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Original Article

Effects of Water-Fertilizer-Heat Coupling on Yield and Resource Utilization Efficiency of Cotton under Drip Irrigation

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Abstract:
Seed cotton yield is a critical factor influencing the international competitiveness of cotton. To enhance water and fertilizer use efficiency and promote sustainable cotton production, a two-year field experiment was conducted during 2024–2025 to explore the effects of plastic film mulch layers, irrigation levels, and fertilizer levels on seed cotton yield, economic benefits, irrigation water use efficiency (IWUE), and nutrient partial factor productivity in the Alar region of southern Xinjiang, China. An $L_9(3^4)$ orthogonal design comprised of nine treatments was employed. Three water levels (W1: 3080 $m^3 \cdot ha^{-1}$, W2: 3850 $m^3 \cdot ha^{-1}$, W3: 4620 $m^3 \cdot ha^{-1}$), three fertilizer levels (F1: 330-135-147 $kg \cdot ha^{-1}$ (N-P_2O_5-K_2O), F2: 412.5-168.75-183.75 $kg \cdot ha^{-1}$ (N-P_2O_5-K_2O), F3: 495-202.5-220.5 $kg \cdot ha^{-1}$ (N-P_2O_5-K_2O)) and three heat levels (H1: one layer of plastic film, H2: two layers of plastic film, H3: three layers of plastic film)were set. The results showed that water levels, fertilizer levels and heat levels all significantly influenced seed cotton yield, IWUE, and nutrient partial factor productivity. Technique for order preference by similarity to an ideal solution (TOPSIS) was adopted for the comprehensive evaluation of seed cotton yield, IWUE, nutrient partial factor productivity, and economic rate of return. The highest seed cotton yield, IWUE, nutrient partial factor productivity, and economic rate of return were achieved in treatment W2F1H2 (T2). These results provide a practical and valuable reference for sustainable cotton production in the Alar region of southern Xinjiang and other regions with analogous agro-ecological conditions in improving both seed cotton yield and water and fertilizer use efficiency.

Keywords: Water-fertilizer-heat coupling, Seed cotton yield, IWUE, Nutrient partial factor productivity, Economic benefit

Introduction

Cotton (*Gossypium hirsutum L.*) cultivation in Xinjiang contributes 91% to China's total cotton production and plays an indispensable role in the global textile supply chain[1]. As both a fiber crop and oil crop, cotton plays a vital role in the economic development of northwest China, but the lack of appropriate field water and nutrient management strategies has hindered the coordinated development of the cotton industry and the environment[2].

Southern Xinjiang is a typical oasis agricultural area, and cotton is the primary cash crop. However, the scarcity of freshwater resources severely constrains agricultural production in this arid region[3]. Scarce rainfall and low water productivity (WP) are the primary problems limiting the sustainable development of crops in the extremely arid region of Xinjiang. Reducing evaporative loss and enhancing the utilization of deep soil water are important measures to address this challenge[4].

Efficient water and fertilizer management is critical in addressing the challenges posed by water scarcity and resource sustainability in agriculture, particularly in semi-arid regions, where water resources are limited[5-8]. Plastic film mulching (PM) combined with irrigation is widely adopted to improve crop yields, IWUE, nutrient partial factor productivity, and economic benefits, especially in arid agricultural regions [9-13].

IWUE measurement reflects the efficiency of water use by assessing the ratio of the crop yield to the amount of water consumed in production[14]. Efficient nitrogen (N), phosphorus (P) and potassium (K) management in drip-irrigated systems is vital for sustainable agriculture in arid and semi-arid regions[15] [16].

Previous research has established that crop yield improvement is closely related to improvements in water use, soil fertility, and the adoption of plastic film mulching[17, 18]. Most studies on improving crop yield have only focused on water and fertilizer management under single-layer plastic film mulching[19-23]. The analysis of improving crop yield focuses solely on the relationship between water and N. [24, 25]. Limited research has been conducted on enhancing crop yield through the synergistic regulation of water, N, P, and K under multi-layer plastic film mulching.

However, optimizing N, P, and K fertilization and soil management practices is key to enhancing crop yield and ensuring the sustainable and efficient utilization of N, P, and K in agricultural systems[26-30]. Conversely, poor fertilizer management has increased crop production costs, reduced crop productivity, and significantly depleted soil nutrients[31].

Agricultural production suffers significant constraints due to low IWUE and nutrient partial factor productivity in southern Xinjiang. The pivotal solution to enhance crop yield, economic benefits, IWUE, and nutrient partial factor productivity lies in optimizing field management practices[32].

To sum up, this study aimed to explore the effect of synergistic regulation of plastic film mulch layers and irrigation-fertilizer regimes on seed cotton yield, economic benefits, IWUE, and nutrient partial factor productivity in southern Xinjiang, optimize the input of water and fertilizer, and provide a practical and valuable reference for sustainable cotton production in the Alar region of southern Xinjiang and other regions with analogous agro-ecological conditions.

1. Materials and Methods

1.1. Experimental Site Description

1.1.1. Study Area

Field experiments on cotton were conducted during the 2024 and 2025 growing seasons at the Modern Agriculture Academician Expert Workstation in Alar (81˚12′36″N, 40°37′12″E), southern Xinjiang, China. The study area is shown in Figure 1. This study site features a warm-temperate continental desert climate, with an average altitude of 1100 m, annual precipitation of 50 mm, annual evaporation of 2800 mm, average air temperature of 10.7 ℃, accumulated temperature ≥ 10 ℃ of 4113 ℃, average sunshine duration of 9.5 h (April–October), annual sunshine duration of 2900 h, and frost-free period of 220 days (https://en.weather.com.cn/). Selected soil physicochemical properties at different depths in the study area are presented in

Table **1**.

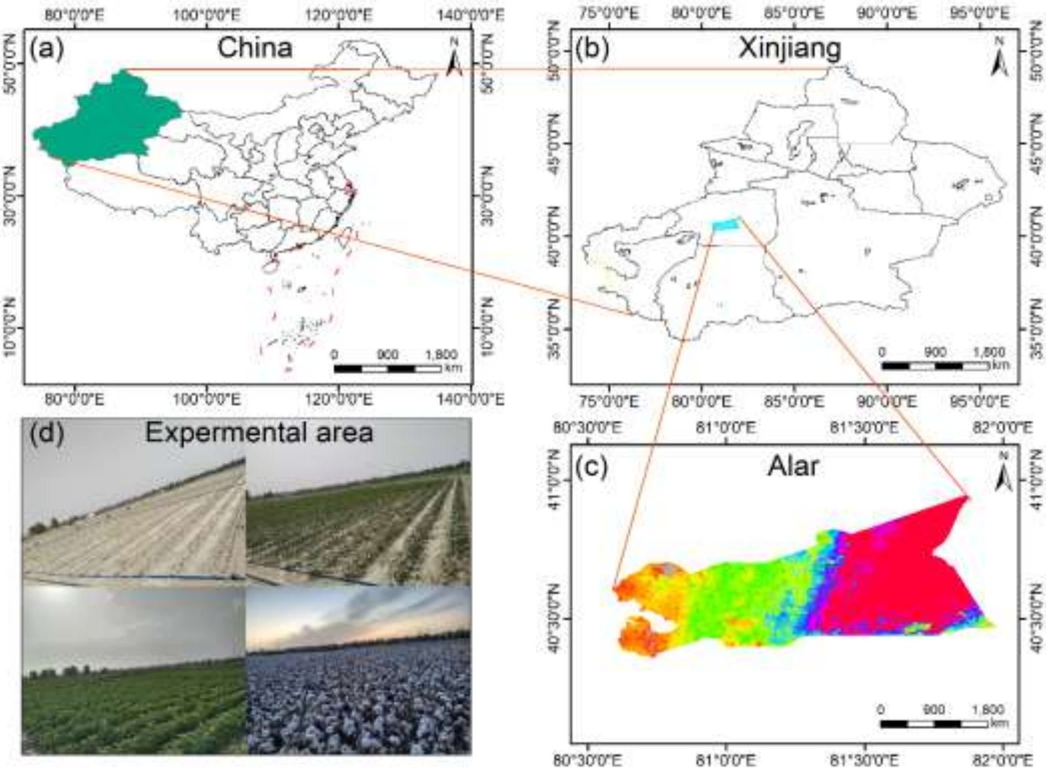

Figure 1. The location of study area: (a) China; (b) Xinjiang Uygur Autonomous Region; (c) Alar City; (d) experimental area.

Table 1 Selected soil physicochemical properties at different depths in the study area

Soil depth (m)	Clay (%)	Silt (%)	Sand (%)	BD ($g\cdot cm^{-3}$)	pH	EC ($dS\cdot m^{-1}$)
0-0.10	1.49±0.19	30.51±3.07	68.01±3.24	1.38±0.03	8.12±0.20	0.22±0.09
0.10-0.20	1.40±0.13	28.09±1.30	70.51±1.43	1.07±0.20	8.09±0.20	0.22±0.06
0.20-0.40	2.01±0.25	38.46±3.86	59.54±4.11	1.44±0.16	8.09±0.60	0.17±0.01
0.40-0.60	1.99±0.45	34.50±7.04	63.51±7.49	1.48±0.06	7.66±0.59	0.19±0.01

Note: BD is bulk density. EC is electrical conductivity.

1.2. Experimental Design

Three factors were adopted in the experiment: water levels, fertilizer levels and heat levels. An L9(3^4) orthogonal experimental design with nine treatments was employed, and each treatment was replicated three times, as shown in

Table 2. Three water levels: 3080 $m^3\cdot ha^{-1}$ (W1), 3850 $m^3\cdot ha^{-1}$ (W2), and 4620 $m^3\cdot ha^{-1}$ (W3), three fertilizer levels: 330-135-147 $kg\cdot ha^{-1}$ (N-P_2O_5-K_2O) (F1), 412.5-168.75-183.75 $kg\cdot ha^{-1}$ (N-P_2O_5-K_2O) (F2), 495-202.5-220.5 $kg\cdot ha^{-1}$ (N-P_2O_5-K_2O) (F3) and three heat levels: one layer of plastic film (H1), two layers of plastic film (H2), three layers of plastic film (H3) were established.

The cotton cultivar used in this study was *Tahe 2*, a locally recommended variety. Sowing was carried out via flat seeding on April 30, 2024, and April 16, 2025. The experiment was conducted under plastic film mulched drip irrigation, adopting a wide-narrow row planting pattern of "one mulch, three belts, and six rows". The film width was 2.05 m, the film thickness was 0.01 mm, the row width was 1.82 m, the gutter width was 0.20 m, and the cotton plant spacing was 0.10 m (Figure 2). The irrigation schedules are presented in Table 3. Fertilizer was applied using water-fertilizer integration technology. The fertilizer schedules are provided in Table 4. The drip fertigation system consisted of pumps, filters, fertilization tanks, pipelines, water meters, and valves. The drip tapes had a dripper spacing of 0.30 m, an operation pressure of 0.1 MPa, and discharge rate of 2.4 L·h^{-1}.

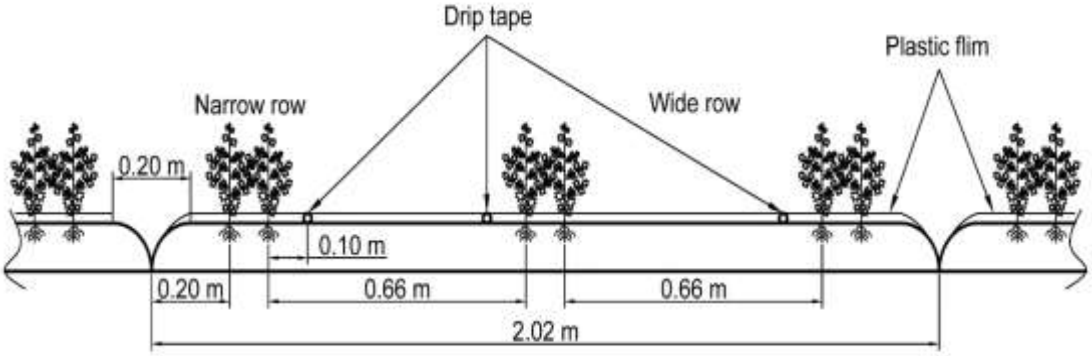

Figure 2 Cotton cropping pattern

Table 2. Orthogonal tables for experimental water-fertilizer-heat coupling for cotton.

Treatment	Fertilizer levels ($N-P_2O_5-K_2O$) (kg·ha^{-1})	Water levels (m^3·ha^{-1})	Heat levels (layer)
T1	330-135-147 (1)	3080 (1)	one (1)
T2	330-135-147 (1)	3850 (2)	two (2)
T3	330-135-147 (1)	4620 (3)	three (3)
T4	412.5-168.75-183.75 (2)	3080 (1)	three (3)
T5	412.5-168.75-183.75 (2)	3850 (2)	one (1)
T6	412.5-168.75-183.75 (2)	4620 (3)	two (2)
T7	495-202.5-220.5 (3)	3080 (1)	two (2)
T8	495-202.5-220.5 (3)	3850 (2)	three (3)
T9	495-202.5-220.5 (3)	4620 (3)	one (1)

Table 3. Water amounts schedule

Data		Water amounts (m^3·ha^{-1})		
		W1	W2	W3
2024-06-16	2025-05-29	157.6	197	236.4
2024-06-23	2025-06-05	157.6	197	236.4
2024-06-30	2025-06-12	157.6	197	236.4
2024-07-07	2025-06-19	576	720	864
2024-07-14	2025-06-26	576	720	864
2024-07-21	2025-07-03	576	720	864
2024-07-28	2025-07-10	576	720	864
2024-08-04	2025-07-17	77.6	97	116.4
2024-08-11	2025-07-24	75.2	94	112.8
2024-08-18	2025-07-31	75.2	94	112.8
2024-08-25	2025-08-07	75.2	94	112.8

Table 4. Fertilizer amounts schedule

Data		Urea (kg·ha^{-1})			Disco 11-36-7 (kg·ha^{-1})			Disco 7-9-42 (kg·ha^{-1})		
		F1	F2	F3	F1	F2	F3	F1	F2	F3
2024-06-16	2025-05-29	24	30	36	12	15	18	—	—	—
2024-06-23	2025-06-05	24	30	36	24	30	36	—	—	—
2024-06-30	2025-06-12	48	60	72	36	45	54	—	—	—
2024-07-07	2025-06-19	72	90	108	60	75	90	12	15	18
2024-07-14	2025-06-26	72	90	108	60	75	90	24	30	36
2024-07-21	2025-07-03	72	90	108	60	75	90	36	45	54
2024-07-28	2025-07-10	72	90	108	48	60	72	36	45	54
2024-08-04	2025-07-17	60	75	90	—	—	—	72	90	108
2024-08-11	2025-07-24	60	75	90	—	—	—	60	75	90
2024-08-18	2025-07-31	60	75	90	—	—	—	60	75	90
2024-08-25	2025-08-07	36	45	54	—	—	—	—	—	—

Urea (46% N) was used as the nitrogen fertilizer. Two kinds of Disco compound fertilizers (http://www.disco-china.com/) were adopted: 11-36-7 ($N-P_2O_5-K_2O$) and 7-9-42 ($N-P_2O_5-K_2O$). Specifically, 11-36-7 ($N-P_2O_5-K_2O$) was selected as the phosphorus source, and 7-9-42 ($N-P_2O_5-K_2O$) was chosen as the potassium source.

Each plot was 13 m × 2.05 m, with an area of 26.65 m^2, and the total area of all plots was 1287 m^2. All other management measures unrelated to the experimental treatments were consistent with local farmers' management practices.

1.3. Data Collection And Measurement

1.3.1. Seed Cotton Yield

The total seed cotton yield was calculated by weighing and averaging the seed-cotton harvested from five replicates of each treatment.

1.3.2. Irrigation Water Use Efficiency

Irrigation water use efficiency (IWUE) was calculated as follows[33]:

$$IWUE = Y/I \#(1)$$

Where $IWUE$ is the irrigation water use efficiency (kg·m^{-3}), Y is the seed cotton yield (kg), and I is the total irrigation amount during the cotton growing season (m^3).

1.3.3. Nutrient Partial Factor Productivity

The fertilizer partial factor productivity (FPFP), nitrogen partial factor productivity (NPFP), phosphorus partial factor productivity (PPFP), and potassium partial factor productivity (KPFP) were calculated as follows[34, 35]:

$$FPFP = Y/F_T \#(2)$$

$$NPFP = Y/N_T \#(3)$$

$$PPFP = \mathrm{Y}/P_T \#(4)$$

$$KPFP = \mathrm{Y}/K_T \#(5)$$

Where F_T, N_T, P_T, and K_T denote the application rates of total fertilizer, nitrogen fertilizer, phosphorus fertilizer, and potassium fertilizer (kg·ha^{-1}), respectively.

1.3.4. Economic Benefit

In 2024, seed cotton was priced at 1.00 \$·kg^{-1}. In 2020, seed cotton was priced at 0.98 \$·kg^{-1}. The costs for inputs are as follows: Irrigation water 0.03 \$·m^{-3}; Electric fee 0.04 \$·kW^{-1}·h^{-1}. Urea 0.19 \$·kg^{-1}; Compound fertilizers 0.39 \$·kg^{-1}; Annual irrigation equipment cost 767.34 \$·hm^{-2}; Rent for farm agricultural machinery work (including weeding, mulching, harvesting) and unmanned machinery (including pesticide spraying and topping) 420.04 \$·hm^{-2}. The annual labor costs 675.45 \$·hm^{-2}.

1.3.5. Basic Principle of TOPSIS Method of Combination of Game Theory Soil Properties Indexes

1) Establish a comprehensive evaluation index system.

2) Establish the data matrix of between evaluation objects and evaluation indicators H:

$$H = (h_{ij})_{m\times n} \#(6)$$

Where h_{ij} is the jth evaluation index in the ith evaluation object, m is the number of evaluation objects (trial treatments) in this study, and n is the number of evaluation indices (including seed cotton yield, IWUE, FPFP, NPFP, PPFP, KPFP, and rate for return).

3) Use the game theory combination weighting method to determine the index weight:

a) The analytic hierarchy process (AHP) is used for subjective weight analysis, and the subjective weights are obtained.

b) Objective weight analysis is conducted using the improved coefficient of variation method and objective weights are thus obtained.

i) A normality test was conducted for each evaluation index in this study, and those with skewed distributions were transformed into approximate normal distributions. Seed cotton yield, IWUE, FPFP, NPFP, PPFP, KPFP, and rate of return exhibited severe skewness due to significant differences in water and fertilizer application levels. Direct analysis of the raw data for these indices would lead to disproportionately high weights, so the logarithmic transformation was applied to approximate their normal distributions, thus resulting in a new decision matrix:

$$R'' = (r''_{ij})_{m\times n} \#(7)$$

ii) Using the vector normalization method, a normalized decision matrix can be obtained:

$$E = (e_{ij})_{m\times n} \#(8)$$

$$e_{ij} = r''_{ij} \cdot \left(\sum_{i=1}^{n} \left(r''_{ij} \right)^2 \right)^{-0.5} \#(9)$$

iii) Calculate the coefficient of variation:

$$v_j = \sigma_j / \bar{x}_j \#(10)$$

Where v_j represents the coefficient of variation of the jth normalized evaluation index, σ_j represents the standard deviation of the jth normalized evaluation index, and $\bar{x}_j$represents the mean value of the jth normalized evaluation index.

iv) Calculate the weight, and normalize the coefficient of variation:

$$w_j = v_j \cdot \left(\sum_{j=1}^{n} v_j \right)^{-1} \#(11)$$

c) Use the principles of game theory for combination weighting.

i) Construct the base weight vector set as $u_k = \{u_{k1}, u_{k2}, \dots, u_{kn}\}(k = 1, 2)$, and perform linear combination of the vectors:

$$u = \alpha_1 u_1 + \alpha_2 u_2 + \cdots + \alpha_{\mathrm{n}} u_{\mathrm{n}} \#(12)$$

Where u is a possible weight vector of the weight set and α_1, α_2, …, α_n are linear combination coefficients, α_1, α_2, …, α_n>0, α_1+α_2+ … + α_n=1.

ii) Optimize the linear combination coefficients α_1 and α_2 using game theory, with the aim of minimizing the deviations among u and u_1, u_2, …, u_n:

$$min = \| (\alpha_1 u_1^T + \alpha_2 u_2^T + \cdots + \alpha_{\mathrm{n}} u_{\mathrm{n}}^T) - u_k \|_{\mathrm{n}} \quad (k = 1, 2, \dots, \mathrm{n}) \#(13)$$

iii) The optimized first derivative condition of Eq. (23) can be converted into a system of equations:

$$\begin{bmatrix} u_1 & u_1^T\, u_1 & u_2^T \\ u_2 & u_1^T\, u_2 & u_2^T \\ & \cdots & \\ u_2 & u_1^T\ u_2 & u_2^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \cdots \\ \alpha_{\mathrm{n}} \end{bmatrix} = \begin{bmatrix} u_1 & u_1^T \\ u_2 & u_2^T \\ \cdots & \\ u_{\mathrm{n}} & u_{\mathrm{n}}^T \end{bmatrix} \#(14)$$

iv) After α_1, α_2, …, α_n are obtained from Eq.

(24), the combined weight vector can be calculated.

$$W = \alpha_1 W_1 + \alpha_2 W_2 + \cdots + \alpha_n W_n \#(15)$$

4) Construct a weighted norm matrix $E' = WE$.

5) Determine the positive ideal solution E^+ and the negative ideal solution E^-.

Positive ideal solution:

$$e_j^+ = \begin{cases} max_{1 \le i \le n} e_{ij} & Benefit\ type\ attribute \\ max_{1 \le i \le n} e_{ij} & Cost\ type\ attribute \end{cases} \#(16)$$

Negative ideal solution:

$$e_j^- = \begin{cases} min_{1 \le i \le n} e'_{ij} & Benefit\ type\ attribute \\ max_{1 \le i \le n} e'_{ij} & Cost\ type\ attribute \end{cases} \#(17)$$

6) Calculate the Euclidean distance D^+ and D^- between each evaluation object and E^+ and E^-.

Positive ideal solution distance:

$$d_i^+ = \left(\sum_{i=1}^{m} \left(e'_{ij} - e_j^+ \right)^2 \right)^{0.5} \#(18)$$

Negative ideal solution distance:

$$d_i^- = \left(\sum_{i=1}^{m} \left(e'_{ij} - e_j^- \right)^2 \right)^{0.5} \#(19)$$

7) Calculate the comprehensive evaluation index, namely the closeness degree F, which reflects the proximity between each evaluation object and the optimal scheme.

$$f_i = \frac{d_i^-}{d_i^+ + d_i^+}, (0 \le f_i \le 1) \#(20)$$

1.4. Statistical analysis

Excel 2016 was applied to organize and sort the experimental data. Subsequently, statistical analyses were conducted using SPSSAU (Beijing Qingsi Technology Co., Ltd., Beijing, China), including analysis of variance (ANOVA) and Pearson correlation analysis. For multiple comparisons, the least-significant difference (LSD) method was chosen. Statistical significance was set at $P < 0.05$. All graphs and figures were created using Origin 2023 (OriginLab, Massachusetts, USA).

2. Results

2.1. Seed cotton yield and IWUE

In order to assess the relationships between seed cotton yield and water, fertilizer, and heat levels repeated-measures analysis of variance (ANOVA) was employed. The results showed that water, fertilizer, and heat levels all exerted a statistically significant positive effect on seed cotton yield in 2024 and 2025 ($P < 0.05$).

Further analysis showed that only different water levels produced a statistically significant effect on IWUE in 2024 and 2025($P < 0.05$).

As shown in Figure 3, the seed cotton yield in 2024 ranged from 7621.57–10857.70 kg·ha^{-1}. The order of seed cotton yield was T2 > T3 > T5 > T6 > T9 > T8 > T7 > T4 > T1. The order of secondary factors was W > F > H, and the optimal composition was W2F1H2. Similarly, the seed cotton yield in 2025 ranged from 4593.82–5915.14 kg·ha^{-1}. The order of seed cotton yield was T3 > T4 > T6 > T7 > T2 > T8 > T9 > T5 > T1. The order of secondary factors was H > W > F, and the optimal composition was W3F1H3. Taken together, these results suggest that there is an association between seed cotton yield and water, fertilizer, and heat levels.

It can be seen that the order of IWUE was T2 > T6 > T7 > T5 > T9 > T3 > T1 > T8 > T4. The order of secondary factors was W > F > H, and the optimal composition was W2F1H2 in 2024. In addition, the order of IWUE was T4 > T7 > T1 > T2 > T8 > T3 > T5 > T6 > T9. The order of secondary factors was H > W > F, and the optimal composition was W1F2H3 in 2025. Overall, these results indicate that there is an association between water, fertilizer, and heat levels and IWUE.

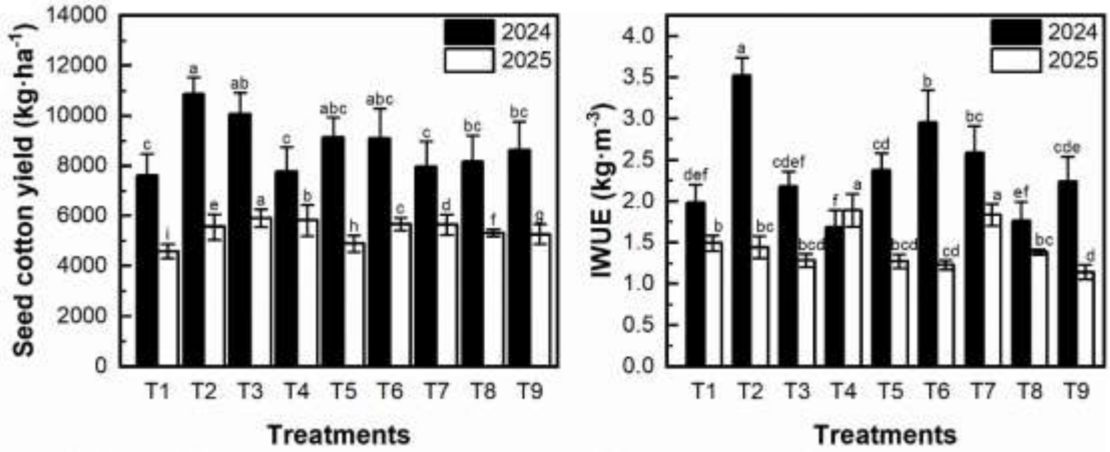

Figure 3. Seed cotton yield and IWUE of different treatments in 2024 and 2025. Error bars represent standard error of the mean (SE, n=3). Different lowercase letters indicate significant differences at P < 0.05. The same applies below.

2.2. Nutrient Partial Factor Productivity

ANOVA revealed that the varying water and fertilizer levels had a statistically significant impact on FPFP, NPFP, PPFP, and KPFP in 2024 ($P < 0.05$). Similarly, water , fertilizer, and heat levels all had a statistically significant impact on FPFP, NPFP, PPFP, and KPFP in 2025 ($P < 0.05$).

As illustrated in Figure 4, the FPFP, NPFP, PPFP, KPFP rankings in 2024 were T2 > T3 > T1 > T5 > T6 > T4 > T9 > T8 > T7, with the order of secondary factors being F > W> H, and the optimal composition identified as W2F1H2. Similarly, FPFP, NPFP, PPFP, KPFP rankings in 2025 were T3 > T2 > T4 > T1 > T6 > T5 > T7 > T8 > T9, with the order of secondary factors being F > H > W, and the optimal composition identified as W3F1H3. In summary, these results show that there is an association between water, fertilizer, and levels and FPFP, NPFP, PPFP, and KPFP.

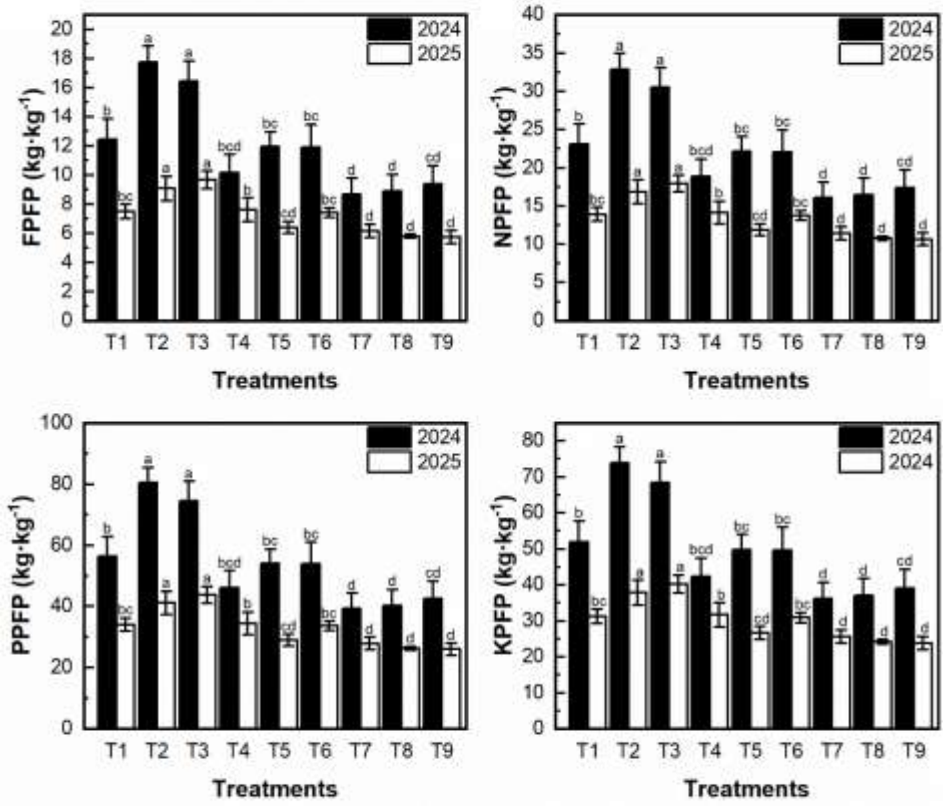

Figure 4. FPFP, NPFP, PPFP, KPFP of different treatments in 2024 and 2025.

2.3 Correlation Analysis

Correlation analysis was performed to generate the heatmap (Error! Reference source not found.), which visualizes the pairwise relationships among seed cotton yield, IWUE, FPFP, NPFP, KPFP, and rate of return. This method quantifies the associations between these indicators, with the heatmap clearly distinguishing significant positive and negative correlations. As shown in the figure, seed cotton yield exhibits substantial correlations with the aforementioned efficiency and benefit metrics. This implies that achieving high seed cotton yield may exert positive effects on economic benefits.

Indicators demonstrating both significant positive and negative correlations. This suggests that the high yield would be positive effects on economic benefits, and there may be adverse effects on the quality of the cotton in the pursuit of higher yields.

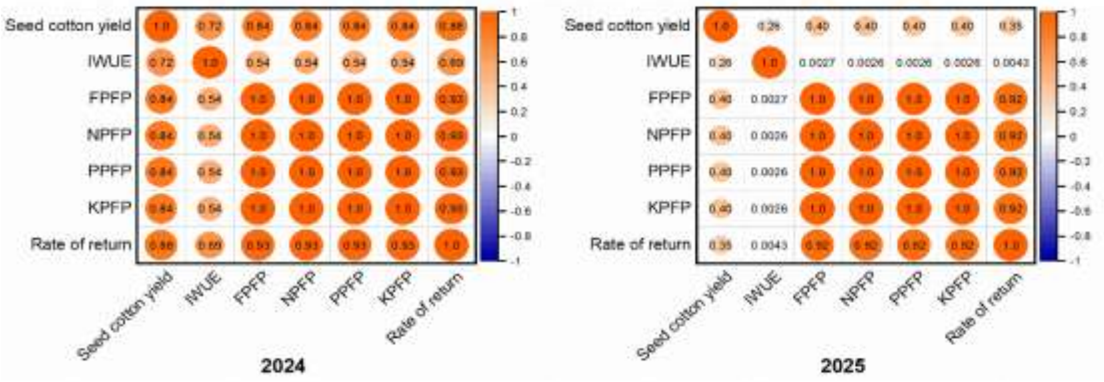

Figure 5. Correlation analysis of seed cotton yield, IWUE, FPFP, NPFP, PPFP, KPFP, and rate of return in 2024 and 2025.

2.3. Economic Benefits Analysis

To compare the differences in economic benefits among different water, fertilizer and heat levels, a simple statistical analysis was performed.

From the data in Table 5, the order of rate of return of different treatments in 2024 was T2 > T3 > T5 > T1 > T6 > T9 > T7 > T4 > T8. Similarly, in 2025, the order was T2 > T3 > T6 > T1 > T4 > T5 > T7 > T9 > T8. The treatment with the highest rate of return was W2F1H2 in both 2024 and 2025.

Table 5. Economic benefits in 2024 and 2025.

Treatments	Fertilization input (\$ ha^{-1})		Irrigation input (\$ ha^{-1})		Plastic film input (\$ ha^{-1})		Total input (\$ ha^{-1})		Cotton income (\$ ha^{-1})		Net income (\$ ha^{-1})		Rare of return	
	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025
T1	170.40		66.84		129.37		1604.40		7951.39	4839.97	6346.99	3219.72	3.91	1.99
T2	170.40		83.55		258.73		1750.47		11327.57	5858.67	9577.10	4090.90	5.47	2.31
T3	170.40		100.25		388.10		1896.55		10500.10	6232.10	8603.55	4316.81	4.54	2.25
T4	340.80		66.84		388.10		2033.53		8119.47	6133.82	6085.94	4080.20	2.96	1.99
T5	340.80		83.55		129.37		1791.51		9534.37	5159.04	7742.86	3349.83	4.32	1.85
T6	340.80		100.25		258.73		1937.58		9498.68	5974.87	7561.10	40.18.14	3.90	2.05
T7	511.20		66.84		258.73		2074.57		8318.88	5955.03	6244.32	3859.96	2.98	1.84
T8	511.20		83.55		388.10		2220.64		8510.14	5610.92	6289.50	3368.34	2.83	1.50
T9	511.20		100.25		129.37		1978.62		8992.14	5552.45	7013.52	3554.28	3.54	1.78

3. Discussion

3.1. Effect of Synergistic Regulation of Water-Fertilizer-Heat Management on Seed Cotton Yield in Cotton

This study found that synergistic regulation of water-fertilizer-heat management exerted a statistically significant effect on seed cotton yield.

Several reports have shown that PM significantly improves crops yield, aboveground dry matter, irrigation water use efficiency, soil organic carbon sequestration rate, the content of soil organic carbon, microbial activity, and urease activity compared to NM[11, 36, 37]. Previous studies have reported a strong relationship between Drip irrigation (DI) and seed cotton yield: DI markedly improved soil hydrothermal conditions, which are essential for creating an ideal environment for crop development. This improvement plays a pivotal role in facilitating the distribution of photosynthetic products to the aboveground biomass, ultimately boosting crop yield[12, 18, 38]. Prior studies have also noted that crop yield improvement is closely associated with enhanced soil fertility and water use efficiency[17, 29, 39]. For example, high nitrogen rates help field-grown cotton recover from stresses such as water restriction and mitigate yield losses[23, 40], while potassium (K) application significantly influences cotton yield[28].

In this study, there was a significant difference in the highest seed cotton yield between 2024 and 2025. This difference may be due to climatic changes[41, 42], as a better soil hydrothermal environment facilitated by increasing plastic film mulch layers favors crop yield formation[43].

This study not only supports previous findings[2, 44-47], but also confirms that plastic film mulch layers, irrigation levels, and fertilizer application levels all affect seed cotton yield. Specifically, we achieved higher seed cotton yield by increasing the number of plastic film mulch layers, a low-input method that yields high economic benefits.

3.2. Effect of Synergistic Regulation of Water-Fertilizer-Heat Management Oon IWUE and Nutrient Partial Factor Productivity in Cotton

Another important finding is that synergistic regulation of water-fertilizer-heat management had a statistically significant effect on IWUE, FPFP, NPFP, PPFP, and KPFP.

Several reports have shown that poor water-fertilizer management has increased production costs, lowered productivity, and significantly depleted soil nutrients[22, 31, 34, 48-50 24]. Soil nutrient deficiency is one of the significant challenges in crop production, particularly nitrogen (N), phosphorus (P), and potassium (K). These deficiencies not only reduce crop yields but also cause associated environmental issues, such as soil structure deterioration and ecosystem services diminution[16].

Previous study has found improving FPFP, NPFP, PPFP, and KPFP is a key goal for developing sustainable crop production[21, 26, 51-55]. Excessive N, P, K fertilization has a negative effect on yield sustainability and FPFP, NPFP, PPFP, and KPFP to varying extents. An appropriate reduction in N, P, and K fertilizer application in crop fields of northeast China could meet agronomic and environmental goals[21, 23, 56, 57].

This study not only broadly supports work linking plastic film mulching, irrigation levels, and fertilizer application levels with IWUE, FPFP, NPFP, KPFP[24, 58, 59], but also provide a new insights into significantly enhancing IWUE, nutrient partial factor productivity through a low-input approach.

3.3. Comprehensive evaluation based on cotton yield, nutrient partial factor productivity, and economic benefit.

Globally, sustainable farming practices such as precision fertilization and water-saving irrigation have been adopted to achieve high crop yields while minimizing nonpoint source pollution. The integration of optimized precision fertilization and water-saving irrigation practices substantially reduced N, P, and K losses, mainly through decreased N, P, and K leaching, while retaining fertilizer-derived N, P, and K in the root-zone soil layer. This is crucial for sustainable and high-yield crop production[36, 40, 60, 61]. Optimizing water and fertilizer application not only improves agricultural production efficiency but also is of great significance for environmental protection, resource conservation, and economic feasibility [30, 62, 63]. This study offers a method that not only improves seed cotton yield and economic benefits, but also reduces water and fertilizer inputs. It also provides a new insight into achieving high returns through a green and environmentally friendly low-input approach.

To comprehensively assess the results, a comprehensive evaluation system encompassing seed cotton yield, water and fertilizer use efficiency, and economic benefits was established. The TOPSIS method was adopted to comprehensively evaluate seed cotton yield, IWUE, FPFP, NPFP, PPFP, KPFP, and rate of return, as shown in Table 6. Regarding the ranking of comprehensive evaluation indices, T2 was ranked first in both 2024 and 2025. The W_2F1H2 treatment achieved the highest comprehensive evaluation index, consistent with its seed cotton yield.

Table 6. **Comprehensive evaluation of seed cotton yield, IWUE, nutrient partial factor productivity, and rate of return via the TOPSIS method for 2024 and 2025.**

Treatment	Positive ideal distance		Negative ideal distance		Comprehensive evaluation index		Ranking	
	2024	2025	2024	2025	2024	20250	2024	2025

T1	0.399	0.236	0.227	0.197	0.363	0.454	5	4
T2	0	0.116	0.607	0.344	1	0.747	1	1
T3	0.215	0.139	0.458	0.386	0.681	0.735	2	2
T4	0.538	0.193	0.081	0.265	0.131	0.578	8	3
T5	0.370	0.342	0.244	0.091	0.397	0.211	4	7
T6	0.358	0.258	0.268	0.190	0.429	0.425	3	5
T7	0.559	0.327	0.125	0.184	0.183	0.361	6	6
T8	0.590	0.394	0.025	0.071	0.041	0.154	9	8
T9	0.518	0.405	0.111	0.063	0.176	0.135	7	9

4. Conclusion

This study aimed to achieve high seed cotton yield and economic benefits through increasing plastic film mulch layers, a low-input method. The results show that water l, fertilizer and heat application levels all have a statistically significant effect on seed cotton yield, IWUE, nutrient partial factor productivity. Furthermore, the findings support the notion of achieving higher seed cotton yield and green-friendly goals via a low-input approach. These results provide insights for future research focused on achieving high seed cotton yield with green-friendly agricultural aims.

Conflict of Interest Statement

The Authors Declare: no conflict of interest.

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