for supporting cotton development and mitigating the impacts of over-fertilization, which is a critical consideration for the Xinjiang cotton system.

Consequently, field-based exploration of full-season water-nitrogen regulation is essential to elucidate its integrated effects and inform optimized management. This research aims to clarify the comprehensive impacts of water-nitrogen synergy throughout the growth cycle on the growth dynamics, water consumption, cotton yield, fiber quality, and resource-use efficiency of drip-irrigated cotton. The specific objectives are to: 1) quantify the effects of different water and nitrogen supply regimes on key growth indicators, seed cotton yield, and yield components; 2) determine the regulatory effects of water-nitrogen interaction on fiber quality, crop water consumption, and water-use efficiency; 3) determine the optimal water and nitrogen fertilizer management plan for jointly enhancing production and quality. This study provides a theoretical basis for efficient water and nitrogen utilization and sustainable cotton industry in Xinjiang region.

2 Materials and methods

2.1 Experimental field

The experiment was conducted in 2019 at the Irrigation Experiment Station of the Water Conservancy Bureau, First Division of the Xinjiang Production and Construction Corps (40°06′N, 81°02′E; elevation 1014 m). The station lies within a plain-desert oasis at the confluence of the three major source rivers of the Tarim River, approximately 10 km from Aral City. This region experiences an extremely arid climate, featuring persistently dry conditions, scarce rainfall, and intense evaporation. The multi-year average temperature is 11.3°C, with annual precipitation averaging 45.7 mm (Figure 1). The area receives about 2950 h of sunshine annually, with a mean total solar radiation of 6000 MJ/m^2 and a pan evaporation rate of 2200 mm. The climate features relative humidity of 47%-60%, an accumulated temperature greater than or equal to 10.0°C of 3450.0°C-4432.0°C, and an average frost-free period of 207 d. The experimental soil is sandy loam (Table 1), with the groundwater table located more than 3 m below the surface. The pH of the cultivated soil ranged from 7.8 to 8.0, and the physicochemical properties of the soil layer at 0-80 cm depth are presented in Table 2.

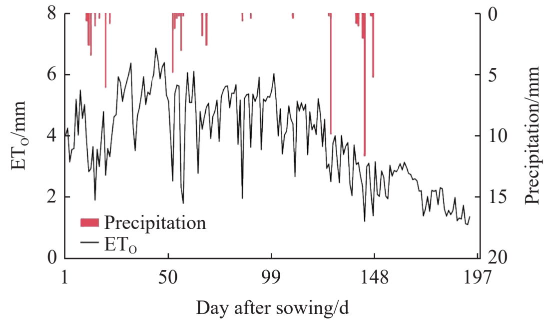


Figure 1 Crop evapotranspiration (ET$_O$) and precipitation during the cotton growing season

Table 1 Soil physical properties

Depths/ cm	Clay/ %	Silt/ %	Sand/ %	Wilting coefficient/ cm^3·cm^{-3}	Saturated water content/ cm^3·cm^{-3}	Field capacity/ cm^3·cm^{-3}	Soil bulk density/ g·cm^{-3}
0-20	2.43	41.49	56.08	0.10	0.25	0.21	1.58
20-40	2.56	41.40	56.05	0.10	0.28	0.24	1.55
40-60	2.88	42.82	54.29	0.12	0.31	0.25	1.46
60-80	2.60	41.40	56.00	0.13	0.34	0.26	1.47
80-100	2.60	41.40	56.00	0.12	0.33	0.25	1.50

Table 2 Basic physical and chemical properties of soil

Depths/ cm	Total N/ mg·kg^{-1}	Total P/ mg·kg^{-1}	Available P/mg·kg^{-1}	Available K/mg·kg^{-1}	Alkaline hydrolysis N/ mg·kg^{-1}	Organic matter/ g·kg^{-1}
0-20	0.39	0.53	35.09	197.25	42.46	5.75
20-40	0.25	0.48	10.44	192.57	25.08	4.71
40-60	0.17	0.42	3.96	139.71	10.15	3.49
60-80	0.12	0.39	2.78	90.19	6.30	2.37

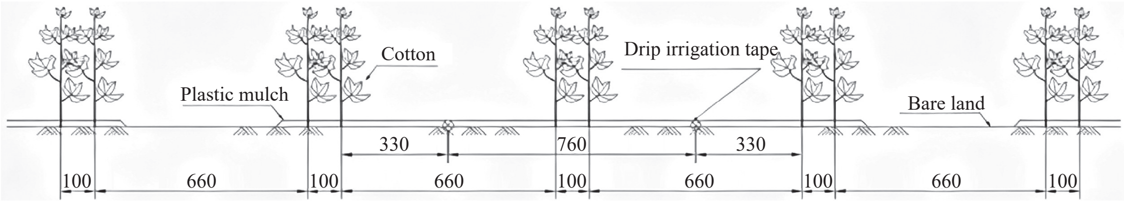
2.2 Cultivation practices

The experimental crop was cotton (variety Xinluzhong 27), provided by Xinjiang Condy Agri-Genetics Co, Ltd. It was cultivated using a machine-harvestable planting system configured in a single-film, double-belt pattern with six rows per film (Figure 2). Plant spacing averaged 10 cm, resulting in a planting density of 2.6×10^5 plants/hm^2. The total experimental area was approximately 1728 m^2. Sowing and harvesting were carried out on April 17 and October 24, respectively. Prior to sowing, a basal fertilizer of diammonium phosphate (total nutrient content≥64%) was applied at a rate of 750 kg/hm^2. At the budding stage, urea (total nitrogen≥46.4%) was top-dressed through fertigation via a pressure differential fertilization tank. Pesticide application and other agronomic practices followed local high-yield cotton field protocols.

The drip irrigation system employed flat drip tapes installed beneath the plastic film, with emitters spaced 30 cm apart and a flow rate of 2.8 L/h^{-1}. Each treatment area was supplied with an independent branch pipe and equipped with a field control valve, ensuring fully independent water supply and management. Pump pressure was regulated by a frequency converter, while the irrigation amount per treatment was monitored and controlled using a dedicated water meter. Three plots were grouped into one experimental unit. The system header was fitted with a pressure-regulating valve and a pressure gauge to maintain stable overall pressure.

2.3 Experimental design

The experiment comprised three factors: irrigation amount (360 and 450 mm, denoted as W$_1$ and W$_2$, respectively), nitrogen fertilizer rate (420 and 560 kg/hm², denoted as N_1 and N_2, respectively), and fertilization frequency (5 and 8 times, denoted as F_1 and F_2, respectively). A control treatment ($W_1N_0F_0$) with no nitrogen application was also included. A total of nine treatment combinations were tested, using a randomized complete block design (RCBD) with three replicates, as detailed in Table 3. The 27 experimental plots were arranged in three blocks, with each block containing all nine treatments assigned randomly.



Note: The units of the numbers in the figure are millimeters, mm.

Figure 2 Planting pattern of cotton with drip irrigation under film mulching

Table 3 Experimental design for irrigation and fertilization scheduling

Treatment	Irrigation account/mm			Irrigation cycles/d			N fertilizer application rate/kg·hm²			Nitrogen application frequency/times		
	Bud stage	Flowering and boll stage	Flocculation stage	Bud stage	Flowering and boll stage	Flocculation stage	Bud stage	Flowering and boll stage	Flocculation stage	Bud stage	Flowering and boll stage	Flocculation stage
$W_1N_1F_1$	45	37.5	45	12	7	20	105	210	105	1	3	1
$W_1N_1F_2$	45	37.5	45	12	7	20	105	210	105	1	6	1
$W_1N_2F_1$	45	37.5	45	12	7	20	70	420	70	1	3	1
$W_1N_2F_2$	45	37.5	45	12	7	20	70	420	70	1	6	1
$W_2N_1F_1$	45	52.5	45	12	7	20	105	210	105	1	3	1
$W_2N_1F_2$	45	52.5	45	12	7	20	105	210	105	1	6	1
$W_2N_2F_1$	45	52.5	45	12	7	20	70	420	70	1	3	1
$W_2N_2F_2$	45	52.5	45	12	7	20	70	420	70	1	6	1
$W_1N_0F_0$	45	37.5	45	12	7	20	0	0	0	0	0	0

2.4 Measurements

2.4.1 Soil water content and crop water consumption

The soil moisture content of cotton field was observed by stratified sampling (0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80, 80-100 cm) with soil drying method. To account for the spatial heterogeneity of cotton growth under film-mulched drip irrigation, three sampling points were designated for each treatment: within the narrow row beneath the film, within the wide row beneath the film, and in the bare soil outside the film. Measurements were taken throughout the cotton growth period at intervals of 5 to 7 d, with observations conducted both before and after irrigation and rainfall events.

According to the principle of water balance[15], the field water consumption of cotton in each treatment was calculated as follows:

$$\mathrm{ET} = \mathrm{P} + \mathrm{M} + \mathrm{G} - \mathrm{R} - \mathrm{SI} + \Delta \mathrm{W} \tag{1}$$

where, ET denotes crop water consumption during the cotton growth period, mm; P, M, G, R, and SI denote precipitation, irrigation amount, groundwater recharge, surface runoff, and deep percolation, respectively, mm. Throughout the growing season, no effective precipitation exceeding 10 mm was recorded, P=0. Groundwater depth in the experimental area exceeded 7.5 m, making any contribution from groundwater recharge negligible, G= 0. Drip irrigation was delivered using a drip belt, confining water to the root zone and eliminating surface runoff, R=0. Irrigation amounts were determined via the water balance equation, and no deep percolation occurred in the experimental field; accordingly, SI=0.

$$\Delta W = W_i - W_{i+1} \tag{2}$$

where, ΔW denotes the reduction in soil water storage, while W_i and W_{i+1} denote the soil water storage within the planned wetting layer at the start and end of the period, respectively, mm.

For water balance, water content was converted to soil water storage, W:

$$W = 10 \times \theta \times \gamma \times h \tag{3}$$

where, W denotes soil water storage, mm; θ denotes mass-based water content, %; γ denotes bulk density, g/cm³; and h denotes wetting layer depth, cm.

2.4.2 Leaf area index (LAI), plant height, and aboveground biomass

At the four-leaf stage (when four true leaves were fully expanded), ten representative cotton plants (five from inner rows and five from outer rows) were selected from each treatment for measurements of plant height, leaf area, and stem diameter. During the key biomass accumulation phase (from the bud stage to the flowering and boll stage), intensive sampling was carried out at approximately 7-day intervals, whereas during periods of slower growth, sampling intervals were extended to about 15 d. Phenological stages were documented throughout the study, along with counts of flowers, buds, and bolls.

Plant height was measured vertically from the ground to the apex of the main stem using a ruler with 1 mm precision. Basal stem diameter was recorded in both east-west and north-south orientations using a Vernier caliper accurate to 0.02 mm. Leaf area was determined by measuring the maximum length and width of each fully green leaf with a 1 mm-precision plastic ruler. For each treatment, aboveground biomass was assessed by sampling 5 plants from both inner and outer rows (10 plants total). Leaves, stems, and buds (including bolls and squares) were dried at 110°C for 30 min in a forced-air oven, then weighed with an electronic balance accurate to 0.01 g. The summarized results are presented as follows:

$$\mathrm{LAI} = 0.75 \times \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \left(L_{ij} \times W_{ij} \right)}{m} \times N/S \tag{4}$$

where, LAI is the leaf area index; L_{ij} is the leaf length of the jth leaf on ith plant, cm; W_{ij} is the largest width of the jth leaf on ith plant, cm; m is the measured number of plants; n is the number of leaves per plant; N is the plant number of a plot; S is land area of a plot, cm^2.

Aboveground biomass measurement: Fresh samples (stems and leaves) were initially placed in an oven at 105°C for 0.5 h, followed by drying at 75°C until constant weight was achieved. The data obtained from these samples were then converted to aboveground biomass per hectare, with reference to plant density.

2.4.3 Cotton yield and composition

At the end of the experiment, 20 plants (10 plants in each row) were continuously selected for each treatment for seed testing. Each plot was picked in batches and dried, weighed with an electronic balance with an accuracy of 0.1 g, and the seed cotton yield was measured by the actual harvest yield, which was converted into cotton yield per hectare.

2.4.4 Cotton quality

After harvest, the cotton quality test was carried out in the Cotton Quality Supervision and Inspection Test Center of the Ministry of Agriculture. Batches of samples were selected, and HVICC (High Volume Instrument Calibration Cotton) standard was used to evaluate the quality indices of cotton fibers, including cotton fiber length, uniformity index, micronaire value, elongation, and breaking strength.

2.4.5 Calculation of water use efficiency (WUE) and nitrogen partial factor productivity (NPFP)

Water use efficiency (WUE, kg/m^3), nitrogen partial factor productivity (PFPN, kg/kg) was calculated by Equation (5).

$$\begin{aligned} \mathrm{WUE} &= Y/\mathrm{ET} \\ \mathrm{NPFP} &= Y/N \end{aligned} \tag{5}$$

where, WUE is water use efficiency, kg/m^3; NPFP is the nitrogen partial factor productivity, kg/kg; Y is cotton yield, kg/hm^2; and N is nitrogen application rate, kg/hm^2.

2.4.6 Meteorological data

The data of maximum temperature, minimum temperature, relative humidity, wind speed, sunshine hours, solar radiation, and precipitation were measured by automatic weather stations installed in the experimental field.

2.5 Statistical analyses

Excel 2019 software was used for data collation, and SPSS 26.0 data analysis software was used for statistical analysis. The analysis of variance used the LSD method to test the significant difference between different levels under the same experimental factor (a=0.05), respectively.

3 Results

3.1 Effects of water and nitrogen regulation on cotton growth index

The study evaluated the effect of water and nitrogen regulation on cotton growth index, with results summarized in Table 4. This study shows that reasonable irrigation and fertilization measures have a significant promoting effect on the growth and development of cotton. Compared with the control treatment ($W_1N_0F_0$), the treatments with nitrogen fertilizer increased the plant height, stem diameter, leaf area index, and aboveground biomass by –1.81% to 16.83%, –5.07% to 20.63%, 5.46% to 30.17%, and 3.36% to 45.58%, respectively. During the bud stage, except for the N_1F_2 treatment which decreased the plant height with the increase of irrigation amount, the plant height of the other treatments showed an upward trend. The plant height of the W_1N_1 and W_2N_2 treatments increased with the increase of fertilization frequency, while the plant height of the W_1N_2 and W_2N_1 treatments decreased with the increase of fertilization frequency; except for the W_2F_1 treatment, the increase in nitrogen application amount increased the plant height. The response of stem diameter to irrigation amount and fertilization frequency was not obvious, but under different water and fertilizer parameters, the $W_1N_1F_1$ and $W_2N_2F_2$ treatments reached the minimum and maximum values respectively, with an increase of –15.72% and 3.73% compared to the control. The leaf area index increased with the increase of irrigation amount and fertilization frequency in all treatments except for the N_1F_2 treatment, which decreased; under the same irrigation amount and fertilization frequency, the leaf area index decreased with the increase of nitrogen application amount. The aboveground biomass increased with the increase of irrigation amount, decreasing in the N_1F_1 and N_1F_2 treatments and increasing in the N_2F_1 and N_2F_2 treatments. With the increase of fertilization frequency, except for the W_1N_2 treatment, all other treatments increased; with the increase of nitrogen application amount, all treatments except the W_1F_2 treatment showed a different degree of increase.

Table 4 Effects of water and nitrogen regulation on cotton growth indices

Treatment	Plant height/cm		Stem thickness/mm		LAI/$cm^2 \cdot cm^{-2}$		Aboveground biomass/$kg \cdot hm^{-2}$	
	Bud stage	Flowering and boll stage	Bud stage	Flowering and boll stage	Bud stage	Flowering and boll stage	Bud stage	Flowering and boll stage
$W_1N_1F_1$	31.50^{d}	85.67^{a}	7.24^{b}	9.22^{a}	1.72^{bc}	4.06^{c}	6398.60^{c}	15 070.47^{ab}
$W_1N_1F_2$	37.90^{bcd}	79.67^{a}	7.46^{ab}	8.70^{a}	2.04^{a}	4.53^{a}	7402.20^{b}	15 299.70^{a}
$W_1N_2F_1$	43.20^{abcd}	68.00^{a}	8.75^{ab}	8.42^{a}	1.15^{e}	3.67^{e}	7554.69^{b}	10 861.93^{e}
$W_1N_2F_2$	42.64^{abcd}	68.67^{a}	8.40^{ab}	8.70^{a}	1.37^{d}	3.83^{d}	6571.93^{c}	15 215.20^{a}
$W_2N_1F_1$	54.10^{a}	72.00^{a}	7.98^{ab}	8.79^{a}	1.75^{b}	4.27^{b}	5850.86^{e}	15 110.33^{ab}
$W_2N_1F_2$	34.98^{cd}	75.67^{a}	8.06^{ab}	8.68^{a}	1.40^{d}	3.88^{d}	6119.53^{d}	14 664.00^{bc}
$W_2N_2F_1$	43.70^{abc}	82.00^{a}	8.80^{ab}	10.77^{a}	1.68^{c}	4.12^{c}	7617.13^{b}	14 385.80^{c}
$W_2N_2F_2$	47.90^{ab}	81.00^{a}	8.91^{a}	8.86^{a}	1.39^{d}	3.87^{d}	8049.47^{a}	11 992.07^{d}
$W_1N_0F_0$	37.20^{bcd}	73.33^{a}	8.59^{ab}	8.87^{a}	0.92^{f}	3.48^{f}	5421.87^{f}	10 509.20^{e}
W	*	ns	ns	ns	ns	ns	ns	ns
N	**	ns	**	ns	**	**	**	**
F	ns	ns	ns	ns	ns	ns	**	**
W×N	ns	*	ns	ns	**	**	**	ns
W×F	ns	ns	ns	ns	**	**	**	**
N×F	ns	ns	ns	ns	ns	ns	**	**
W×N×F	**	ns	ns	ns	**	**	**	**

Note: W, N, F denote irrigation amount, nitrogen fertilizer rate, fertilization frequency, respectively. Different lowercase letters in the same column indicate significant differences between treatments (p<0.05). * is the level of significance (p<0.05); ** is the level of extreme significance (p<0.01); and ns is non-significant.

Entering the flowering and boll stage, there was no significant difference in plant height and stem diameter among the treatments, but the plant height of the $W_1N_1F_1$ treatment and the stem diameter of the $W_2N_2F_1$ treatment were the maximum values, increasing by 16.83% and 20.63% compared to the control. The leaf area index and aboveground biomass showed the same trend of change: in the W_1 treatment, both increased with the increase of fertilization frequency, while in the W_2 treatment, the opposite was true; under the same irrigation amount and fertilization frequency, both decreased with the increase of nitrogen application amount. Finally, the leaf area index and aboveground dry matter of the $W_1N_1F_2$ treatment reached the highest values, increasing by 30.17% and 45.58% compared to the control (p<0.01).

Analysis of variance shows that: irrigation amount has a significant effect on plant height at the bud stage (p<0.05); nitrogen application amount has an extremely significant effect on plant height, stem diameter, leaf area index, and aboveground biomass at the bud stage (p<0.01); fertilization frequency has an extremely significant effect on aboveground biomass (p<0.01). The interaction between water and nitrogen has a significant effect on leaf area index and aboveground biomass at the bud stage (p<0.01), and on plant height at the boll-filling stage (p<0.05); the interaction between water and nitrogen has an extremely significant effect on aboveground biomass (p<0.01); the interaction between nitrogen application amount and fertilization frequency has an extremely significant effect on aboveground biomass (p<0.01); the interaction between irrigation amount, nitrogen application amount, and fertilization frequency has an extremely significant effect on plant height, leaf area index, and aboveground biomass at the bud stage (p<0.01).

3.2 Effects of water and nitrogen regulation on cotton yield and components

The study evaluated the effects of water and nitrogen regulation cotton yield and its components, with results summarized in Figure 3. Nitrogen application significantly improved cotton yield and associated traits (p<0.01). Compared with the control treatment, the application of nitrogen fertilizer significantly increased cotton yield by 9.02% to 36.86%, boll weight by 0.17% to 5.76%, and boll number per plant by 4.55% to 31.82% (p<0.01).

Holding irrigation amount and fertilization frequency constant, higher nitrogen rates generally reduced both yield and boll weight. An exception occurred at the W_2F_2 treatment, where boll number per plant increased by 13.04% with greater nitrogen application. Under fixed irrigation and nitrogen levels, yield and its components displayed a consistent response: at the W_1 irrigation level, all measured parameters rose with increasing fertilization frequency, while at the W_2 level they declined as fertilization frequency increased. With nitrogen rate and fertilization frequency unchanged, yield increased under higher irrigation for the N_1F_1, N_2F_1, and N_2F_2 treatments. In contrast, the $W_1N_1F_2$ treatment showed a slight yield reduction with increased irrigation, yet it remained significantly higher than all other treatments, achieving a 36.86% increase over the control. Significant increases of 5.59% in boll weight and 31.82% in boll number per plant were also recorded for this treatment compared to the control (p<0.01).

Statistical analysis revealed significant effects of irrigation, nitrogen application, and fertilization frequency on cotton yield and its components. Irrigation amount had a highly significant effect on boll number per plant (p<0.01) and a significant effect on yield (p<0.05). Nitrogen application rate exerted highly significant effects on yield, boll weight, and boll number per plant (p<0.01). Fertilization frequency significantly influenced boll number per plant (p<0.01). The interaction between water and nitrogen significantly affected yield and boll number per plant (p<0.01). The irrigation-fertilization frequency interaction had highly significant effects on yield and boll number per plant (p<0.01), and a significant effect on boll weight (p<0.05). The interaction between nitrogen application and fertilization frequency significantly affected boll number per plant (p<0.01). The three-way interaction among irrigation, nitrogen, and fertilization frequency showed highly significant effects on yield and boll number per plant (p<0.01), and a significant effect on boll weight (p<0.05).

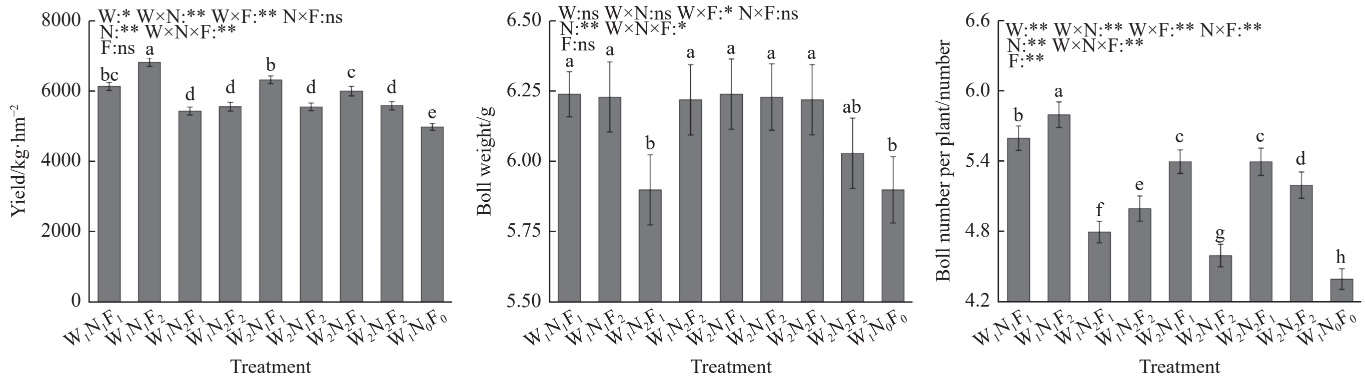


Figure 3 Effects of water and nitrogen regulation on cotton yield and components

3.3 Effects of water and nitrogen regulation on water consumption, water use efficiency, and nitrogen partial factor productivity of cotton

The study evaluated the effect of water and nitrogen regulation on cotton water consumption, water use efficiency and nitrogen partial factor productivity, with results summarized in Figure 4 and Table 5. The irrigation amount has a significant impact on the evapotranspiration during the cotton planting process and is the main factor causing the variation in evapotranspiration. There is a positive correlation between irrigation amount and evapotranspiration. Compared with the control treatment ($W_1N_0F_0$), the water consumption of the W_2 treatment increased by 11.52% to 22.68%. With the increase in fertilization frequency, water consumption also increased accordingly; in the case of increased nitrogen application, there was no significant difference in water consumption in the W_2F_1 treatment, while it increased in the W_2F_2 treatment. There was no significant difference in water consumption among the W_1 treatments, but all were lower than the control treatment. Among them, the water consumption of the $W_1N_2F_1$ treatment was the lowest, reducing by 1.18% compared to the control.

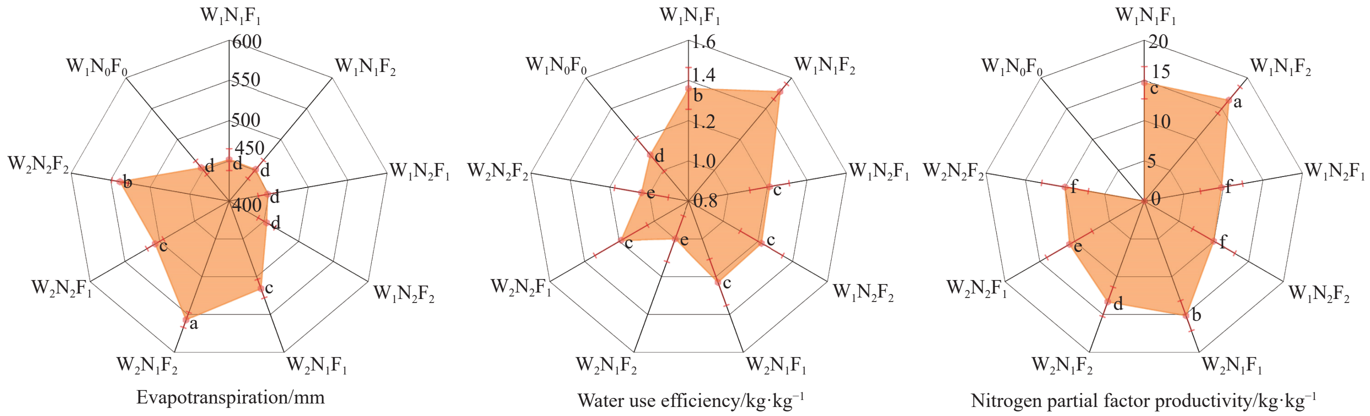


Figure 4 Effects of water and nitrogen regulation on water consumption, water use efficiency, and nitrogen partial factor productivity of cotton

Table 5 Significance analysis of technical parameters of irrigation and fertilization on water consumption, water use efficiency, and nitrogen partial factor productivity of cotton

Factor	Water consumption	Water use efficiency	Nitrogen partial factor productivity
W	*	**	**
N	*	**	**
F	*	**	ns
W×N	*	**	**
W×F	*	**	**
N×F	ns	ns	ns
W×N×F	ns	**	**

The water use efficiency of the W_1 treatment was similar to the trend of nitrogen fertilizer productivity change, both decreasing with the increase in nitrogen application and increasing with the increase in fertilization frequency. The water use efficiency of the W_2 treatment decreased with the increase in fertilization frequency, but there was no significant difference among the treatments with increased nitrogen application. In terms of nitrogen fertilizer productivity, it decreased with the increase in fertilization frequency in the W_2F_1 treatment and increased in the W_2F_2 treatment, and all decreased with the increase in nitrogen application. The study shows that the water use efficiency of the $W_1N_1F_2$ treatment increased the most compared to the control, by 37.27%, and the nitrogen fertilizer productivity of this treatment reached the highest value of 16.36 kg/kg.

3.4 Effects of water and nitrogen regulation on cotton quality index

The study evaluated the effect of water and nitrogen regulation on fiber quality of cotton, with results summarized in Table 6. The study found that as the irrigation amount or fertilization frequency increased, there was no significant difference in fiber length among the various treatments (p>0.05). The fiber length of all nitrogen-fertilized treatments was higher than that of the control treatment ($W_1N_0F_0$), with an increase ranging from 0.10% to 3.86%, and it showed a downward trend as the nitrogen application amount increased; among them, the fiber length of the $W_1N_1F_1$ treatment was the highest.

In terms of uniformity, fiber strength and lint percentage, changes in irrigation amount, nitrogen application amount, and fertilization frequency did not cause significant differences among the various treatments. The micronaire value increased with the increase in fertilization frequency in the W_1N_1, W_2N_1, and W_2N_2 treatments, while it decreased with the increase in fertilization frequency in the W_1N_2 treatment. When the nitrogen application level increased from N_1 to N_2, the micronaire value of the W_1F_1 treatment fluctuated most significantly, increasing by 13.59% compared to N_1.

Table 6 Effects of irrigation and fertilization practices on fiber quality of cotton

Treatment	Fiber length/mm	Uniformity/%	Fiber strength/cN·tex^{-1}	Micronaire	Elongation/%	Lint percentage/%
$W_1N_1F_1$	30.43^{a}	85.30^{a}	25.97^{a}	4.93^{cd}	6.70^{a}	42.1^{a}
$W_1N_1F_2$	29.77^{ab}	84.83^{a}	26.83^{a}	5.27^{abcd}	6.23^{bc}	42.4^{a}
$W_1N_2F_1$	29.80^{ab}	85.53^{a}	26.23^{a}	5.60^{a}	6.20^{bc}	43.4^{a}
$W_1N_2F_2$	29.33^{b}	85.17^{a}	26.13^{a}	5.40^{ab}	6.17^{bc}	43.0^{a}
$W_2N_1F_1$	29.70^{ab}	84.97^{a}	26.17^{a}	5.13^{bcd}	6.33^{bc}	42.0^{a}
$W_2N_1F_2$	30.13^{ab}	85.67^{a}	25.63^{a}	5.27^{abcd}	6.37^{b}	43.2^{a}
$W_2N_2F_1$	29.40^{ab}	84.87^{a}	26.83^{a}	4.90^{d}	6.43^{ab}	43.2^{a}
$W_2N_2F_2$	29.63^{ab}	85.30^{a}	25.97^{a}	5.30^{abc}	6.40^{b}	43.1^{a}
$W_1N_0F_0$	29.30^{b}	83.87^{a}	25.90^{a}	5.37^{ab}	6.03^{c}	43.4^{a}
W	ns	ns	ns	ns	ns	ns
N	*	ns	ns	ns	ns	ns
F	ns	ns	ns	ns	ns	ns
W×N	ns	ns	ns	**	*	ns
W×F	ns	ns	ns	ns	ns	ns
N×F	ns	ns	ns	ns	ns	ns
W×N×F	ns	ns	ns	*	ns	ns

The elongation rate of all nitrogen application treatments was higher than that of the control, with an increase ranging from 2.32% to 11.11%. As the irrigation amount increased, the elongation rate of the N_1F_1 treatment significantly decreased, while the N_1F_2, N_1F_1, and N_2F_2 treatments showed an upward trend. When subjected to the W_1 irrigation level, the elongation rate decreased with the increase in nitrogen application amount and fertilization frequency; while under the W_2 irrigation condition, it increased with the increase in nitrogen application amount. Under the W_2N_1 treatment, the elongation rate increased with the increase in fertilization frequency, but under the W_2N_2 treatment, it showed the opposite trend. Finally, the elongation rate of the $W_1N_1F_1$ treatment reached the maximum value, which was significantly higher than the control by 11.11% (p<0.01).

Furthermore, the statistical analysis indicates that the amount of nitrogen application has a significant impact on fiber length (p<0.05); the interaction between water and nitrogen has an extremely significant effect on the micronaire (p<0.01), and also has a significant effect on elongation rate (p<0.05); the three-factor interaction of irrigation, nitrogen application, and fertilization frequency also has a significant effect on the micronaire (p<0.05).

3.5 The optimal irrigation and nitrogen application index of cotton by principal component analysis (PCA) method

3.5.1 Principal component extraction

Using the SPSS analysis software, comprehensive analyses were conducted on indicators such as cotton plant height, stem thickness, LAI, aboveground biomass, water consumption, water use efficiency, nitrogen partial factor productivity, fiber length, uniformity, fiber strength, micronaire, elongation, and lint percentage. The correlation coefficient matrix between the characteristic values and scores was calculated (Table 7). The results showed that under different water and nitrogen conditions, the cumulative contribution rate of the four principal components (with characteristic values greater than 1) of Xinjiang mulched drip-irrigated cotton reached 88.019%.

3.5.2 Principal component score and ranking

Based on the standardized data, the expression of the score function for each main component corresponding to cotton can be obtained as Y (Table 8). The variance contribution rate corresponding to each main component serves as the weight, and the comprehensive evaluation function F can be derived according to the comprehensive evaluation score (Table 9).

After conducting a comprehensive evaluation of each cotton treatment using the principal component analysis method, the results show that the $W_1N_1F_1$ treatment (irrigation amount of 360 mm, nitrogen application rate of 420 kg/hm^2, and fertilization frequency of 5 times) has the highest comprehensive score, indicating that these water and fertilizer management parameters can synergistically optimize yield, water and nitrogen utilization efficiency, and fiber quality, and maximize the coordinated growth of various indicators of local cotton. The second is the $W_1N_1F_2$ treatment (irrigation amount of 360 mm, nitrogen application rate of 420 kg/hm^2, and fertilization frequency of eight times), which mainly manifests as the pursuit of maximum yield as a single goal under the conditions of this experiment. In summary, the $W_1N_1F_1$ treatment is determined as the optimal water and fertilizer management mode for this experiment to simultaneously improve cotton yield, water and nitrogen utilization efficiency, and fiber quality.

Table 7 Eigenvalues, contribution rates, cumulative contribution rates, and loading matrix determined by principal component analysis

Characteristic	Component			
	PC1	PC2	PC3	PC4
Plant height	0.170	0.864	0.254	0.066
Stem thickness	0.038	0.849	–0.418	–0.126
LAI	0.923	0.269	–0.055	0.083
Aboveground biomass	0.835	0.231	0.084	–0.102
Water consumption	–0.042	–0.195	–0.090	0.913
Water use efficiency	0.658	0.060	–0.012	0.739
Nitrogen partial factor productivity	0.913	0.089	0.356	–0.138
Fiber length	0.259	0.198	0.893	0.011
Uniformity	0.371	–0.185	0.557	–0.520
Fiber strength	0.534	0.238	–0.630	0.312
Micronaire	–0.332	–0.906	–0.06	0.034
Elongation	0.325	0.676	0.593	–0.16
Lint percentage	–0.702	–0.209	–0.355	–0.319
Eigenvalue	4.046	3.094	2.370	1.932
Contribution rate/%	31.124	23.804	18.233	14.859
Cumulative contribution rate/%	31.124	54.927	73.161	88.019

Table 8 Score function expression and comprehensive evaluation function expression of principal components

Function expressions
Y_1=–0.126X_1–0.047X_2+0.283X_3+0.262X_4–0.092X_5+0.126X_6+0.278X_7–0.071X_8+0.151X_9+0.202X_{10}+0.033X_{11}–0.059X_{12}–0.123X_{13}
Y_2=0.329X_1+0.322X_2-0.037X_3–0.048X_4–0.016X_5–0.037X_6-0.116X_7+0.052X_8–0.159X_9+0.019X_{10}–0.310X_{11}+0.219X_{12}+0.005X_{13}
Y_3=0.132X_1–0.232X_2–0.144X_3–0.093X_4+0.122X_5+0.033X_6+0.028X_7+0.430X_8+0.138X_9–0.344X_{10}+0.010X_{11}+0.242X_{12}–0.143X_{13}
Y_4=0.118X_1–0.103X_2–0.066X_3–0.143X_4+0.528X_5+0.360X_6–0.135X_7+0.146X_8–0.274X_9+0.018X_{10}–0.003X_{11}+0.010X_{12}-0.176X_{13}
F=0.3112/0.8802Y_1+0.2380/0.8802Y_2+0.1823/0.8802Y_3+0.1486/0.8802Y_4

Note: F: The comprehensive evaluation score; Y_1, Y_2, Y_3, and Y_4: The principal component scores. X_1: Plant height, X_2: Stem thickness, X_3: LAI, X_4: Aboveground biomass, X_5: Water Consumption, X_6: Water Use Efficiency, X_7: Nitrogen Partial Factor Productivity, X_8: Fiber length, X_9: Uniformity, X_{10}: Fiber strength, X_{11}: Micronaire, X_{12}: Elongation, X_{13}: Lint percentage

Table 9 Comprehensive score evaluation of cotton index

Treatment	Score	Ranking
$W_1N_1F_1$	0.98	1
$W_1N_1F_2$	0.55	2
$W_1N_2F_1$	–0.42	8
$W_1N_2F_2$	–0.33	7
$W_2N_1F_1$	0.21	3
$W_2N_1F_2$	–0.20	5
$W_2N_2F_1$	0.12	4
$W_2N_2F_2$	–0.24	6
$W_1N_0F_0$	–0.68	9

4 Discussion

4.1 Effects of water and nitrogen regulation on cotton growth index

Soil water and nitrogen availability are primary determinants of crop growth, underpinning the biosynthesis of enzymes, proteins, and amino acids essential for photosynthetic function[16]. Optimized water and nitrogen management enhances photosynthetic efficiency and nutrient translocation during crop development, thereby mitigating yield losses induced by water deficit at critical growth stages in cotton[12]. Furthermore, adequate combined supplies of water and nitrogen significantly improve light interception and photosynthetic capacity within the canopy. Sustaining sufficient levels of both resources is particularly crucial for maintaining photosynthetic productivity in flag leaves during the late reproductive phase[17].

Experimental evidence indicates that optimal nitrogen fertilization promotes vegetative growth, as reflected by increased stem diameter and plant height. At the flowering initiation stage, the $W_2N_1F_1$ treatment exhibited the maximum plant height, and the $W_2N_2F_2$ treatment exhibited the maximum stem diameter, surpassing the control ($W_1N_0F_0$) by 45.43% and 3.73%, respectively. These results highlight the significant promoting effect of nitrogen application on cotton growth. However, inappropriate water-nitrogen ratios may restrict plant development. For instance, a single nitrogen application under water-deficient conditions ($W_1N_1F_1$) or split nitrogen applications under well-watered conditions ($W_2N_1F_2$) resulted in reduced plant height and stem diameter relative to the control. Conversely, under identical irrigation amount and nitrogen application rate, optimizing fertilization frequency improved both agronomic indices, underscoring the importance of appropriate fertilization frequency for plant growth, nutrient acquisition, and yield formation[18,19].

The underlying mechanisms may be attributed to the fact that suboptimal irrigation and fertilization regimes restrict the infiltration and diffusion range of water in the soil profile, thereby impairing root water uptake[20]. Under water stress, nitrogen fertilization can inhibit biomass allocation to roots, leading to a decreased root-to-shoot ratio, constrained root expansion, and adverse consequences for subsequent growth. Excessive nitrogen application can also suppress root system architecture, manifested as reduced root length and surface area[21], and may intensify the impact of drought stress on young seedlings[22]. Under high-frequency drip irrigation, considerable quantities of water and fertilizer remain in the surface or shallow soil layers for extended durations, and only a limited proportion is effectively absorbed and utilized by roots. This diminishes nutrient uptake efficiency and hinders overall plant growth and development[23].

Upon entering the flowering and boll stage, topping is routinely implemented in cotton production to enhance yield and fiber quality. Consequently, no significant differences in plant height were observed among treatments. The stem functions as the principal conduit for nutrient transport. As the plant transitions from vegetative to reproductive growth, nutrients are progressively redirected toward fruit branches and bolls, resulting in a deceleration of stem diameter increment[24,25]. Appropriate irrigation and fertilization regimes not only promote cotton growth but also facilitate increases in leaf area index (LAI) and biomass accumulation. Consistent with prior studies, nitrogen application resulted in higher LAI and aboveground biomass relative to non-nitrogen controls across all growth stages[26], indicating that insufficient nitrogen supply retards crop development and reduces biomass allocation[27]. Frequent irrigation can effectively alleviate soil water depletion by shortening drought intervals and replenishing soil moisture in a timely manner, thereby reducing the risk of soil water deficit stress[28]. In this study, the $W_1N_1F_2$ treatment achieved the highest LAI and aboveground biomass, establishing a foundation for high yield; however, it decreased when the soil moisture and nitrogen fertilizer content exceeded the range that cotton could normally tolerate for growth. The $W_2N_1F_2$ treatment achieved a synergistic coordination among water supply, root distribution, and nitrogen uptake, thereby supporting normal root function. By modulating biomass partitioning between vegetative and reproductive structures and optimizing root-shoot coordination, this treatment contributed to sustaining long-term yield potential.

4.2 Effects of water and nitrogen regulation on cotton yield and components

The dynamic interaction between soil moisture and nitrogen supply is the core mechanism for regulating crop yield[29]. The application of nitrogen fertilizer has a significant positive impact on cotton yield[30], mainly by increasing the number of bolls per cotton plant and the weight of each boll[31]. Studies have shown that proper application of water and nitrogen can significantly increase crop yields, and its promoting effect is significantly better than that of single irrigation treatment. Under the W_1 irrigation level, the cotton yield and the number of bolls per plant decreased with the increase in nitrogen application amount and increased with the increase in fertilization frequency; among them, the weight of bolls in the $W_1N_2F_1$ treatment was significantly lower than that in other treatments. The reason is that excessive application of nitrogen will disrupt the growth balance of cotton plants, inhibit photosynthesis, weaken the efficiency of organic matter synthesis and transportation, and ultimately lead to delayed maturity, increased shedding of bolls and flowers, and an increase in the proportion of flowers that fall before frost, thereby limiting the increase in yield[32]. In contrast, the method of applying fertilizer in small amounts repeatedly can continuously replenish nutrients in the shallow soil layer, effectively reduce nitrogen leaching, promote the accumulation of nitrate nitrogen in the root zone, and thereby enhance the absorption and utilization by crops[33].

At the W_2 irrigation level, the cotton yield, seed weight, and the number of bolls per plant showed a downward trend as the fertilization frequency increased. Specifically, in the W_2F_1 treatment, the yield gradually decreased as the nitrogen application amount increased from N_1 to N_2; while in the W_2F_2 treatment, the number of bolls per plant gradually increased as the nitrogen application amount increased from N_1 to N_2. The possible reasons might be as follows: Under the condition of a fixed total nitrogen application amount, increasing the frequency of fertilization means a corresponding reduction in the amount of nitrogen applied per time. In the case of high irrigation, if the water-nitrogen ratio is unbalanced, especially when the irrigation amount is high while the nitrogen application amount increases, it is likely to cause excessive vegetative growth of cotton, disrupting the balance between vegetative growth and reproductive growth. In addition, due to insufficient water-nitrogen supply in the later growth stage, the shedding of bolls and seeds is further exacerbated. Furthermore, appropriately increasing the amount of irrigation and nitrogen application can help increase the total amount of dry matter accumulation, especially enhancing the dry matter accumulation of economic organs and their proportion. However, excessive water and nitrogen input in the short term will delay the development of bolls and spikelet at the flowering and boll stage, causing the cotton plants to grow prematurely and late-maturing, and ultimately having a negative impact on yield formation[34-36].

Under the present experimental conditions, the $W_1N_1F_2$ treatment (irrigation amount of 360 mm, a nitrogen application rate of 420 kg/hm^2, and fertilization frequency of 8 times) achieved the optimal yield performance. Nevertheless, the conclusions of this study are subject to certain limitations, as only one-year experimental data is available in the present work. Further research is recommended to implement treatments with reduced irrigation amount in combination with high-frequency fertilization regimes, so as to systematically elucidate the trade-off between water-saving potential and yield sustainability. Such efforts would contribute to identifying the most precise and efficient water-nitrogen coupling regime, thereby providing a more robust scientific basis for promoting the sustainable development of cotton production in the arid and saline-alkali areas of Xinjiang.

4.3 Effects of water and nitrogen regulation on water consumption, water use efficiency, and nitrogen partial factor productivity of cotton

The absorption, transportation, accumulation, and distribution of nitrogen by crops are closely related to the formation of yield[37]. The moisture condition not only affects the availability of nitrogen in the soil, but also regulates the absorption, transportation, and assimilation processes of nitrogen by crops during their growth and development[38]. Under the experimental conditions, at the W_1 irrigation level, there was no significant difference in water consumption among the various treatments (p>0.05); however, at the W_2 irrigation level, there were significant differences in water consumption among the treatments. Specifically, it increased with the increase in fertilization frequency, and in the W_2F_2 treatment, it showed a decreasing trend as the nitrogen application rate increased. This indicates that irrigation water amount is the main factor causing the differences in water consumption, and they are positively correlated[39,40].

The results of this experiment indicate that there are differences in the responses of water use efficiency and nitrogen fertilizer productivity to the frequency of fertilization under different irrigation levels: at the W_1 level, both increased with the increase in fertilization frequency; while at the W_2 level, both decreased with the increase in fertilization frequency. Meanwhile, both declined progressively with rising nitrogen application rate. Further analysis indicates that the method of applying fertilizer in small amounts multiple times can continuously replenish nutrients to the shallow soil, effectively reduce nitrogen loss, and promote the accumulation of nitrate nitrogen in the root zone, thereby enhancing the absorption and utilization of water and nutrients by crops, and improving resource utilization efficiency[33]. The regulation of the supply-demand relationship between soil moisture and crop water consumption by nitrogen fertilizer helps ensure that crops can fully absorb water during the critical growth stages. On the other hand, appropriate nitrogen fertilizer application improves the process of soil nitrogen supply[41], promotes the stable release of nutrients[38], and meets the crop's needs during the critical nutrient-demanding periods, achieving water and fertilizer coordination.

In addition, the application method of nitrogen fertilizer also plays a significant regulatory role in the generation and distribution of photosynthetic products. Frequent and excessive application of nitrogen fertilizer can easily lead to excessive nitrogen metabolism in leaves and a decrease in the carbon-nitrogen ratio. This inhibits the transport and output efficiency of photosynthetic products and has a feedback inhibitory effect on the formation of photosynthetic organs, ultimately being unfavorable for substance accumulation and yield formation, while the divided application of nitrogen fertilizer can effectively alleviate this negative effect[42].

4.4 Effects of water and nitrogen regulation on cotton quality index

The quality of cotton fibers is an important target trait in cotton production management. The main indicators for evaluating cotton fiber quality include fiber length, uniformity, fineness, maturity, and specific strength, among others. Among these, fiber length, specific strength, and micronaire value are the most crucial[43]. The results of this study show that fiber length decreases with increasing nitrogen application rate, which is inconsistent with the findings of Wu et al.[44]. This discrepancy may be attributed to differences in baseline soil fertility and nitrogen application levels between the experimental sites. The study also found that there were no significant differences in the uniformity index, fracture strength ratio, and fiber content among the various treatments, which was similar to the results of previous studies[44-46]. The reason for this might be that the formation of fiber quality is mainly controlled by genetic factors and has no significant correlation with the amount of nitrogen fertilizer applied[45].

The relationship between cotton fiber quality and micronaire value is not a simple, monotonous linear one[43]. Both excessively high or low micronaire values will reduce the fiber quality: a low value indicates that the fibers are finer and less mature, and they are more prone to breaking during processing and use; a high value indicates that the fibers are too coarse and stiff, which can lead to decreased yarn strength, a coarse and hard fabric feel, pale dyeing, and severely limited spinnability[47]. Generally, a micronaire value within the range of 3.5 to 4.9 is considered ideal[48]. This study found that the micronaire values of the nitrogen application treatment were all lower than those of the non-nitrogen application treatment, while the elongation rate was higher than that of the non-nitrogen application treatment. This phenomenon may be related to the nitrogen nutrition status of leaves during the cotton boll development period. Research has shown that the nitrogen content in leaves is significantly positively correlated with traits such as fiber length, while it is significantly negatively correlated with micronaire value[49]. In addition, optimizing water and nitrogen management can improve the photosynthetic efficiency and nutrient transport capacity of the crop. Adequate supply of water and nitrogen can significantly enhance the light energy interception and photosynthetic capacity of the canopy, especially in the reproductive growth stage. Maintaining an appropriate water and nitrogen level is crucial for maintaining the photosynthetic function of leaves[12,17].

5 Conclusions

1) Different treatments of cotton show varying degrees of differences in growth traits, yield, water and nitrogen use efficiency, and fiber quality. Compared with the control treatment ($W_1N_0F_0$), the $W_1N_1F_1$ treatment (irrigation amount of 360 mm, nitrogen application of 420 kg/hm^2, and fertilization frequency of 5 times) performed particularly well. Its plant height, stem diameter, and fiber elongation rate increased significantly by 16.83%, 20.63%, and 11.11% respectively (p<0.01); meanwhile, the water use efficiency of this treatment was 23.64% higher than that of the control, and the nitrogen fertilizer productivity reached 42.86 kg/kg, with both water use efficiency and nitrogen fertilizer productivity being at a relatively high level.

2) In production practice, if the sole aim is to maximize cotton yield, the $W_1N_1F_2$ treatment (irrigation amount of 360 mm, nitrogen application of 420 kg/hm^2, and fertilization frequency of 8 times) has the best yield increase effect, increasing by 36.86% compared to the control treatment, and the boll weight and boll number also increased significantly simultaneously. However, the water use efficiency and nitrogen fertilizer productivity of this treatment were lower than those of the $W_1N_1F_1$ treatment.

3) Through principal component analysis (PCA), the growth traits, yield components, water and nitrogen use efficiency, and fiber quality of cotton were comprehensively evaluated. The results showed that the $W_1N_1F_1$ treatment (irrigation amount of 360 mm, nitrogen application of 420 kg/hm^2, and fertilization frequency of 5 times) had the highest comprehensive score. This treatment achieved excellent performance in both maintaining a high yield and having superior water use efficiency and nitrogen fertilizer productivity, achieving a synergistic improvement in yield, resource utilization efficiency, and fiber quality. Therefore, the $W_1N_1F_1$ treatment can provide a theoretical basis for water and fertilizer management of cotton in Xinjiang.

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