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Appropriate Water and Nitrogen Regulation Promotes Soybean Yield Formation and Improves Water–Nitrogen Use Efficiency

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Abstract: To address water scarcity and soil damage in the Hexi Oasis irrigation area of China, a study was conducted on regulating water and nitrogen levels for soybean growth under film drip irrigation over two growing seasons (2020 and 2021). Two irrigation levels were tested: mild deficit (W1, 60–70% of field water capacity, FC) and full irrigation (W2, 70–80% of FC), along with three nitrogen levels: low (N1, 60 kg·ha^{-1}), medium (N2, 120 kg·ha^{-1}), and high (N3, 180 kg·ha^{-1}). The control treatment was no nitrogen with full irrigation (W2N0), totaling seven treatments. Results showed that during both growing seasons, soybean plant height reached its peak at the tympanic ripening stage, while the leaf area index (LAI), net photosynthesis rate (Pn), and transpiration rate (Tr) decreased at the tympanic ripening stage. The highest values for the plant height, LAI, Pn, Tr, yield, and the cost–benefit ratio were observed under the W2N2 treatment, significantly outperforming the W2N0 in all aspects ($p < 0.05$). Over the two-year period, the plant height and LAI were notably higher by 22.86% and 7.09%, respectively, in the W2N2 treatment compared to the W1N1. Full irrigation under N1 and N2 conditions resulted in an enhanced soybean Pn and Tr. However, under N3 conditions, a deficit-tuned irrigation treatment led to a 15.71% increase in the Pn and a 13.34% increase in the Tr on a two-year average. The W2N2 treatment had the highest yield, with a significant 4.93% increase over the W1N3 treatment on a two-year average. The highest rate of change in yield was observed in W1. The two-year cost–benefit ratio and unilateral water benefit reached their peak values in W2N2 and W1N2, respectively. Water use efficiency (WUE) was lower in N1 but significantly increased by 21.83% on a two-year average in W1N3 compared to W1N2. Additionally, W1 had a 14.21% higher WUE than W2 over two years. N3 had the lowest partial factor productivity of nitrogen, which increased by 17.78% on a two-year average in W2N1 compared to W1N1. All nine indicators related to yield formation and water–nitrogen use efficiency showed a positive correlation ($p < 0.05$) in this study. The highest composite scores were achieved with the W2N2 treatment in both years using the entropy weight and TOPSIS method. Overall, the W2N2 treatment provides a water and nitrogen combination that enhances soybean water and fertilizer efficiency, making it a promising option for high-yield soybean cultivation with water and nitrogen conservation in the Hexi Oasis irrigation area of China. This study offers valuable insights for achieving efficient soybean production while saving water and reducing nitrogen use.

Keywords: growth dynamics; Hexi Oasis irrigation area; photosynthetic characteristics; soybean; water–nitrogen use efficiency

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1. Introduction

An adequate supply of water and fertilizer resources is essential for achieving stable and high crop yields [1,2]. About 40% of the global land area is affected by drought, and agricultural productivity in these areas is severely limited by adverse factors such as water scarcity and soil degradation [3]. Soybean (*Glycine max* (Linn.) Merr.) is an annual herbaceous crop belonging to the genus Soybean in the Leguminosae family. It not only holds a high nutritional value but also possesses nitrogen fixation abilities in its rhizomes, making it crucial for sustainable agro-ecological development [4]. Despite being the fourth largest soybean producer globally, China has witnessed consecutive yield reductions, with an annual soybean production of 1,750,000 tonnes in 2020 [5]. The judicious use of water and fertilizer resources stands as a key factor that is limiting crop yield improvements in China [6]. Currently, China's agricultural water utilization rate hovers around 30–40% of that in developed countries, while the seasonal fertilizer utilization rate is a mere 30%, leading to significant wastage of these resources [7]. The Hexi region, a vital commercial grain cultivation hub in the west, relies on the distribution of three major inland rivers for irrigation. Despite this, the overall water resources in the region only account for 21% of the Gansu province's total, irrigating 75% of the province's irrigation area. This scarcity of agricultural irrigation water resources poses a significant challenge [8]. Despite the extensive research that has been conducted on the effects of irrigation and nitrogen fertilizer on crop growth, there remains a lack of studies focusing on the specific impacts of these applications in particular regions and on specific crops. Given the current scenario of a declining soybean supply coupled with a rising demand, achieving high-yield, efficient, and sustainable soybean production despite a reduction in the water resources and nitrogen supply has emerged as an urgent scientific challenge for soybean cultivation in the Oasis irrigation area.

The concept of water–nitrogen coupling aims to optimize the water and nitrogen supplies for crop growth, while minimizing nitrogen loss, alleviating drought stress, and preventing water body eutrophication [9]. This coupling involves integrating water and nitrogen fertilizer to collectively impact crop growth, yield, quality, and water–nitrogen use efficiency [10]. Current research primarily focuses on wheat [11], corn [12], cotton [13], and soybean, etc., with varying results due to geographical disparities in soil fertility, irrigation practices, and fertilizer application. Studies have shown that increased nitrogen fertilizer application with adequate soil moisture can boost the grain yield [14,15]. Subsequently, researchers have explored the effects of water and nitrogen coupling on crop growth across different conditions, suggesting a reciprocal relationship between water and fertilizer [16,17]. For instance, soybean dry matter accumulation benefits from supplemental irrigation, leading to a significant increase in the leaf area index compared to rainfall treatment [18]. Nitrogen application under water deficit regulation has been found to enhance nutrient indexes but may not significantly impact the soybean yield and pod production [19].

Numerous studies have confirmed the effects of water and nitrogen interactions on soybean yields. However, there is a lack of reports on the comprehensive evaluation of how water and nitrogen regulation impact soybean yield formation and water–nitrogen use efficiency. Given the current challenges in agricultural production, such as water scarcity, the excessive use of chemical fertilizers, soil degradation, and groundwater pollution, this study was conducted in the Hexi Oasis irrigation area in China over two growing seasons. The research focused on studying the regulation of water and nitrogen on soybean under film drip irrigation. By analyzing different nitrogen application rates and irrigation volumes, the study aimed to understand soybean yield formation, economic benefits, and water–nitrogen use efficiencies. The findings highlight key strategies for reducing water and nitrogen use while maintaining high yields in the region. The study employed the entropy weight and TOPSIS method to identify the optimal combinations of water and nitrogen for soybean cultivation. These findings offer valuable insights for enhancing water and fertilizer efficiency in soybean production in the Hexi Oasis irrigation area.

2. Materials and Methods

2.1. Overview of the Study Area

The field experiment was conducted in May–October 2020 and 2021 at Yimin Irrigation Experimental Station (100°43′ E, 38°39′ N), Minle County, Zhangye City, Gansu Province (Figure 1). The area has a large temperature difference between day and night, which is typical of a temperate continental desertified grassland climate. There is sufficient sunshine (annual sunshine hours of 2666.1–3248.7 h, about 1000 h during the growth season), low precipitation, and high evapotranspiration (annual average precipitation of 200 mm, evapotranspiration more than 2000 mm), and the contradiction between the supply and demand of water resources is prominent. An overview of the meteorological elements of the two growing seasons is shown in Figure 2 (experimental station meteorological data were obtained from the county's meteorological services). The soil quality of the test area is loamy, with good water and fertilizer retention; the field water holding capacity of the test soil is about 24%, the pH value is 7.2, the soil bulk density is 1.46 g·cm^{-3}, the groundwater depth is more than 20 m, there is no salinization, and the tillage layer is 0–40 cm.

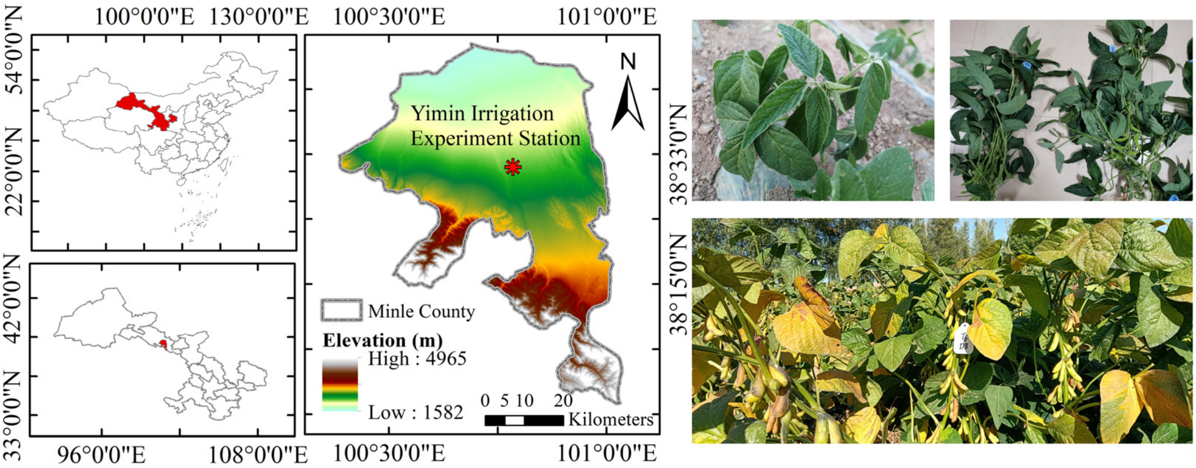

Figure 1. Overview map of the study area.

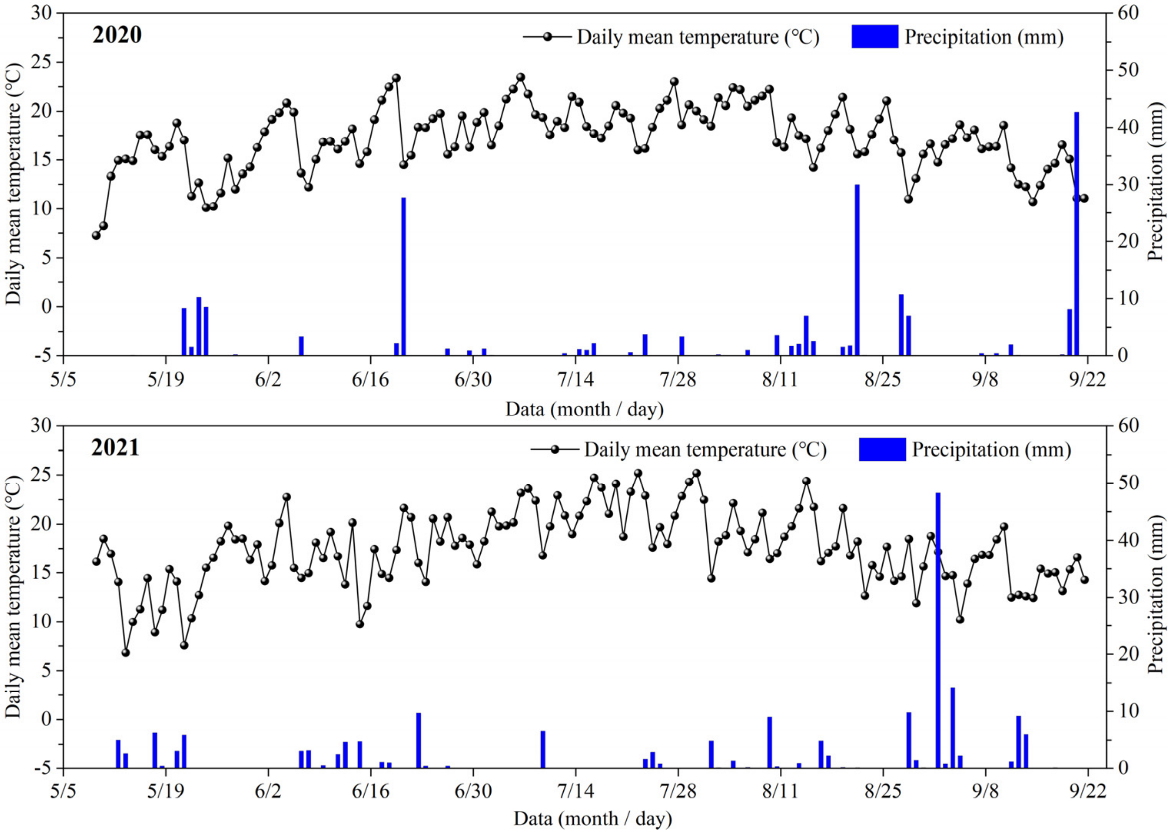

Figure 2. Overview of meteorological elements for the two growing seasons.

2.2. Experimental Design

In this study, the "Heihe No.3" soybean was used as the research object. The entire growing season was divided into four reproductive periods: the seedling stage, branching stage, flowering and podding stage, and tympanic ripening stage. The experiment was conducted in a randomized block design with two moisture gradients: water stress W1 (60–70% in FC) and fully irrigated W2 (70–80% in FC). There were three nitrogen application gradients: low nitrogen level N1 (60 kg·ha^{-1}), medium nitrogen level N2 (120 kg·ha^{-1}), and high nitrogen level N3 (180 kg·ha^{-1}), as well as no nitrogen application with full irrigation as the control treatment (W2N0). There were seven treatments with three replications for each treatment, and a total of 21 plots with a plot area of 10.80 m^2 (2.7 m × 4.0 m). The specific experimental design is shown in Table 1.

Table 1. Test treatments for water–nitrogen coupling in soybean.

Treatments		Nitrogen Application /(kg·ha^{-1})	Soil Water Deficit Regulation Level (%)
N1	W1N1	60	60–70% FC [a]
	W2N1	60	70–80% FC
N2	W1N2	120	60–70% FC
	W2N2	120	70–80% FC
N3	W1N3	180	60–70% FC
	W2N3	180	70–80% FC
N0	W2N0	0	70–80% FC

[a] The lower and upper limit of soil water level (% in field water-holding capacity).

Soybeans were sown by hole sowing on 10 May 2020 and 6 May 2021, and harvested on 22 September 2020 and 20 September 2021, respectively. Before sowing, 40% of the total nitrogen fertilizer was applied as basal fertilizer, while the remaining 60% was applied in two equal fertilizer doses at the flowering and podding stage and at the tympanic ripening stage. The planting pattern of "one film, two rows, and one belt" was adopted, and the field was covered with 70 cm of plastic film with a spacing of 45 cm and 50 cm between plants and rows, respectively. The fertilizer was applied by Venturi fertilizer applicators, with drip irrigation at a spacing of 30 cm and an average flow rate of 2.5 L·h^{-1}, and with a 60 cm deep isolation zone between the subzones. The experimental layout is shown in Figure 3.

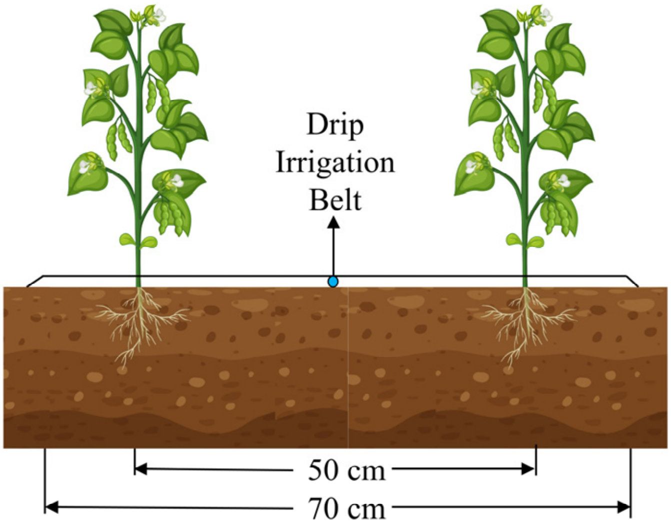

Figure 3. Test layout diagram.

2.3. Indicators and Methods

2.3.1. Growth Dynamics

(1) Plant height

Plant height was determined by using a steel tape measure with an accuracy of 1 mm to randomly select five uniformly growing soybean plants in each plot before the end of each growth stage.

(2) Leaf area index

Leaf area was determined using the length and width coefficient method, in which five uniformly growing soybeans were randomly selected in each plot before the end of each fertility period to determine the length and width of the leaf blades. The length and width of the leaf blades were measured by CJW888 electronic digital reading vernier calipers (accuracy 0.01 mm), and the leaf area was calculated using Formula (1). The leaf area index is the number of plants corresponding to the leaf area per unit of the cultivated area.

$$LA = L \times W \times K \tag{1}$$

where L is the maximum length of the blade, mm. W is the maximum width of the blade, mm. K is the correction factor, take 0.73 [20].

2.3.2. Photosynthetic Characteristics

The photosynthetic physiological indexes such as the net photosynthetic rate (Pn) and transpiration rate (Tr) were measured by a portable photosynthesis tester (LI-6400XT: produced by LI-COR, an American company, Lincoln, NE, USA). The measurements were made on cloudless and windless sunny days during the flowering and podding stage and the grain maturity stage; three soybean plants with the same growth conditions were randomly selected from each plot during the time period from 9:00 a.m. to 11:00 a.m.

2.3.3. Yield

The yield of soybean was determined by sampling with reference to the Irrigation Test Specification. For each of the different treatments, three uniformly growing soybean plants were selected and threshed, and then the seeds were dried in full sunlight and air-dried, and then the individual grain weights of the soybean plants were measured. The average of the three plants was taken and the yield per plant was converted to the yield per hectare.

2.3.4. Economic Benefits

(1) Cost–benefit ratio

The main costs of water and nitrogen-regulated soybean production include seeds, fertilizer, mulch, water costs, drip irrigation tapes, labor, and machinery, and the cost–benefit ratio is equal to the ratio of the total economic benefits to the cost inputs.

(2) Unilateral water benefit

The unilateral water benefit is equal to the ratio of the net benefit to the total water consumption ($\text{CNY} \cdot \text{m}^{-3}$).

2.3.5. Water–Nitrogen Use Efficiency

(1) Evapotranspiration

The evapotranspiration during the reproductive stage of the soybean plants was calculated by the water balance method [21]:

$$ET = \left(W_0 - W_f\right) + P + K + M - C \tag{2}$$

where ET is the water consumption of soybean, mm. W_0 and W_f are the planned wet layer storage at the beginning and the end of the fertility time period, respectively, mm. P is the effective precipitation during the fertility time period of the crop ($p > 5$ mm), mm. M is the amount of irrigation water, mm. K is the amount of deep soil water recharge, mm. C is the amount of deep soil water seepage, mm. The depth of the groundwater in the experimental area is greater than 20 m, so $K = 0$. The amount of irrigation water is lower than the amount of water held in the field, which will not produce deep seepage, so $C = 0$.

(2) Water Use Efficiency

Formula (3) can be used to calculate soybean water use efficiency (*WUE*), kg·m^{-3} [22]:

$$WUE = Y/ET \tag{3}$$

where Y is the soybean yield, kg·ha^{-1}. ET is the amount of water consumed over the full life span of the soybean, m^3·ha^{-1}.

(3) Partial Factor Productivity of Nitrogen

The formula for calculating the partial factor productivity of nitrogen (*PFPN*), kg·kg^{-1} [23]:

$$NPFP = Y/F_N \tag{4}$$

where Y is the soybean yield in the nitrogen application area, kg·ha^{-1}. F_N is the amount of nitrogen applied per hectare of soybean planted, kg·ha^{-1}.

2.4. Multi-Objective Comprehensive Evaluation Based on the Entropy Weight and TOPSIS Method

2.4.1. Entropy Weighting Method

① Construct the original matrix for evaluation system A:

$$A = (x_{ij})_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{21} & \vdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{5}$$

where x_{ij} denotes the jth evaluation indicator for the ith treatment. $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$.

② Normalize the original matrix to obtain matrix B:

$$b_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{6}$$

$$B = (b_{ij})_{m\times n} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{21} & \vdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix} \tag{7}$$

where b_{ij} denotes the jth evaluation indicator for the ith treatment after standardization. $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$.

③ The weights of the indicators were calculated as follows:

$$p_{ij} = \frac{b_{ij}}{\sum_{i=1}^{m} b_{ij}} \tag{8}$$

$$E_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} p_{ij} \ln(p_{ij}) \tag{9}$$

$$\mathrm{w}_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \tag{10}$$

where p_{ij} denotes the feature weight, E_j denotes information entropy, and W_j denotes indicator weight.

2.4.2. Entropy Weight and TOPSIS Method

① Based on steps ① and ② in the entropy weighting method, determine the weighted decision matrix W of the evaluation system:

$$W = (Z \times w_j)_{m \times n} \tag{11}$$

② Calculate the positive ideal solution (Z^{+}) and negative ideal solution (Z^{-}) for each evaluation metric:

$$Z^{+} = (Z_{\text{max1}}, Z_{\text{max2}}, \ldots, Z_{\text{maxn}}) \tag{12}$$

$$Z^{-} = (Z_{\text{min1}}, Z_{\text{min2}}, \ldots, Z_{\text{minn}}) \tag{13}$$

③ Scores were calculated for each water–nitrogen combination:

$$D_i^{+} = \sqrt{\sum_{j=1}^{n} (M_{ij} - Z_j^{+})^2} \tag{14}$$

$$D_i^{-} = \sqrt{\sum_{j=1}^{n} (M_{\text{ij}} - Z_j^{-})^2} \tag{15}$$

$$C_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}},\ 0 \le C_i \le 1 \tag{16}$$

where D_i^{+} is the distance of the evaluation index from Z^{+}. D_i^{-} is the distance of the evaluation index from Z^{+}. C_i is the score of each water–nitrogen combination, and the larger the C_i value, the better the water–nitrogen combination.

2.5. Data Analysis

Data were collated and analyzed using Microsoft Excel 2016 and IBM SPSS Statistics 26 software for the soil water content, plant height, LAI, Pn, Tr, yield, economic benefits, and water–nitrogen use efficiency of soybean. Significant differences in the data were analyzed by a one-way analysis of variance (ANOVA) with a significance level of 0.05 and a highly significant level of 0.01 between treatments. Plots were made using ArcMap 10.3, Microsoft PowerPoint 2016 (Manufactured by the Microsoft Corporation (Redmond, WA, USA), version 2016), and Origin 2021 (Manufactured in the Northampton, Massachusetts, USA by the OriginLab Corporation, version 2021).

3. Results

3.1. Effect of Water and Nitrogen Regulation on the Growth Dynamics of Soybeans

3.1.1. Plant Height

As shown in Figure 4 and Table 2, the nitrogen fertilizer supply could significantly affect plant height at all the reproductive stages of soybean, and the results of the two-year experiments were basically consistent. Throughout the soybeans' reproductive stages, N2 significantly promoted the relative plant growth, and at the branching stage, soybean plant height was significantly ($p < 0.05$) reduced by an average of 5.93%, 4.92%, and 1.98%, in the N0, N1, and N3 conditions, respectively, in the two-year period compared with that of the N2 conditions. The branching stage was the stage with the least differences in the change in plant height during the whole growing season. At the flowering and podding stage, soybean plant height at the N0, N1, and N3 levels were on average 19.99%, 18.57%, and 9.94% lower than that of N2, respectively, which was highly significant ($p < 0.01$) over the two-year period, with the greatest differences being between treatments at each nitrogen application level. Under the same soil water content condition (W2), plant height at the flowering and podding stage and the tympanic ripening stage without nitrogen application was significantly reduced by an average of 7.13–21.13% and 3.29–20.77%, respectively, compared to the nitrogen application treatment over the two years. A moisture deficit also significantly affected plant height at all the reproductive stages of soybean, and water and nitrogen fertilizer showed significant interactive effects on plant height in both growing seasons, except at the branching stage. At the seedling, flowering and podding, and tympanic ripening stages, plant height in the W2N1 was significantly higher than that in the W1N1 by an average of 9.73%, 10.97%, and 7.58% in the two growing seasons, respectively. There were no significant differences among the remaining irrigation treatments at all nitrogen application levels. Overall, the combination of moderate nitrogen application with fully irrigated water and nitrogen resulted in maximum plant heights (74.77 cm and 75.33 cm) at the end of both growing seasons, which were significantly higher by 25.70% (2020) and 26.72% (2021) in both growing seasons, respectively, as compared to the no nitrogen application treatment.

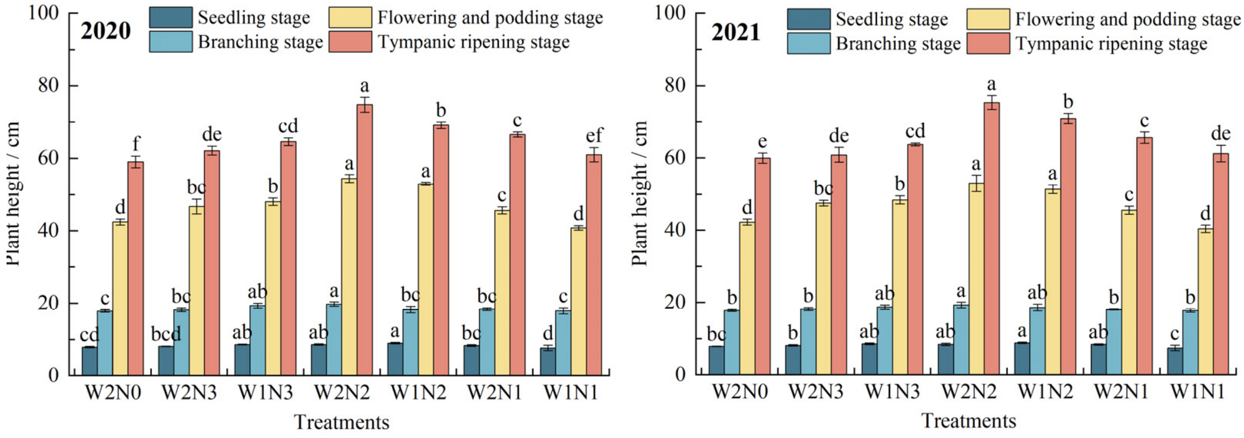

Figure 4. Effect of water and nitrogen regulation on the soybean plants' height. Note: Lowercase letters in the graphs indicate significant differences at the $p = 0.05$ level. The absence of the same lowercase letters among treatments at the same fertility period indicates significant differences; the presence of the same lowercase letters indicates non-significant differences.

Table 2. Analysis of variance for the effect of different water and nitrogen regulation on the plant height and LAI of soybean.

Index	Year	*F* Value	Seedling Stage	Branching Stage	Flowering and Podding Stage	Tympanic Ripening Stage
Plant height	2020	F_W	0.519 ns	9.117 **	37.852 **	5.471 *
		F_N	3.706 *	4.297 *	39.421 **	27.297 **
		$F_{W \times N}$	11.594 **	3.356 ns	119.766 **	85.233 **
	2021	F_W	0.651 ns	4.626 *	41.678 **	0.917 ns
		F_N	4.845 *	1.835 ns	31.069 **	16.85 **
		$F_{W \times N}$	8.479 **	4.477 *	63.686 **	80.696 **
LAI	2020	F_W	12.371 **	19.239 **	23.823 **	0.843 ns
		F_N	2.318 ns	30.857 **	14.462 **	15.48 **
		$F_{W \times N}$	3.518 ns	24.714 **	31.345 **	18.047 **
	2021	F_W	14.471 **	25.129 **	24.379 **	0.18 ns
		F_N	3.636 *	11.468 **	11.897 **	12.294 **
		$F_{W \times N}$	3.859 *	18.34 **	13.71 **	20.192 **

Note: F_W is the ANOVA value of the degree of water deficit; F_N is the ANOVA value of the amount of nitrogen applied; and $F_{W \times N}$ is the ANOVA value of water–nitrogen interaction. * denotes a significant difference ($p < 0.05$), ** denotes a highly significant difference ($p < 0.01$), and ns denotes a non-significant difference ($p > 0.05$).

3.1.2. The Leaf Area Index

The effects of different water and nitrogen combinations on the LAI of soybean are shown in Figure 5. It can be seen that both water and nitrogen had significant effects ($p < 0.05$) on the soybean LAI over two years, and both of them showed significant interaction effects in both growing seasons. The effect of the nitrogen fertilizer on the soybean LAI reached highly significant levels ($p < 0.01$) in all the reproductive stages except the tympanic ripening stage. Within two growing seasons, under W1 conditions, the LAI of soybean at the seedling and branching stage reached the maximum peak at N3 with the increase of nitrogen application, while the LAI of soybean at the flowering and podding stage and the tympanic ripening stage showed the trend of increasing and then decreasing, and reached the maximum peak at N2, i.e., the LAI of the W1N2 treatment was the largest, and it was significantly increased by 4.42% over two years on average compared to the W1N1 treatment, and increased by 2.63% over two years on average compared to W1N3 treatment. Under the W2 conditions, the LAI increased firstly and then decreased with the increase of nitrogen application, and at the end of the reproductive stage, the LAI of the W2N2 treatment was the largest, and it was significantly increased by an average of 11.46%, 4.07%, and 7.05% compared with that of N0, N1, and N3, respectively. The effect of moisture on the LAI of soybean reached a highly significant level in all the reproductive stages except the seedling stage. Under the N1 and N2 conditions, W2 increased by an average of 2.47–6.39% and 1.57–7.80% more than W1 over two years, respectively, whereas under N3, water irrigation was negatively correlated with the LAI, with the LAI decreasing by 0.96–2.89%, and the pattern of change in the LAI was consistent in the two growing seasons of 2020 and 2021. Overall, irrigation under appropriate nitrogen fertilizer supply conditions (N1 and N2) could promote the increase of the soybean LAI, while excessive nitrogen inputs would inhibit plant growth and consequently reduce the LAI. In addition, compared with full irrigation, deficit-regulated irrigation had a more significant effect on the soybean LAI under the condition of maintaining a moderate amount of applied nitrogen.

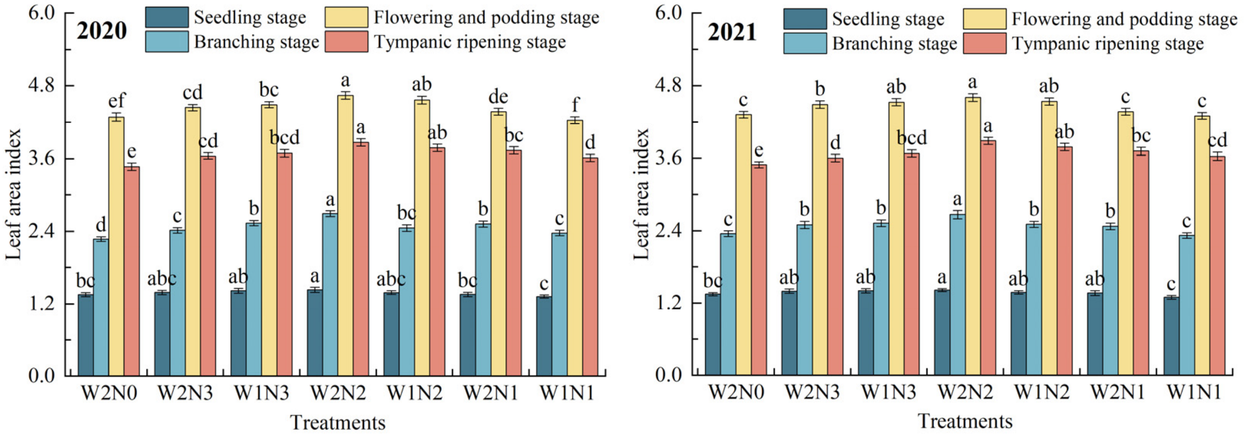

Figure 5. Effect of water and nitrogen regulation on the leaf area index of soybean. Note: Lowercase letters in the graphs indicate significant differences at the $p = 0.05$ level. The absence of the same lowercase letters among treatments at the same fertility period indicates significant differences; the presence of the same lowercase letters indicates non-significant differences.

3.2. *Effect of Water and Nitrogen Regulation on Photosynthetic Characteristics of Soybean*

3.2.1. Net Photosynthetic Rate

Figure 6 shows the effect of different water and nitrogen regulation on the Pn during the reproductive growth stages (the flowering and podding stage and the tympanic ripening stage) of soybean. As shown in Table 3, the effect of water on the Pn during the reproductive growth stages of soybean showed as highly significant ($p < 0.01$) in both growing seasons. Under the N3 conditions, W1 significantly ($p < 0.05$) increased the Pn by about 15.71% and 14.69% on average over the two years compared to W2, respectively. The increase in the water supply under the N2 conditions significantly increased the Pn only at the flowering and podding stage, with a two-year average value of 9.15%. A positive correlation between the irrigation volume and the Pn under the N1 conditions was observed but the significance performance was inconsistent over the two years. The Pn value at the reproductive growth stages of soybean under the nitrogen-free (N0) condition was the minimum, and the two reproductive stages were 23.67% and 26.89% lower than the W2N2 treatment (two-year average), respectively. The effect of nitrogen fertilizer on the soybean Pn was significant (at the highly significant level) only at the flowering and podding stage, and it interacted significantly with water throughout the reproductive growth stages in both years. Under the same watering conditions in both growth stages, the soybean Pn showed a single-peaked trend of increasing and then decreasing with increasing nitrogen application, reached the maximum at N2, with a significant increase of 16.13% and 14.70% on average over the two-year period compared with N1, and by 31.38% and 36.83% on average over the two-year period compared with N0, respectively.

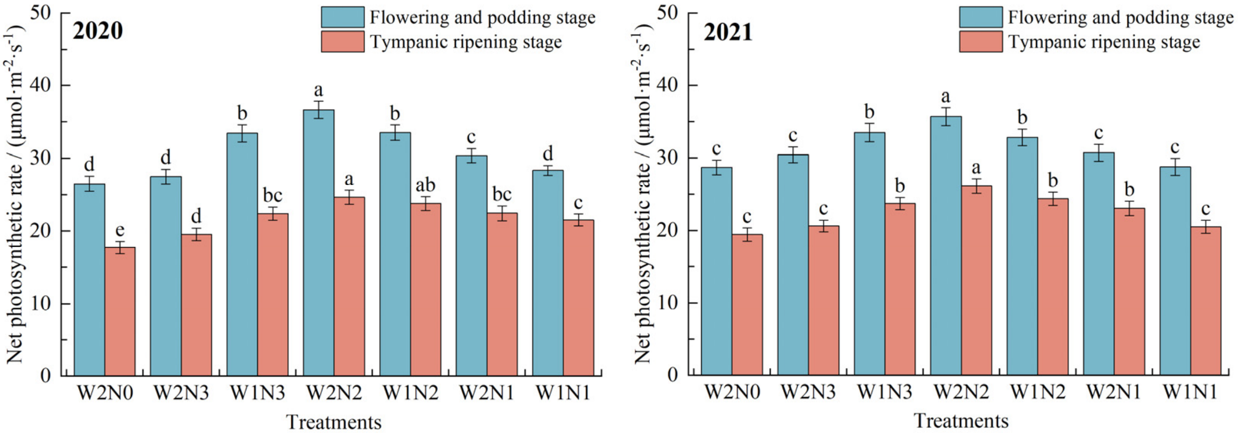

Figure 6. Effect of water and nitrogen regulation on net photosynthetic rate of soybean. Note: Lowercase letters in the graphs indicate significant differences at the $p = 0.05$ level. The absence of the same lowercase letters among treatments at the same fertility period indicates significant differences; the presence of the same lowercase letters indicates non-significant differences.

Table 3. Analysis of variance for the effect of different water and nitrogen regulation on the Pn and Tr in soybean.

Index	Year	*F* Value	Flowering and Podding Stage	Tympanic Ripening Stage
Pn	2020	F_W	13.476 **	0.828 ns
		F_N	29.382 **	20.729 **
		$F_{W \times N}$	73.728 **	24.888 **
	2021	F_W	20.261 **	3.957 ns
		F_N	11.755 **	15.957 **
		$F_{W \times N}$	24.527 **	39.574 **
Tr	2020	F_W	53.592 **	116.679 **
		F_N	52.339 **	79.327 **
		$F_{W \times N}$	114.831 **	121.107 **
	2021	F_W	16.025 **	98.734 **
		F_N	60.058 **	59.321 **
		$F_{W \times N}$	138.706 **	65.385 **

Note: F_W is the ANOVA value of the degree of water deficit; F_N is the ANOVA value of the amount of nitrogen applied; and $F_{W \times N}$ is the ANOVA value of water–nitrogen interaction. ** denotes a highly significant difference ($p < 0.01$), and ns denotes a non-significant difference ($p > 0.05$).

3.2.2. Transpiration Rate

Shown in Figure 7 are the effects of different water and nitrogen fertilizer combinations on the soybean Tr during the reproductive growth stages. From the Figure 7, it can be seen that the values of the soybean Tr decreased at the tympanic ripening stage compared with the flowering and podding stage, and the effects of water and nitrogen as well as water–nitrogen interactions on the Tr of soybean over two years of reproductive growth reached highly significant levels ($p < 0.01$). When the irrigation volume was kept the same, the Tr tended to increase and then decrease with the increase of nitrogen application, and the W2N2 treatment obtained the maximum value in the whole reproductive growth stage, which was significantly increased by 10.73% and 20.73% (two-year average) compared with the W1N2 treatment for the two fertility periods, respectively. The W2N0 treatment had the lowest Tr, which was reduced by 35.53% and 47.37% on average over the two years of the reproductive growth stages compared with the W2N2 treatment, respectively. Adequate irrigation increased the soybean Tr at the N1 and N2 levels, with W2 significantly increasing the Tr by 22.49% and 21.05% and 10.73% and 20.72% on average over two years of the reproductive growth stages compared to the W1 level, respectively. At the N3 level, deficit-regulated irrigation was beneficial in increasing the soybean Tr, with W1 significantly increasing the Tr by about 12.23% and 15.69% on average compared to W2 at the flowering and podding stage and at the tympanic ripening stage, respectively. Overall, the moderate supplementation of nitrogen fertilizer under deficit-regulated irrigation conditions was beneficial to increase the Tr during the reproductive growth stages of soybean, which was significantly higher in the W1N2 treatment compared with the W1N1 treatment, but not significantly different from the W1N3 treatment, suggesting that the combination of a water deficit and nitrogen fertilizer reduction could increase the Tr during the reproductive growth stages of soybean.

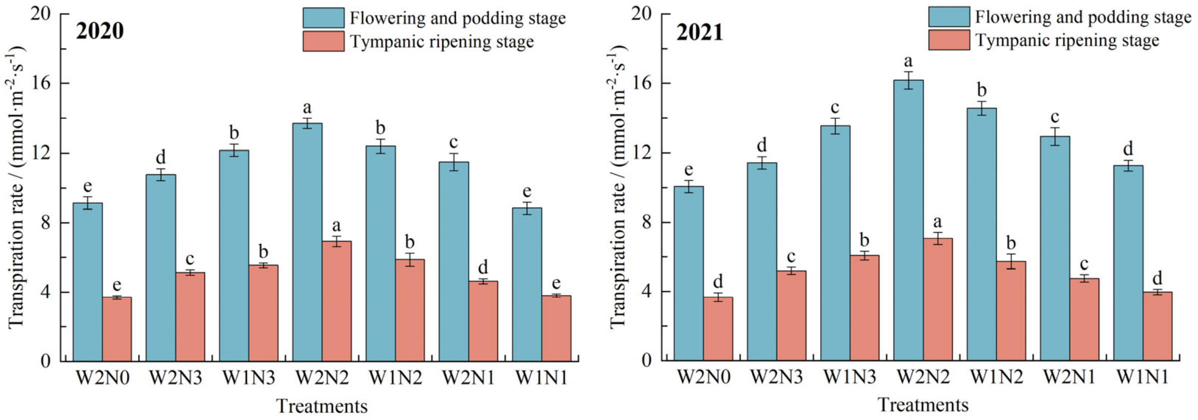

Figure 7. Effect of water and nitrogen regulation on net transpiration rate of soybean. Note: Lowercase letters in the graphs indicate significant differences at the $p = 0.05$ level. The absence of the same lowercase letters among treatments at the same fertility period indicates significant differences; the presence of the same lowercase letters indicates non-significant differences.

3.3. *Effect of Water and Nitrogen Regulation on Soybean Yield and Economic Benefits*

3.3.1. Yield

The effects of different water and nitrogen regulation on the soybean yield, cost–benefit ratio, and unilateral water benefit are shown in Figure 8.

The effects of water and nitrogen as well as water–nitrogen interactions on the soybean yield, cost–benefit ratio, and unilateral water benefit over two years reached highly significant levels ($p < 0.01$). As shown in Figure 8a, the W2N2 treatment had the highest yield in both growing seasons with a two-year average of 3288.25 $kg \cdot ha^{-1}$, which was significantly higher by 77.49% on average over two years compared to the W2N0 treatment. Under the same conditions of nitrogen application (N1 and N2), deficit-regulated irrigation significantly ($p < 0.05$) reduced the soybean yield with a two-year average of 12.10% and

5.13%, respectively. Whereas, deficit-regulated irrigation significantly increased the yield by 9.29% (two-year average) at the N3 level. At the same irrigation level, the soybean yield showed an increasing and then decreasing trend with increasing nitrogen application, in which a moderate increase in nitrogen fertilizer (N2) under the W1 level condition significantly increased the yield by 31.50% (two-year average), whereas excessive nitrogen fertilizer inputs (N3) did not significantly increase the soybean yield. The excessive application of nitrogen (N3) under the W2 level condition significantly reduced the yield by 12.59% (two-year average). This indicates that under adequate irrigation, excessive nitrogen application will not increase the soybean yield but will lead to a yield reduction.

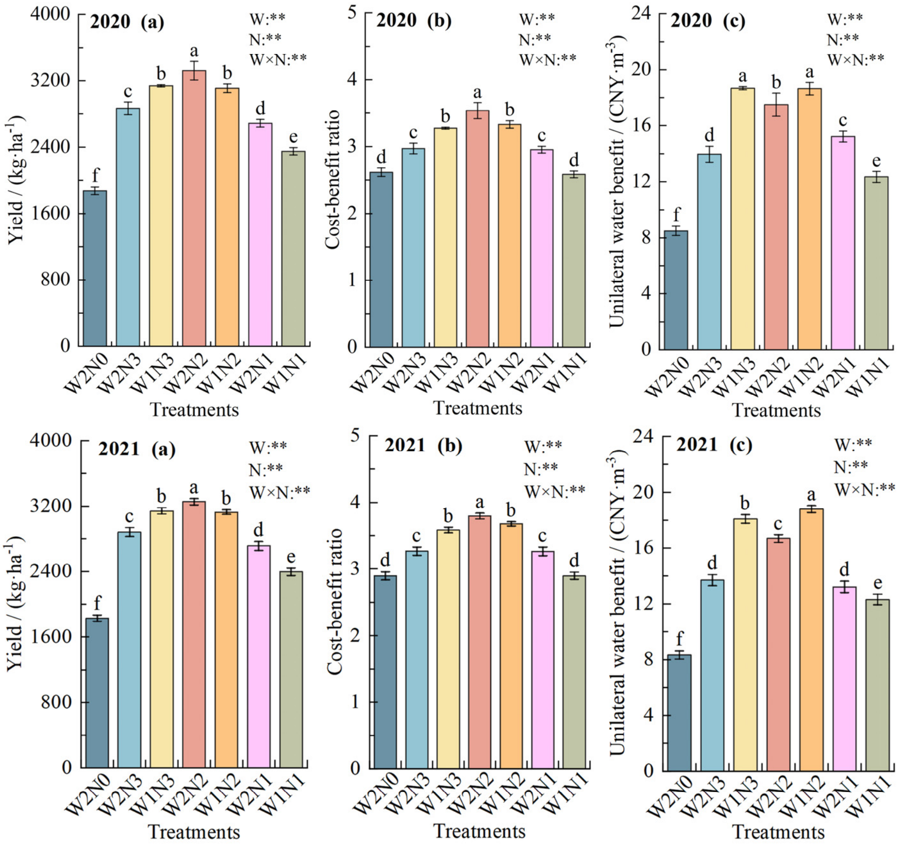

Figure 8. Effect of water and nitrogen regulation on soybean yield and economic benefit. Note: Lowercase letters in the graphs indicate significant differences at the $p = 0.05$ level. The absence of the same lowercase letters among treatments at the same fertility period indicates significant differences; the presence of the same lowercase letters indicates non-significant differences. ** denotes a highly significant difference ($p < 0.01$).

3.3.2. Cost–Benefit Ratio

As can be seen in Figure 8b, the W2N2 treatment had the highest cost–benefit ratio, which was significantly ($p < 0.05$) increased by 33.18% on average over two years compared to the W2N0 treatment. With the same amount of nitrogen application (N1 and N2), full irrigation significantly increased the cost–benefit ratio by 13.47% and 4.74% over two years, respectively. Indicating that the increase in the cost–benefit ratio gradually slowed down with the increase in irrigation water under this condition, whereas the increase in irrigation water significantly decreased the cost–benefit ratio under the N3 condition. Under the condition of the same amount of irrigation, the soybean cost–benefit ratio increased and then decreased with the increase of nitrogen application, and the changes were consistent in both years, reaching the maximum value of the cost–benefit ratio in N2, and the W1N2 and W2N2 treatments significantly increased the cost–benefit ratio by 27.16% and 33.18%, respectively, compared with that of the W2N0 treatment (two-year average).

3.3.3. Unilateral Water Benefit

Figure 8c shows the effect of different irrigation amounts and nitrogen application on the unilateral water benefit of soybean. As can be seen from Figure 8c, the W1N2 treatment had the highest unilateral water benefit, with a two-year average value of 18.72 CNY·m^{-3}, which was significantly ($p < 0.05$) increased by 9.64% (two-year average) compared with the W2N2 treatment. The unilateral water benefit showed an increasing and then decreasing trend with increasing nitrogen application at the same level of irrigation, while increasing irrigation under the N1 condition significantly increased the unilateral water benefit by 15.28% (two-year average) at the same level of nitrogen application, and increasing irrigation under N2 and N3 levels significantly decreased the unilateral water benefit, but the values were larger than that those at the N1 level. There was no significant difference ($p > 0.05$) in unilateral water benefits between the reduced nitrogen fertilizer (N1) and excess nitrogen (N3) treatments under fully irrigated conditions, whereas the N2 level significantly increased unilateral water benefits. Overall, the combination of reduced nitrogen application and deficit-regulated irrigation would not only improve the yield, but also increase the cost–benefit ratio and unilateral water benefits.

3.4. Effect of Water and Nitrogen Regulation on Water–Nitrogen Use Efficiency in Soybean

3.4.1. Water Use Efficiency

The effects of irrigation and nitrogen application on the water use efficiency (WUE) and partial factor productivity of nitrogen (PFPN) in soybean are shown in Table 4. From Table 4, it can be seen that the effects of water and nitrogen fertilizer, as well as water–nitrogen interactions, on the WUE and PFPN of soybean in two growing seasons reached the highly significant level ($p < 0.01$). The effect of adequate irrigation on the WUE of soybean in both growing seasons was significant at the N1 level, even though it increased the WUE by 3.22% (two-year average), but the difference between the treatments was not significant ($p > 0.05$). At the N2 and N3 levels, deficit-regulated irrigation in both growing seasons significantly increased WUE by an average of 3.71% and 42.64%, respectively. When irrigation levels were consistent, WUE was positively correlated with nitrogen application under the W1 level, and the maximum value was obtained in the W1N3 treatment, which was significantly increased by 54.10% (two-year average) compared to the W1N1 treatment. Whereas, WUE under the W2 level condition showed an increasing and then decreasing trend with the increase of nitrogen application, and the maximum value for WUE was obtained in the W2N2 treatment, which was significantly increased by 65.20% and 18.19% (two-year average) compared with W2N0 and W2N1, respectively. Overall, the combination of excessive fertilizer and adequate irrigation significantly reduced soybean WUE, while the combination of deficit irrigation and adequate nitrogen fertilizer or adequate irrigation and moderate nitrogen application could be beneficial to increase soybean WUE.

Table 4. Effect of water and nitrogen regulation on WUE and PFPN in soybean.

Treatments	2020			2021		
	Average Value of Water Consumption/(mm)	**WUE/ (kg·ha^{-1}·mm)**	**PFPN/ (kg·kg^{-1})**	**Average Value of Water Consumption/(mm)**	**WUE/ (kg·ha^{-1}·mm)**	**PFPN/ (kg·kg^{-1})**
W2N0	305.24	6.14 ± 0.14 f	/	304.46	6.30 ± 0.16 e	/
W2N3	315.84	9.12 ± 0.18 d	16.01 ± 0.31 f	315.15	9.07 ± 0.24 c	15.92 ± 0.43 f
W1N3	241.98	12.98 ± 0.16 a	17.46 ± 0.21 e	291.84	12.97 ± 0.06 a	17.44 ± 0.08 e
W2N2	320.04	10.17 ± 0.12 c	27.12 ± 0.32 c	317.11	10.38 ± 0.35 b	27.69 ± 0.94 c
W1N2	292.75	10.69 ± 0.10 b	26.07 ± 0.24 d	288.61	10.62 ± 0.18 b	25.92 ± 0.44 d
W2N1	310.42	8.74 ± 0.18 e	45.20 ± 0.93 a	310.09	8.65 ± 0.15 d	44.76 ± 0.76 a
W1N1	281.63	8.50 ± 0.16 e	39.91 ± 0.75 b	285.53	8.34 ± 0.16 d	39.16 ± 0.76 b
F_W	/	423.295 **	4459.057 **	/	277.927 **	2962.091 **
F_N	/	820.864 **	927.603 **	/	417.735 **	660.492 **
$F_{W \times N}$	/	566.44 **	473.56 **	/	314.669 **	344.429 **

Note: Lowercase letters indicate significant differences at the $p = 0.05$ level. The absence of the same lowercase letters among treatments at the same fertility period indicates significant differences; the presence of the same lowercase letters indicates non-significant differences. F_W is the ANOVA value of the degree of water deficit; F_N is the ANOVA value of the amount of nitrogen applied; and $F_{W \times N}$ is the ANOVA value of water–nitrogen interaction. ** denotes a highly significant difference ($p < 0.01$).

3.4.2. Partial Factor Productivity of Nitrogen

Under the condition of the same amount of irrigation, the soybean PFPN decreased with the increase of nitrogen application in both growing seasons, and both of them achieved the maximum value in the W1N1 and W2N1 treatments, with a significant decrease of 64.51% in W1N3 compared with the W1N1 treatment (two-year average), and a significant decrease of 55.88% in W2N3 compared with the W2N1 treatment (two-year average). Under the same conditions of nitrogen application, the PFPN at the N1 and N2 levels was positively correlated with the amount of irrigation, and full irrigation could significantly increase the soybean PFPN in both cases, while deficit-adjusted irrigation at the N3 level could significantly increase the soybean PFPN, with a two-year increase mean value of 9.29%. Taken together, an adequate water supply under low nitrogen supply conditions can significantly increase the soybean PFPN throughout the growing season.

3.5. Overall Assessment

3.5.1. Correlation Analysis

The results of the correlation analysis of water and nitrogen regulation on the soybean plant height, LAI, Pn, Tr, yield, cost–benefit ratio, unilateral water benefit and water–nitrogen use efficiency in two growing seasons are shown in Figure 9. As can be seen from Figure 9, the LAI, Pn, Tr, yield (except for the year of 2021), and cost–benefit ratio were positively correlated ($p < 0.05$) with plant height. The Pn, Tr, yield, cost–benefit ratio, and unilateral water benefit were positively ($p < 0.05$) correlated ($p < 0.05$) with the LAI. The Tr, yield, cost–benefit ratio, and unilateral water benefit were positively correlated ($p < 0.05$) with the Pn. The yield, cost–benefit ratio, unilateral water benefit, and WUE (except for 2020) were positively correlated with the Tr ($p < 0.05$). The cost–benefit ratio, unilateral water benefit, and WUE were positively correlated ($p < 0.05$) with the yield. The unilateral water benefit and WUE were positively correlated ($p < 0.05$) with the cost–benefit ratio. The unilateral water benefit was positively correlated with WUE ($p < 0.05$).

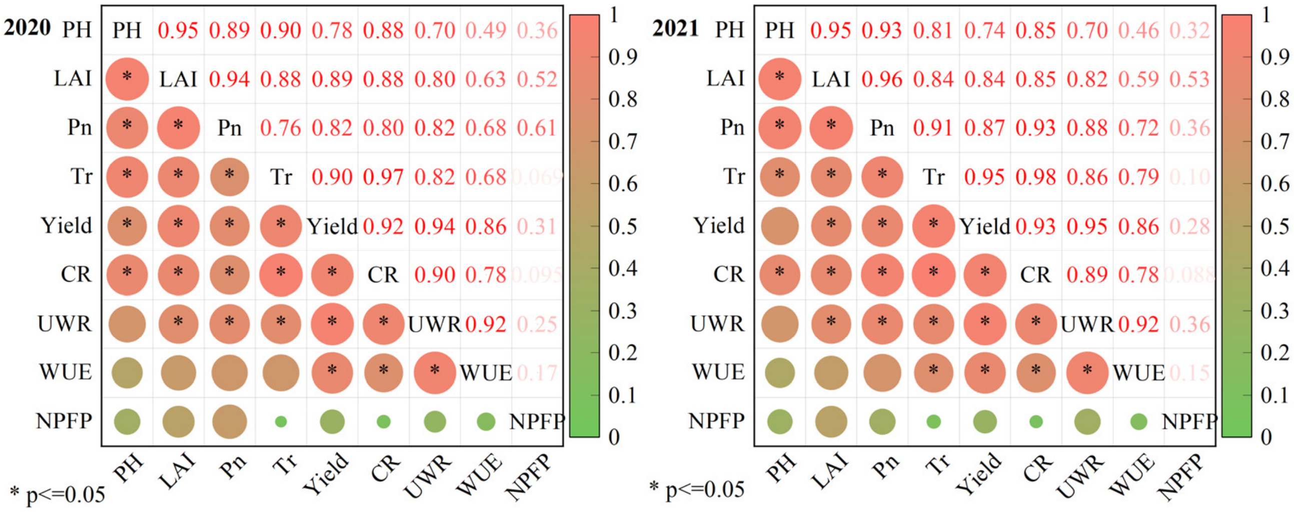

Figure 9. Heatmap plot correlation among the plant height, LAI, Pn, Tr, yield, cost–benefit ratio, unilateral water benefit, WUE, and PFPN. Note: PH, plant height; LAI, leaf area index; Pn, net photosynthesis rate; Tr, transpiration rate; CR, cost–benefit ratio; UWB, unilateral water benefit; WUE, water use efficiency; PFPN, Partial Factor Productivity of Nitrogen.

3.5.2. Optimization of Water and Nitrogen Combinations Based on the Entropy Weight and TOPSIS Method

The results of the entropy weight and TOPSIS method analysis of nine individual indicators of the soybean plant height, LAI, Pn, Tr, Yield, WUE, and PFPN based on the 2a experiment in 2020–2021 are shown in Table 5. Among them, the two-year weights mean size of each indicator in the evaluation system were calculated based on the entropy weight method were as follows: plant height (16.83%) > cost–benefit ratio (15.02%) > Tr (13.09%) > Pn (10.72%) > WUE (9.23%) > LAI (8.99%) > PFPN (8.88%) > unilateral water benefit (8.45%) >yield (7.98%). The composite scores of different water and nitrogen combinations of soybean that were calculated based on the entropy weight and TOPSIS method ranged from 0 to 0.850, with the W2N2 treatment having the highest score in both years (two-year average of 0.841), performing optimally and being the optimal soybean water and nitrogen combination. The W2N0 treatment had the lowest composite score (two-year average of 0.006). The nitrogen application treatment with deficit-regulated irrigation and low nitrogen application combination (W1N1) had the lowest rating and was the inferior water–nitrogen combination pattern. Taken together, the preferred water and nitrogen combination pattern for efficient soybean production in the cool irrigation areas of the Hexi Oasis is the treatment comprising an adequate irrigation level combined with medium nitrogen application (W2N2), i.e., a nitrogen application of 120 kg·ha^{-1} with an irrigation level of 70–80% FC is the water and nitrogen combination pattern for high-yield and high-quality production in this region.

Table 5. Comprehensive evaluation and preference for soybean water and nitrogen supply modes based on entropy weight and TOPSIS method.

Treatments	**2020**				**Treatments**	**2021**			
	D_i^+	D_i^-	C_i	**Rank**		D_i^+	D_i^-	C_i	**Rank**
W2N0	1.000	0.000	0.000	7	W2N0	0.995	0.012	0.012	7
W2N3	0.609	0.429	0.414	5	W2N3	0.690	0.382	0.356	5
W1N3	0.403	0.697	0.633	3	W1N3	0.451	0.677	0.600	3
W2N2	0.186	0.920	0.832	1	W2N2	0.165	0.935	0.850	1
W1N2	0.268	0.777	0.743	2	W1N2	0.290	0.739	0.718	2
W2N1	0.517	0.559	0.519	4	W2N1	0.538	0.529	0.496	4
W1N1	0.761	0.388	0.338	6	W1N1	0.798	0.332	0.294	6

Note: The D_i^+ and D_i^- values in the table represent the distance (Euclidean distance) of the evaluation object from the optimal or worst solution (i.e., Z^+ or Z^-), respectively. C_i denotes the composite degree score of each treatment.

4. Discussion

Water and nitrogen fertilizer play a crucial role in promoting the growth and development of nutrient organs in crop plants. Healthy growth during the nutrient growth stage significantly impacts yield formation and quality enhancement during the reproductive growth stage [24,25]. This study revealed that moderate nitrogen application during the flowering and podding stage increased the soybean plant height, LAI, Pn, and Tr. Conversely, no nitrogen application reduced these parameters throughout the reproductive stage, while excessive nitrogen did not significantly increase the plant height and LAI, even with increased soil water content. Excessive nitrogen under adequate soil moisture conditions resulted in a decreased soybean yield. The highest soybean yield was achieved with an appropriate nitrogen supply (moderate level), which increased the WUE and PFPN. The synergistic effect of water and nitrogen fertilizer was evident. These findings align with previous research by Ingrid Silva Setubal et al. [18], highlighting the importance of adequate irrigation and nitrogen supply for maximizing soybean yield and the positive impact of water supply on nutrient organ growth and yield formation.

Changes in dry matter accumulation due to the plant height and LAI growth during the crop's growth cycle are considered crucial for the final yield [26,27]. In this study, soybean plant height increased continuously as the fertility period progressed, peaking at the tympanic ripening stage. Meanwhile, the LAI reached its maximum during the flowering and podding stage, showing a different pattern compared to plant height. This discrepancy could be attributed to physiological leaf senescence during the soybean's tympanic ripening stage and the gradual decrease in temperature in the study area during this time. The decrease in the LAI during the tympanic ripening stage of soybean may be attributed to an increase in abscisic acid synthesis leading to leaf abscission and reduced leaf retention on the plant. While there is no specific research linking abscisic acid to leaf abscission in soybean during this stage, changes in the LAI are influenced by various factors such as soybean varieties and planting densities. Further analysis considering field conditions, soybean varieties, and other characteristics is necessary to validate this hypothesis [28]. Additionally, a decrease in the leaf Pn and Tr during the tympanic ripening stage of soybean compared to the flowering and podding stage has been observed, which is consistent with previous studies [29,30]. This decline in photosynthetic activity may be attributed to the plant utilizing more photosynthesis products for reproductive growth, specifically seed nutrient filling [31]. As soybean matures, physiological activity slows down, leading to a decline in the leaf function and photosynthetic rate as leaves yellow and photosynthesis decreases [32].

Under the status quo of severe water scarcity and excessive fertilizer application in the study area, the present study also found that there were significant differences in the soybean yield under different water and nitrogen conditions; increasing irrigation at the same level of nitrogen application resulted in a significant increase in the soybean yield, whereas increasing the nitrogen fertilizer at the same level of irrigation resulted in a decrease in the soybean yield when nitrogen application exceeded the medium level of nitrogen application, which occurred even with adequate irrigation: a finding that is consistent with the findings of Joseph Burns et al. [33], where excessive nitrogen fertilizer application adversely affected soybean yield (22.00% yield reduction). In terms of water–nitrogen use efficiency (WUE and PFPN), the combination of deficit-regulated irrigation and nitrogen fertilizer reduction was effective in increasing the soybean WUE and PFPN. Water and fertilizer availability in the soil was closely related to the effective nutrient uptake, translocation, and energy conversion by the root system of the plant. Aminifard et al. [34] showed that nitrogen is an integral part of the vitamin and energy system in the plant, and that water promotes the energy conversion of nitrogen in the phyllosome, which increases vigor for crop growth and thus accelerates the efficiency of water and nitrogen fertilizer use in the crop population. Taken together, both water and nitrogen fertilizer are key factors affecting soybean yield, and there is an interaction between them. Reasonable water and nitrogen management can improve soil fertility and promote the growth and development of soybeans, thus increasing yields [35]. Therefore, in order to make soybean cultivation in the Hexi Oasis irrigation area more productive, efficient, and ecological, the water and nitrogen supply strategy proposed in this study when deficit-regulated irrigation is combined with nitrogen fertilizer reduction can be borrowed or adopted. The ecological and efficient cultivation of soybean is increasingly challenging due to unstable climate change, frequent extreme weather events, and the degradation of arable soil environments [36,37]. This study focuses on the experimental investigation of two factors: water and nitrogen fertilizer. It aims to elucidate the effects of these factors, as well as their interactions, on the formation and quality of soybean yields from a mechanistic perspective. However, the study acknowledges a limitation in its scope and emphasizes the necessity for further research on the reduction of water and nitrogen inputs to enhance the investigation.

5. Conclusions

A two-year soybean water and nitrogen regulation experiment was conducted in the Hexi Oasis irrigation area in China. The results indicated that a water deficit and excessive nitrogen fertilizer application significantly inhibited soybean yield formation by slowing down the growth of nutrient organs (the plant height and LAI) and reducing photosynthetic characteristics (the Pn and Tr). It was observed that water plays a crucial role in nitrogen fertilizer efficacy, but over-application of fertilizer, even under fully irrigated conditions, led to growth slowdown, reduced light and efficiency, yield reduction, and inefficient water–nitrogen use efficiency, ultimately impacting the cost–benefit ratio of soybean cultivation. Correlation analyses showed a positive correlation between soybean yield formation indicators across the two growing seasons. The study also identified the W2N2 treatment as the optimal water and nitrogen supply combination based on a multi-objective comprehensive evaluation using the entropy weight and TOPSIS method, while the W1N1 treatment scored the lowest. The findings of this study, which focus on the combination of moderate fertilizer application and adequate irrigation, can be utilized to optimize the water and nitrogen balance for high-yield and efficient soybean cultivation in the Hexi Oasis irrigation area, China.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request and the approval of the data owner.

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