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Optimizing Spring Maize Growth and Yield through Balanced Irrigation and Nitrogen Application: A TOPSIS Method Approach

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Posted Date: 17 June 2024

doi: 10.20944/preprints202406.1117.v1

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Optimizing Spring Maize Growth and Yield through Balanced Irrigation and Nitrogen Application: A TOPSIS Method Approach

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Abstract: The current design of irrigation and fertilization systems often depends on a single index, leading to irrational systems due to the lack of a comprehensive multi-index evaluation. The aim of this study is to optimize the irrigation and nitrogen fertilizer application levels of spring maize using the TOPSIS method, in order to achieve a balance between growth characteristics, yield, water use efficiency, and soil nitrogen content. In the typical semi-arid region of Northeast China, through precise control experiments from 2022 to 2023, we adopted a two factor quadratic saturation D-optimal design method to study the effects of different irrigation amounts (145.40, 271.70, 348.20, 436.20 mm) and nitrogen fertilizer application amounts (34.80, 185.90, 277.40, 382.80 kg·hm^{-2}) on spring maize. Results indicate that increasing both irrigation and nitrogen application rates can enhance dry matter accumulation by 15.17% to 32.70%. The impact of irrigation and fertilization on the net photosynthetic rate (Pn) of spring maize was found to be greater for irrigation amount than nitrogen application, particularly at 9:00 am and 13:00 pm, and slightly less so at 11:00 am and 15:00 pm. Concurrently, there was a significant increase in total nitrogen (TN1 by 20.85% for 0-20 cm soil layer, TN2 by 33.33% for 20-40 cm soil layer) and alkali-hydrolyzed nitrogen (AHN1 by 14.65% for 0-20 cm, AHN2 by 28.86% for 20-40 cm). Yields improved by 12.02% to 44.09%, and water use efficiency (WUE) saw an increase ranging from 20.08% to 140.07%. The optimal water and fertilizer management mode for spring maize SBDI (shallow buried drip irrigation) in semi-arid areas was determined through comprehensive analysis using TOPSIS entropy weight method. When the irrigation amount is 436.20 mm and the nitrogen fertilizer application amount is 277.40 kg·hm^{-2}, it can significantly promote the accumulation of dry matter, yield, water use efficiency, photosynthetic characteristics, and soil nitrogen content of spring maize. This study provides a theoretical basis for the practical application of SBDI water fertilizer coupling technology for spring maize.

Keywords: water and nitrogen coupling; shallow buried drip irrigation; TOPSIS; Spring maize

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1. Introduction

The western semi-arid region of Northeast China, a pivotal area for maize cultivation, boasts a continental monsoon climate that is rich in light and heat but characterized by scarce and erratic precipitation [1]. The scarcity of water resources stands as a primary constraint to achieving sustainable, high, and stable yields of maize in this region. Moreover, the irrational application of fertilizers, coupled with significant waste, poses another major challenge to maize production. Statistics indicate that the utilization rate of maize fertilizer in this area is a mere 20.0%-30.0%, leading to substantial nutrient wastage [2]. Fertigation, the combined application of irrigation and fertilizer, emerges as an effective strategy to address the dual limitations of water and fertilizer [3]. Consequently, elucidating the theoretical underpinnings of technological applications aimed at

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enhancing the efficiency of irrigation water and fertilizer use is crucial for combating drought and bolstering the productivity of maize cultivation in this region.

Maize exhibits a high sensitivity to water deficits, which significantly impacts its growth, as well as its physical and chemical properties [4]. Water stress can severely impede the growth of maize, curtailing yield potential [5]. Conversely, over-irrigation poses its own risks, leading to reduced yields, water wastage, soil salinization, and a decline in soil fertility [6]. Drip irrigation offers a solution by delivering water directly to the plant's root zone, which allows for precise control over water usage and substantially reduces evaporation and deep percolation losses [7]. This targeted approach not only mitigates the issues associated with both water scarcity and over-irrigation but also leads to marked improvements in crop yield [8] and overall water productivity [9], making it an effective strategy for spring maize production.

Nitrogen is an indispensable and abundant element that plays a crucial role in maize growth [10], driving key processes such as growth and development, dry matter accumulation, yield formation [11], and nutrient uptake [12]. It also stimulates the formation of new cells and the development of the crop's vegetative organs [13]. Timely supplementation of soil nitrogen is critical; a deficiency can result in premature senescence [14], reduced seed setting rates [15], and consequently, decreased grain yields. Urea, a prevalent nitrogen fertilizer, is typically applied as a base dressing. However, an excess of nitrogen early in the maize growth cycle can elevate the risk of nitrogen leaching [16]. Traditional nitrogen application practices may lead to insufficient uptake later in the growth period, adversely affecting the filling effect and reducing grain yield [17]. To address these challenges, some researchers advocate for the adoption of drip irrigation technology to facilitate the integration of water and nitrogen, optimizing their combined application to enhance both nitrogen and water use efficiency [18]. Wang et al. [19] demonstrated that integrating water and fertilizer can boost spring maize yields by 19.0% and improve water use efficiency by 8.7%. Yin et al. [20] explored the interplay between irrigation volume, nitrogen, and phosphorus application, identifying an optimal combination for higher yields and economic returns in the semi-arid regions of Northeast China: an irrigation volume of 930.40 $m^3 \cdot hm^{-2}$, nitrogen application at 304.9 $kg \cdot hm^{-2}$, and phosphorus at 133.2 $kg \cdot hm^{-2}$.

Numerous scholars have investigated the optimal burial depth for drip irrigation tape, comparing depths of 5 cm [21], 10 cm [22], and 15 cm [23]. Research has demonstrated that a burial depth of 5 cm significantly enhances both crop yield and water use efficiency (WUE). This finding has led to the proposal of Shallow Buried Drip Irrigation (SBDI) measures. SBDI, an efficient water-saving irrigation technique, employs a mechanical operation to bury the drip tape 3-5 cm underground during sowing. This method not only prevents residual film pollution but also minimizes surface evaporation, offering benefits such as water conservation, reduced soil evaporation, increased fertilizer efficiency, higher yields, and environmental sustainability [24].

The integration of water and nitrogen in SBDI has been shown to enhance the leaf area index, SPAD (Soil Plant Analysis Development), and yield by 6.35%, 11.02%, and 18.20%, respectively [25]. When water, nitrogen, and potassium are concurrently applied, with irrigation volumes ranging from 43.25 to 58.87 mm, nitrogen application between 229.93 and 382.97 kg·hm^-2, and potassium application between 104.94 and 148.49 kg·hm^-2, optimal yield and water use efficiency (WUE) are achieved [26]. Compared to traditional border irrigation, adopting drip irrigation at 60% of the volume used in border irrigation has led to respective increases of 20.29% in leaf area, 14.80% in chlorophyll content, 21.37% in nitrogen utilization efficiency, and 3.24% in enzyme activity, without compromising yield [27]. Furthermore, SBDI significantly boosts the distribution of dry matter in maize roots and the proportion of root strips in the 0-20 cm topsoil layer, thereby enhancing the efficiency of water and fertilizer use [28]. A well-calibrated system of irrigation and fertilization not only elevates spring corn yield but also the efficiency with which water and fertilizer are utilized. However, current systems for formulating irrigation and fertilization often rely on single-index comparative analysis, omitting a comprehensive assessment of multiple indicators, which can result in suboptimal strategies. In this study, we employed the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to identify the optimal irrigation and fertilization regime for spring maize

 doi:10.20944/preprints202406.1117.v1

under SBDI in Northeast China, with the goal of achieving a harmonious balance among various parameters.

Currently, there is a paucity of research that employs a comprehensive analysis of multiple indicators to devise rational combinations of water and fertilizer applications for Shallow Buried Drip Irrigation (SBDI). To address this gap, we have utilized the TOPSIS comprehensive evaluation model to assess the coupling effects of water and nitrogen in SBDI and to optimize the modalities of irrigation and nitrogen application. The primary aims of our research are twofold: (1) to ascertain the impacts of varying rates of irrigation and nitrogen application on soil physicochemical properties, crop yield, water use efficiency (WUE), and additional indicators, followed by a holistic evaluation; (2) to propose the most efficacious measures for conserving water and fertilizer within the SBDI system in Northeast China. These investigations contribute a scientific foundation for the efficacious stewardship of spring maize cultivation in the region.

2. Materials and Methods

2.1. Site Description

The experiments were conducted in Fuxin Mongolian Autonomous County, a quintessential semi-arid region located in the western part of Northeast China, from 2022 to 2023. Situated between latitudes 41°44′N and 42°34′N, and longitudes 121°01′E and 122°26′E, this area is renowned for its significant maize production. The topography is characterized by an average altitude of 235 meters. Climatically, the area experiences a moderate annual temperature of 7.8°C, with a crop growth stage temperature averaging 20.2°C over 169 days where the accumulated temperature exceeds 10 °C. The region enjoys 1295.8 hours of sunshine during the growth stage, yet faces challenges such as uneven precipitation distribution, with an average of 493.10 mm annually, and frequent droughts across spring, summer, and autumn. The average annual evaporation rate is notably high, reaching 1847.6 mm. The soil in this region is classified as sandy loam, with a plough layer unit weight of 1.44 $g{\cdot}cm^{-3}$, a field capacity of 23%, and a pH value of 6.15. It is endowed with organic matter at a concentration of 16.43 $g{\cdot}kg^{-1}$, total nitrogen (TN) at 1.05 $g{\cdot}kg^{-1}$, alkali-hydrolyzable nitrogen (AHN) at 92.15 $mg{\cdot}kg^{-1}$, and available potassium at 201.43 $mg{\cdot}kg^{-1}$, indicating a fertile yet well-drained soil profile.

2.2. Experimental Design

A Two-Factor Secondary Saturation D-optimal design approach, as outlined in Table 1, was implemented for the experiments. The design focused on two variables: irrigation amount and nitrogen application rate. The irrigation amount was calculated based on a 0 level code value, which corresponded to 70% of the average annual precipitation (493.10 mm) during the maize growth period in the test area, excluding any precipitation exceeding 50.00 mm, which was deemed ineffective. The +1 level represented 1.5 times the 0 level, indicative of an exceptionally water-rich year, while the -1 level was set at half of the 0 level, reflecting an extremely dry year. Consequently, the irrigation amounts were established at 145.40, 271.70, 348.20, and 436.20 mm. The nitrogen application rate was determined similarly, with the 0 level representing the conventional rate of 208.80 $kg{\cdot}hm^{-2}$ applied in the test area. The rate was adjusted by ±174.00 $kg{\cdot}hm^{-2}$, based on the technical measures for water and fertilizer integration, aiming to enhance fertilizer utilization efficiency by 20% [59]. This adjustment served as the basis for setting the ±1 level gradient, resulting in nitrogen application rates of 34.80, 185.90, 277.40, and 382.80 $kg{\cdot}hm^{-2}$. Each of the six treatment combinations was replicated three times. Urea, containing 46.40% nitrogen, was chosen as the nitrogen fertilizer. At sowing, one-third of the total nitrogen was applied to the furrow, with the remainder divided equally and applied through drip irrigation during the jointing and tasseling stages. The specific irrigation frequency and volume for each growth phase are detailed in Table 2. Shallow Buried Drip Irrigation (SBDI) was utilized, with the drip tape buried at a depth of 3-5 cm. The maize variety “Yufeng 303” was selected.

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Table 1. experimental design.

Treatments	Code		Application rate	
	X1 (Irrigation)	X2 (Nitrogen)	Irrigation (mm)	Nitrogen ($kg·hm^{-2}$)
W1N1	-1	-1	145.40	34.80
W4N1	1	-1	436.20	34.80
W1N4	-1	1	145.40	382.80
W2N2	-0.1315	-0.1315	271.70	185.90
W4N3	1	0.3945	436.20	277.40
W3N4	0.3945	1	348.20	382.80

Table 2. Implementation plan of SBDI treatments throughout the crop growth period.

Treatments	Seeding stage-Jointing stage		Jointing stage-Heading stage		Heading stage-Filling stage		Filling stage - Maturation stage	
	Times	Irrigation (mm)	Times	Irrigation (mm)	Times	Irrigation (mm)	Times	Irrigation (mm)
W1N1	1	27.60	2	39.80	1	32.00	2	46.00
W4N1	2	82.90	3	119.50	2	96.00	3	137.80
W1N4	1	27.60	2	39.80	1	32.00	2	46.00
W2N2	2	51.60	2	74.40	2	59.80	2	85.90
W4N3	2	82.90	3	119.50	2	96.00	3	137.80
W3N4	2	66.20	3	95.40	2	76.60	3	110.00

2.3. Measurement and Methods

2.3.1. Soil Moisture Content

The soil moisture content was ascertained using the oven-drying method. Soil samples were collected at various intervals, including prior to sowing, at the conclusion of each growth stage, and post-harvest, using a soil drill. The sampling depth extended to 140 cm, segmented into seven equal layers of 20 cm each. These samples were subjected to a constant temperature of 105 °C in an oven to achieve a fixed dry weight. The soil's water content was thereafter computed utilizing the gravimetric water content method, which quantifies moisture by the weight difference before and after drying.

2.3.2. Soil Nitrogen Content

Soil drilling method was used to take 0~40 cm soil layer (one layer every 20 cm). Total nitrogen was determined by the Vario MACRO cube element analyzer (ElementarAnalysensysteme GmbH, Hanau, Germany). Soil alkali-hydrolyzed nitrogen was determined by alkali-diffusion method.

Soil samples were collected from the 0 to 40 cm depth interval, with stratification occurring every 20 cm using a soil coring technique. Total nitrogen was determined by the Vario MACRO cube element analyzer (ElementarAnalysensysteme GmbH, Hanau, Germany). Soil alkali-hydrolyzed nitrogen was determined by alkali-diffusion method.

2.3.3. Photosynthetic Index

During the filling stage of plant development, a selection of representative plants was chosen for assessment. Photosynthetic indices were measured at four distinct time points throughout the day: 9:00, 11:00, 13:00, and 15:00. The parameters recorded included the photosynthetic rate (Pn), expressed in micromoles of CO_2 per square meter per second ($\mu molCO_2·m^{-2}·s^{-1}$), the transpiration rate (Tr) in millimoles of H2O per square meter per second ($mmolH_2O\ m^{-2}·s^{-1}$), stomatal conductance (Gs) in moles per mole per square meter per second ($molmolH_2O\ m^{-2}·s^{-1}$), and photosynthetically active radiation (PAR) in micromoles per square meter per second ($\mu molm^{-2}·s^{-1}$). These measurements were conducted using the LI-COR 6400 photosynthesisometer, a device renowned for its precision in assessing plant physiological responses.

2.3.4. Dry Matter Accumulation

We selected maize plants exhibiting moderate growth for the dry matter accumulation assessment. The above-ground portions of these plants were carefully harvested, placed into bags, and then introduced into a controlled-environment oven. Initially, the samples were defoliated at a temperature of 80℃for a duration of 30 minutes to remove moisture. Subsequently, the temperature was incrementally raised to 105 ℃ to ensure thorough drying. The samples were baked at this elevated temperature until their weight stabilized, indicating complete dehydration.

2.3.5. Yied (Y)

At the stage of maturity, we harvested two rows of corn ears from the central portion of the experimental micro-plot and recorded their fresh weight. The ears were then subjected to a period of airing and natural air drying to reduce surface moisture. Following this, a comprehensive seed quality analysis was conducted. The moisture content of the grains was determined using a grain moisture meter (model PM8188). The measured values were subsequently used to calculate the grain yield per hectare, providing a standardized assessment of productivity.

2.3.6. Crop Water Consumption (ET_a)

Crop water consumption was calculated as follows:

$$ET_a = Pr + Cr + Ir - Rr - Dw - \triangle S \quad (1)$$

Where ET_a is crop water consumption (mm); Pr is rainfall (mm); Cr is the capillary rise of groundwater (mm); Ir is the irrigation amount (mm); Rr is surface runoff (mm); Dw is the deep leakage (mm); △S is the change of soil moisture at the end and beginning of the borrowing period (mm). Since the test was carried out in a mobile rainproof shelter and the irrigation method was drip irrigation, Pr, Rr and Dw in the formula could be ignored. Because the groundwater depth of the test site is greater than 8m, Cr could also be ignored [60].

2.3.7. Water Use Efficiency(WUE)

Water use efficiency (WUE) was calculated as follows:

$$WUE = Y/ETa \quad (2)$$

Where Y is the grain yield ($kg \cdot hm^{-2}$), ET_a is water consumption during crop growth stages (mm).

2.4. TOPSIS Entropy Weight Model

TOPSIS entropy weight model conducts a comprehensive evaluation and analysis of multiple indicators through combination algorithm, and obtains positive and negative ideal solutions and proximity by calculating weight, so as to obtain optimal treatment and make reasonable judgments [61,62]. Because of its wide applicability, it is commonly used in agricultural production [63,64].

2.5. Data Analysis

Data and figures of soil water content, soil nitrogen content, crop net photosynthetic rate, transpiration rate, stomatal conductance, yield, water consumption and water use efficiency were processed using Microsoft Excel 2020 (Microsoft Crop., Raymond, WA, USA). IBM SPSS Statistical Analysis 20.0 (IBM Inc., New York, NY, USA), and Origin 2022 (Originlab Corp., Northampton, MA, USA). Fisher's least significant difference (LSD) test was used to analyze whether there was significant difference between the means of different treatments ($p < 0.05$). TOPSIS entropy weight method was used to evaluate the advantages and disadvantages of each treatment combination.

TOPSIS-entropy weight method was used for analysis using Matlab software (version 2021, MathWorks, Natick, USA).

3. Results

3.1. Soil Nitrogen Content

The content of total nitrogen (TN) and alkali-hydrolyzale nitrogen (AHN) in 0-20cm and 20-40cm soil during harvesting stage were shown in Figure 1.

The soil layer from 0-20 cm exhibited higher concentrations of Total Nitrogen (TN1) and Alkali-Hydrolyzable Nitrogen (AHN1) compared to the 20-40 cm layer, as illustrated in Figure 1. A comparison between the highest and lowest nitrogen content across the soil layers revealed that the treatment W3N4 yielded the highest TN1 levels, with W1N1 showing a potential increase of 20.85%. The treatment W2N2 demonstrated the highest levels of TN2, marking a 33.33% increase over the W4N1 treatment, which registered the lowest TN2 values. For AHN1, the W1N4 treatment recorded the highest levels, 14.65% greater than the W3N4 treatment, the lowest in this category. Furthermore, the W1N1 treatment had the highest AHN2 content, surpassing the W4N1 treatment by 38.77%. At lower nitrogen application rates (W4N1 and W1N1), an increase in the irrigation rate did not significantly affect TN1 and AHN1, resulting in a slight 3.53% reduction in TN1 and a 0.50% increase in AHN1. Conversely, the levels of TN2 and AHN2 were reduced by 19.40% and 38.77%, respectively. When nitrogen application rates were elevated (W1N4 and W3N4), an increase in irrigation promoted the accumulation of TN1 by 12.87%, with no significant effect on TN2. At higher irrigation levels (W4N1 and W4N3), an increase in nitrogen application significantly boosted the levels of TN1, TN2, and AHN2, with increases of 19.78%, 18.98%, and 34.54%, respectively.

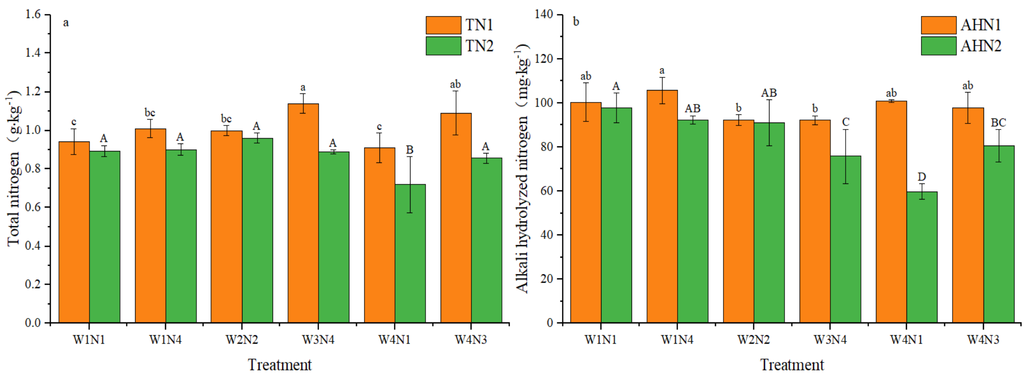

Figure 1. Soil TN and AHN content. TN1 and AHN1 represent total nitrogen and alkali-hydrolyzale nitrogen content of 0-20 cm soil layer; TN2 and AHN2 refer to the total nitrogen and alkali-hydrolyzale nitrogen content of soil in 20-40 cm soil layer. The uppercase and lowercase letters only distinguish the difference of soil nitrogen content in different soil layers. The same letter indicates no significantly difference ($p > 0.05$), while different letters indicate significantly difference ($p \le 0.05$); The same below.

3.2. Dry Matter Accumulation

The dry matter accumulation (DMA) in spring maize at the tasseling stage, under varying water and nitrogen treatments, was evaluated and is depicted in Figure 2. When water and nitrogen were applied in combination, the quantity of both irrigation and fertilization significantly influenced the DMA at the tasseling stage. The analysis revealed a ranking in DMA among the treatments, with W3N4 outperforming the others, followed by W4N3, W2N2, W1N4, W4N1, and W1N1, which exhibited the lowest DMA. The W1N1 treatment, representing the lowest DMA, showed a reduction of 15.17% to 32.70% in dry matter compared to the other treatments. The W3N4 treatment demonstrated a notably higher DMA than W1N1. When the irrigation volume was held constant across treatments (comparing W1N1 with W1N4, and W4N1 with W4N3), an increase in nitrogen

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application resulted in a 6.17% to 17.06% enhancement in DMA. Conversely, with a fixed nitrogen application amount (across treatments W1N1, W4N1, W1N4, and W3N4), augmenting the irrigation volume led to a 13.36% to 15.17% increase in dry matter.

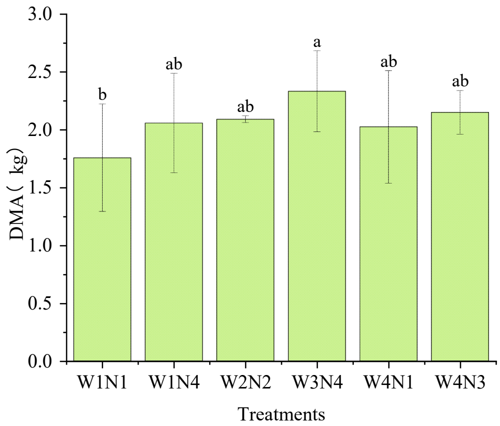

Figure 2. DMA at tasseling stage. The lower case letters in the figure represent significantly difference, different letters represent significantly difference (p<0.05), and the same letter represents no significantly difference. The same below.

3.3. Photosynthetic Characteristics

The impact of water and nitrogen coupling on leaf photosynthetic rate (Pn), stomatal conductance (Cond), and transpiration rate (Tr) is illustrated in Figures 3–5.

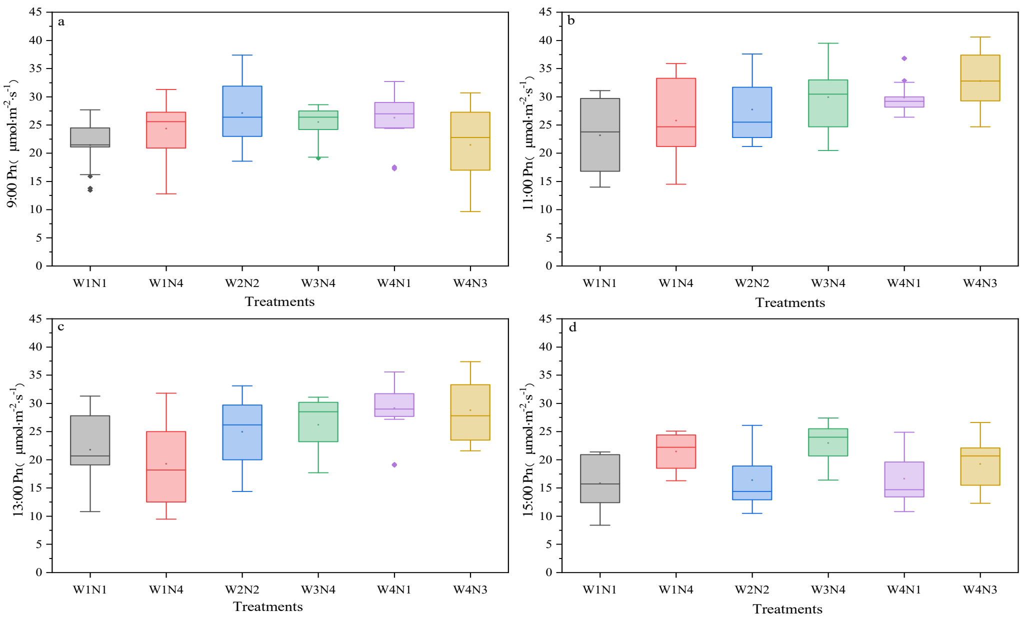

Figure 3. Leaf photosynthetic rate of nitrogen coupling in SBDI on P_n on spring maize.

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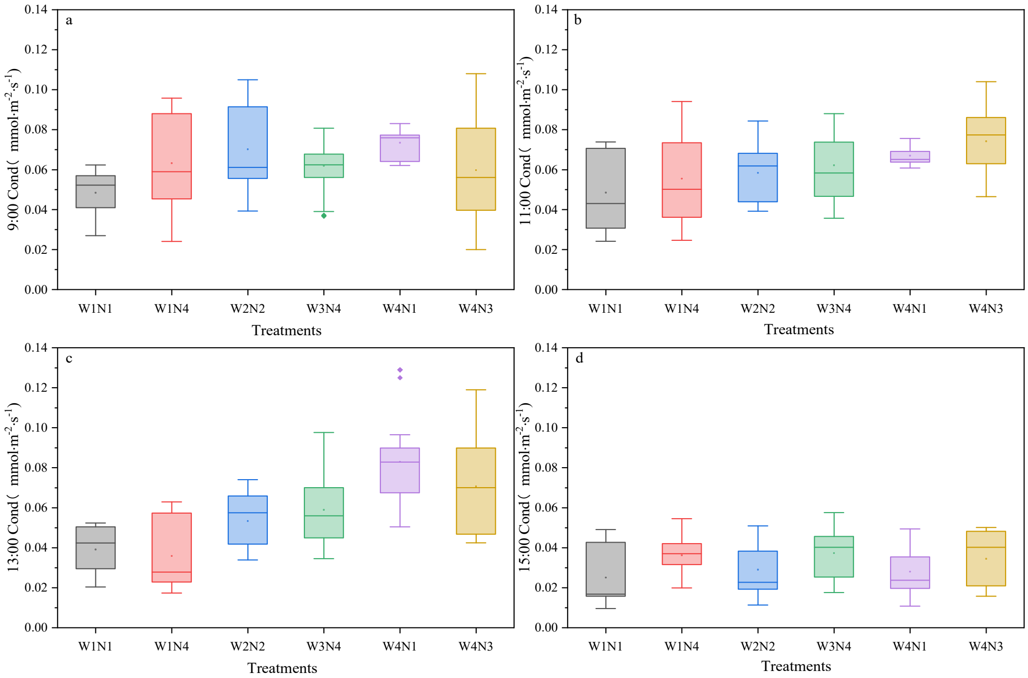

Figure 4. Effect of nitrogen coupling in SBDI on Cond of spring maize.

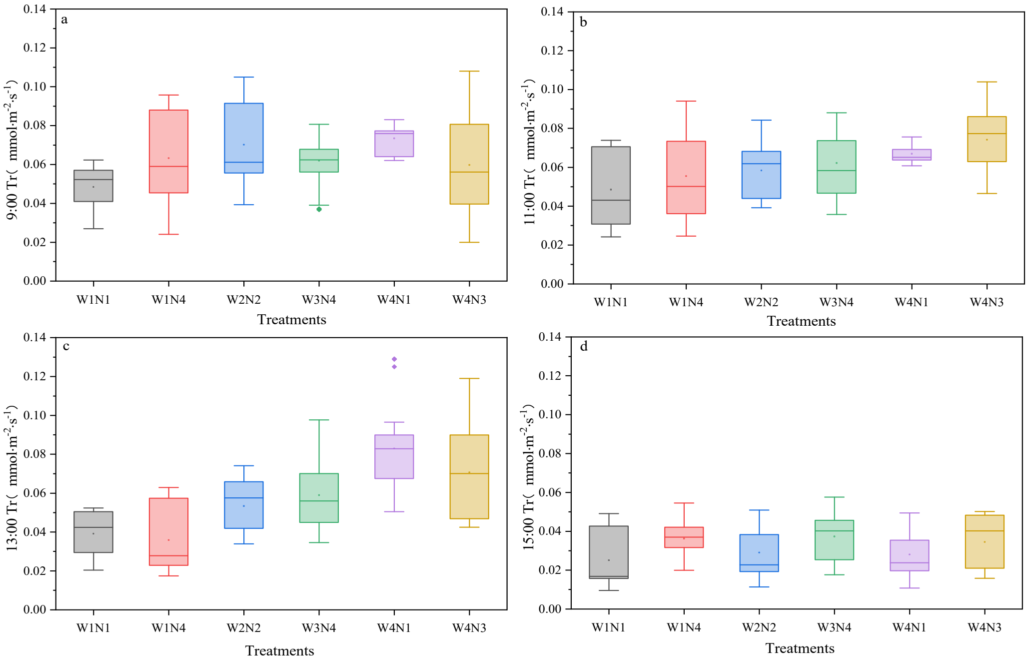

Figure 5. Leaf Tr rate of nitrogen coupling in SBDI on spring maize.

At 11:00 am, Pn was notably higher compared to other time points, with a slight decline observed at 13:00 pm, and the lowest values recorded at 15:00 pm (Figure 3). At 9:00 am, the W1N1 treatment registered the lowest Pn, whereas the W1N4 treatment exhibited a 13.70% increase over the W1N1 treatment. Furthermore, the Pn in the W2N2 treatment was 26.47% greater than in the W1N1 treatment. When irrigation was insufficient to meet the requirements of spring maize, increasing the nitrogen application did not significantly enhance Pn. With the nitrogen application amount set at the N1 level, raising the irrigation amount in the W1N1 and W4N1 treatments resulted in a 22.71%

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increase in Pn. Conversely, when the nitrogen application rate was elevated to a higher level (W4N1, W4N3), the increases in Cond and Tr were curtailed, with respective decreases of 18.69% and 16.82%, and Pn also dropped by 18.42% (Figures 3a, 4a and 5a). At 9:00 am, the influence of irrigation on Pn was more pronounced than that of nitrogen application.

At 11:00 am, the photosynthetic rate (Pn) in the W1N1 treatment was the lowest. However, an increased nitrogen application rate in the W1N4 treatment elevated Pn by 11.24%, yet this enhancement was not statistically significant. Conversely, maintaining the nitrogen level constant and augmenting irrigation (as in the W4N1 treatment) led to a more pronounced 28.82% increase in Pn, surpassing the effect of nitrogen application alone (Figure 3b). When nitrogen application was held constant, increasing irrigation across treatments (W1N1, W4N1, W1N4, and W3N4) resulted in a rise in Cond and Tr by 37.98% and 22.42%, and 12.06% and 0.97%, respectively (Figures 4b and 5b). Notably, the Pn values for the W4N1 treatment were slightly lower than those for the W3N4 treatment by a margin of 0.21%. It was evident that while increased irrigation can improve Cond and Tr, neglecting nitrogen fertilizer application could hinder the enhancement of photosynthetic capacity. Under these conditions, the nitrogen application rate had a more substantial impact on Pn than irrigation volume.

At 13:00 pm, the W1N4 treatment exhibited the lowest values for Pn, Cond, and Tr, which were 11.45%, 8.45%, and 10.39% lower than those in the W1N1 treatment, respectively (Figure 3c). In contrast, the W4N1 treatment showed a 33.82% increase in Pn compared to W1N1, and was 1.28% higher than the W4N3 treatment. Given that 13:00 pm marks the peak temperature of the day, maintaining a constant irrigation amount while increasing nitrogen fertilizer application (as in W4N1 and W4N3) resulted in a suppression of Cond and Tr increases and a decrease in Pn by 1.28%, 17.45%, and 13.55%, respectively (Figures 4c and 5c). Conversely, at this hour, increasing the irrigation amount (as in W1N4 and W3N4) significantly boosted Pn by 35.96%, accompanied by increases in Cond and Tr by 64.54% and 45.11%, respectively. The effect of irrigation on elevating Pn at 13:00 pm was more pronounced than that of nitrogen application.

At 15:00 pm, the W1N4 and W3N4 treatments demonstrated higher Pn values compared to other treatments, with increases of 35.68% and 5.14%, respectively, over the W1N1 treatment. Notably, the W1N4 treatment's enhancement of Pn was more pronounced, showing a 29.05% improvement relative to the W4N1 treatment. In contrast, the W2N2 treatment had a 23.65% reduction in Pn when compared to the W1N4 treatment (Figure 3d). Among the four observed periods, the light intensity at 15:00 pm was the dimmest, resulting in significantly lower Cond and Tr rates than those recorded during other periods (Figures 4d and 5d). During this time, nitrogen application emerged as a more effective strategy for improving Pn than irrigation.

3.4. Yield and WUE

The effects of different treatments on grain Y and WUE under SBDI with the water and nitrogen coupling experiment were shown in Table 3.

Table 3. Yield of water and nitrogen coupling on Spring Maize.

Treatments	Y ($kg{\cdot}hm^{-2}$)	WUE ($kg{\cdot}hm^{-2}{\cdot}mm^{-1}$)
W1N1	7042.20±92.30d	36.30±5.80ab
W4N1	8554.00±342.30b	17.30±2.00d
W1N4	7893.90±81.20c	41.60±3.80a
W2N2	9029.40±118.60b	28.60±1.50bc
W4N3	9109.50±14.90b	20.80±0.50cd
W3N4	10204.20±214.60a	25.60±0.40cd

The yield model was constructed according to the yields of different treatments, with Y was as the dependent variable, and the code X1 and X2 were corresponding to the irrigation and nitrogen application amount as the independent variables, was shown in model (3):

 doi:10.20944/preprints202406.1117.v1

$$Y=10855.79+705.96X1+502.92X2+336.63X1X2-831.65X1^2-496.31X2^2 \quad (3)$$

The dimension reduction analysis was conducted for model (3), and the single factor effect models of irrigation and nitrogen application on Y were obtained, which was shown in models (4) and (5):

$$\text{Irrigation: } Y=10855.79+705.96X1-831.65X1^2 \quad (4)$$

$$\text{Nitrogen: “}Y=10855.79+502.92X2-496.31X2^2 \quad (5)$$

When analyzing the impact of irrigation and nitrogen application on yield (Y), it was observed that the effect initially increases with the amount of application and then declines (as depicted in Figure 6). The interaction between these two factors revealed an optimal point where the yield was maximized when the coded values for both irrigation and nitrogen application were close to 1. Consistent irrigation or nitrogen application levels, when increased, resulted in a gradual rise in yield. Specifically, the W3N4 treatment, with an irrigation volume of 348.20 mm and a nitrogen application rate of 382.80 kg·hm^{-2}, yielded the highest results, significantly outperforming other treatments. A comparison among treatments W4N1, W4N3, and W1N4 with W3N4 indicated that maintaining a constant irrigation volume while increasing nitrogen fertilizer, or vice versa, could substantially enhance the yield of spring maize by 6.49% to 29.27%. The W1N1 treatment, characterized by low water and nitrogen levels, resulted in the lowest yield at 7042.20 kg·hm^{-2}. However, under the coupled water and nitrogen conditions of Shallow Buried Drip Irrigation (SBDI), increasing both water and nitrogen inputs compared to the W1N1 treatment could significantly boost the yield of spring maize by 12.02% to 44.90%. In the maize cultivation environment, the influence of irrigation on yield was found to be more substantial than that of nitrogen application, as illustrated in Figure 7.

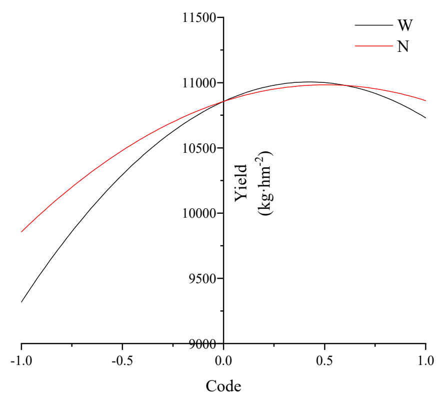

Figure 6. Single factor of water and nitrogen application on Y.

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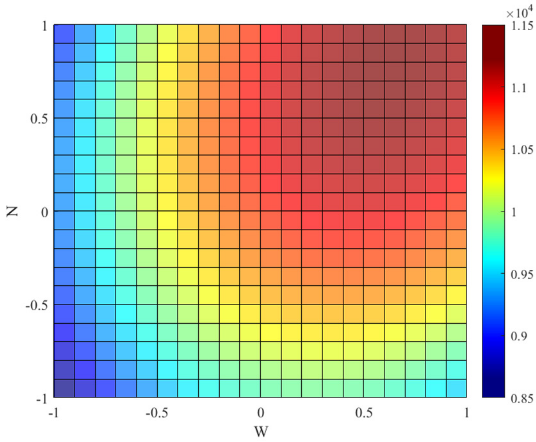

Figure 7. Yield effect of water and nitrogen coupling.

Water use efficiency (WUE) typically declines as the irrigation amount increases. However, in comparison to the W4N1 treatment, WUE experienced an increase, ranging from 20.08% to 140.07%. The treatments with the lowest irrigation amounts, W1N1 and W1N4, demonstrated higher WUE, whereas no significant differences in WUE were observed among treatments W4N1, W4N3, and W3N4. This indicates that further increasing the irrigation amount does not necessarily lead to improved WUE. When the irrigation amount was kept constant, the WUE was found to follow the order W1N4 > W1N1 and W4N3 > W4N1. A moderate increase in nitrogen application was observed to enhance WUE, with improvements of 14.75% and 20.08%, respectively. When comparing treatments with the same nitrogen application amount, such as W1N1, W4N1, and W1N4 with W3N4, it was evident that an increased irrigation amount led to a significant decrease in WUE by 52.20% and 38.51%, respectively. However, when comparing W4N3, which received a medium rate of nitrogen, with W3N4, which received a high rate, it was found that while reducing the irrigation rate increased WUE, an excessive nitrogen rate did not favor the increase in WUE. This suggests that there is an optimal range for nitrogen application to maximize WUE.

3.5. Interaction Relationship between Different Indicators

Figure 8 illustrates the interaction relationships between different indicators, showing a significantly positive correlation between total nitrogen (TN2) in the 20-40 cm soil layer and alkali-hydrolyzable nitrogen (AHN2). In contrast, the content of AHN1 was observed to decrease with increasing TN1 levels, with no significant impact on either AHN1 or AHN2. TN2 was found to have a more substantial influence on soil nitrogen content than the 0-20 cm soil layer. Moreover, the content of AHN2 was identified as a significant factor in enhancing WUE, indicating that an increase in alkali-hydrolyzable nitrogen in the 20-40 cm soil layer positively affects WUE. While TN1 effectively improved yield (Y), the content of alkali-hydrolyzable nitrogen did not notably contribute to the increase in Y. A positive correlation was observed between photosynthetic rate (Pn) and Y across all stages, with the strongest correlation occurring at 11:00 am. Thus, yield can be improved by increasing the TN1 content, and WUE can be increased by elevating AHN2 content. The significant positive correlation between Y and Pn at 11:00 am suggests that irrigation and fertilization strategies prior to this time can be employed to boost the yield of spring maize.

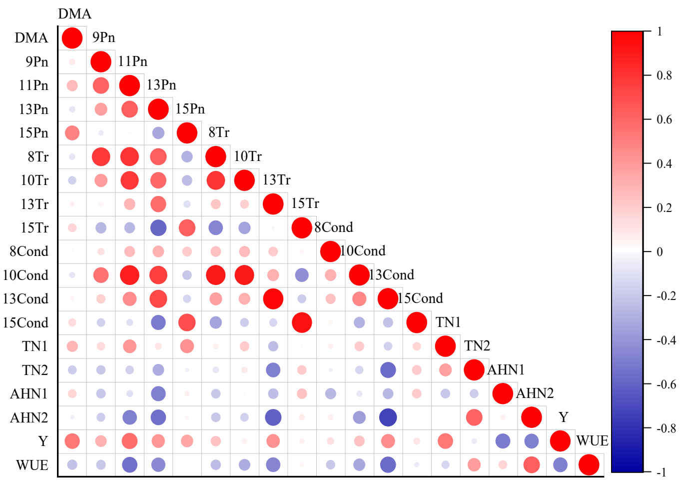

Figure 8. Correlation of indicators. * indicates that the correlation coefficient is greater than 0.05.

3.6. Multi-Objective Decision and Evaluation Based on the TOPSIS Method

The redundancy analysis results indicate a positive correlation among the irrigation amount, nitrogen application amount, and photosynthetic characteristics, which are crucial for plant growth and yield. Additionally, the total nitrogen content in the 0-40 cm soil layer and the alkali-hydrolyzable nitrogen content in the 20-40 cm soil layer were found to be significantly related to water use efficiency (WUE) and yield (Y). Given these correlations, the TOPSIS entropy weight method was employed for a comprehensive analysis of these indicators. This approach aimed to identify the optimal irrigation and nitrogen application strategy. By integrating the data on soil nitrogen content, photosynthetic traits, WUE, and yield, the TOPSIS method provided a systematic way to evaluate various scenarios and determine the most effective management practices for enhancing crop productivity and resource use efficiency.

As illustrated in Figure 8, the photosynthetic rate (Pn), stomatal conductance (Cond), transpiration rate (Tr), and total nitrogen content (TN1) at various times of the day-9:00 am, 11:00 am, 13:00 pm, and 15:00 pm, each contributed to the enhancement of yield (Y). These indices were subjected to a comprehensive evaluation employing the TOPSIS-entropy weight method. This analytical approach was utilized to determine the most suitable irrigation and fertilization practices within the SBDI system. The outcomes of this evaluation are presented in Table 4.

Table 4. Comprehensive evaluation results of water nitrogen coupling in Spring Maize.

Treatments	D^+	D^-	Si	ranking
W1N1	0.9566	0.2765	0.2242	6
W4N1	0.8165	0.5229	0.3904	2
W1N4	0.8697	0.4358	0.3338	3
W2N2	0.8045	0.3535	0.3053	5
W4N3	0.3835	0.8866	0.6980	1
W3N4	0.8254	0.4057	0.3295	4

In the comprehensive evaluation's ranking, treatments W4N1 and W4N3 emerged at the top, while W2N2 and W1N1 were at the bottom. The results indicated that a higher volume of irrigation more effectively enhanced yield (Y), photosynthetic rate (Pn), and soil total nitrogen (TN1). Conversely, when irrigation was limited (at the W1 level), an increase in nitrogen application hindered the improvement of overall indicators. However, at higher irrigation levels (W4 level), increasing nitrogen application positively influenced the comprehensive indicators. At a low water level (N1 level), the augmentation of irrigation significantly promoted the enhancement of these indicators. Yet, when the nitrogen application rate exceeded the conventional local amount (at the N4 level), further increasing the irrigation amount began to impede the improvement of the comprehensive indicators.

In conclusion, the optimal water and fertilizer combination for SBDI's water-nitrogen coupling was identified when the irrigation volume was 436.20 mm and the nitrogen application rate was 277.40 kg·hm^{-2}. This combination significantly contributed to the increase in dry matter accumulation (DMA), yield (Y), water use efficiency (WUE), photosynthetic rate (Pn), and soil nitrogen levels in spring maize.

4. Discussion

4.1. Effect of Water and Nitrogen Coupling on Dry Matter Quality and Photosynthetic Index of Spring Maize

The integration of water and fertilizer in SBDI offers the dual advantage of conserving both resources. This method facilitates the synchronized delivery of water and nutrients to the soil, enhancing the transport of fertilizer and ensuring a balanced supply of soil water and nutrients [29]. Nitrogen, an essential macronutrient for maize, is crucial for improving yield (Y), promoting photosynthesis, and supporting organ development [30]. It also contributes to the formation of dry matter by influencing leaf area and nitrogen content per unit leaf area [31]. This study's findings indicate that under ample irrigation conditions, the dry matter accumulation in the W4N3 treatment was 6.17% greater than in the W4N1 treatment, suggesting that increasing nitrogen fertilizer can effectively enhance dry matter accumulation in spring maize. Furthermore, the W3N4 treatment showed an 8.53% increase compared to W4N3, highlighting the importance of balancing irrigation and nitrogen application. Overlooking nitrogen input while increasing irrigation can result in reduced dry matter accumulation (DMA), a key determinant of maize yield [32]. In this experiment, all treatments except W1N1 showed improved dry matter accumulation compared to the control. A significant positive correlation between DMA and yield during the tasseling stage underscores the potential of SBDI to increase yield by optimizing irrigation and fertilization practices, thereby enhancing nutrient delivery to the grain and minimizing nutrient loss under the rainproof shelter [33].

The synergistic application of water and nitrogen significantly enhances the photosynthetic physiological activity in closely planted maize. This improvement is primarily attributed to water's substantial impact on the physiological activity of leaves during the growth stage [34]. Increased irrigation at the early growth phase of maize notably boosts the photosynthetic rate and transpiration rate (Tr) of ear leaves and effectively postpones the decline in chlorophyll value [35]. In conditions of inadequate water supply, the timely application of nitrogen fertilizer as a topdressing markedly raises the leaf's SPAD value and stomatal conductance (Cond), enhancing the photosynthetic rate (Pn) and promoting the accumulation and transfer of photosynthates [36]. The photosynthetic rate at 11:00 am exhibits an upward trend with increased irrigation. However, this pattern varies at other times. For instance, at 9:00 am and 13:00 pm, the W4N3 treatment, which had ample water, showed a reduced Pn when more nitrogen fertilizer was applied compared to W4N1. This suggests the existence of a threshold for effective water-nitrogen coupling, beyond which an excessive increase in either irrigation or fertilization can lead to a decrease in Pn [37].

4.2. Effect of Water and Nitrogen Coupling on Y and WUE of Spring Maize

Nitrogen fertilizer is an essential nutrient for maize, yet traditional application methods often involve excessive amounts, leading to serious waste [38]. The study revealed a significant correlation between the yield increase from nitrogen fertilizer and the volume of irrigation water. When irrigation was limited, an increase in nitrogen fertilizer resulted in a significant reduction in yield. However, with an adequate amount of irrigation, the yield response to additional nitrogen fertilizer was pronounced [39]. This paper also observed that even under low irrigation conditions, nitrogen fertilizer could still boost yield, as a small amount of water could mitigate soil drought [40].

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Nonetheless, too much nitrogen could exacerbate soil drought under rainproof shelters, negatively affecting yield. Experiments conducted under minimal water conditions showed that nitrogen fertilizer could still sustain the yield increase effect. Abedi [41] noted no significant difference in yield when nitrogen application exceeded 240 kg·hm^{-2}. Conversely, Fang [42] found that yields plateaued when nitrogen rates surpassed 200 kg·hm^{-2}, indicating a threshold for effective water-fertilizer integration. Below this threshold, increasing irrigation and fertilization significantly improves crop yield, but beyond it, further inputs may reduce yield [43]. Interestingly, the study found that the W3N4 treatment yielded significantly higher than W4N3, with the highest yield achieved when nitrogen application rates surpassed 277.4 kg·hm^{-2}. This suggests that regional variations in climate, soil, and other factors can influence these thresholds [44].

The integration of water and nitrogen exhibits a potent interactive effect. As nitrogen fertilizer is introduced into the soil with water, it boosts the fertilizer's mobility, facilitating easier access to crop roots and enhancing root absorption and utilization [45]. Concurrently, nitrogen fertilizer stimulates root development, augmenting the plant's capacity to absorb both irrigation and soil water [46]. This dual action significantly ameliorates the water use efficiency (WUE) of spring maize [47,48]. Among the treatments compared, W1N1 and W1N4 demonstrated the highest WUE, with W1N4 showing a 14.60% increase over W1N1. This indicates that even under minimal irrigation, augmenting nitrogen fertilizer can stimulate root growth and enhance soil water uptake, thus improving WUE [49]. Furthermore, even with a limited volume of irrigation water, WUE can be effectively enhanced [50].

4.3. Effect of Water Nitrogen Coupling on Soil Nitrogen Content

Soil nitrogen content is intricately linked to the final yield of spring maize [51]. Specifically, the nitrogen content in the 0-20 cm soil layer significantly influences the increase in spring maize yield [52,53]. However, under drip irrigation, soil nitrogen tends to migrate with water, moving downward and potentially leading to nitrogen leaching losses with excessive irrigation [54]. It is noted that at the 30 cm soil depth, nitrogen content peaks [55]. The water-nitrogen coupling in Shallow Buried Drip Irrigation (SBDI) effectively mitigates these issues. When irrigation and nitrogen application are coupled in SBDI, there is a significant increase in the total nitrogen (TN1) content of the 0-20 cm soil layer, which is a primary determinant of yield (Y). This enhancement in TN1 content through SBDI's water-nitrogen coupling technology demonstrates its potential in boosting spring maize yield by facilitating nutrient accumulation in the critical topsoil layer, thereby verifying the technique's effectiveness and feasibility [55].

4.4. Water Fertilizer Coupling Effect of Drip Irrigation on Y Increase

Guo [56] conducted field experiments to compare yield changes under various treatment conditions and found that the optimal yield (Y) was achieved when the irrigation amount was 37.50 mm and the nitrogen application was 306.50 kg·hm^{-2}. Previous research on the impact of water-fertilizer coupling on yield often focused on comparing yields across treatments to identify the best water-fertilizer combination [57]. However, these studies frequently overlooked the correlation between yield and other critical indicators such as photosynthesis, dry matter accumulation, water use efficiency (WUE), and soil nutrients, and did not sufficiently investigate the overall crop yield increase effect [42,58]. In the present study, a combination of Redundancy Analysis (RDA), correlation analysis, and the TOPSIS entropy weight method was employed to assess the impact of different irrigation and fertilization levels on a range of maize-related indicators. The selected yield increase indicators were then analyzed comprehensively to determine the most suitable irrigation and nitrogen application ratio for Shallow Buried Drip Irrigation (SBDI) in the semi-arid northeastern region, with the goals of conserving water and fertilizer while increasing yield. The study identified that when the irrigation volume was 348.24 mm and the nitrogen application rate was 382.80 kg·hm^{-2}, yield reached its peak. However, after a thorough evaluation considering total nitrogen (TN1), photosynthesis, yield, WUE, and other factors, it was concluded that an irrigation amount of 436.2 mm and a nitrogen application rate of 277.7 kg·hm^{-2} provided the best results. This analysis underscores the importance of considering multiple efficiency indicators when assessing the impact of water-fertilizer coupling on yield enhancement.

The semi-arid region in the western part of Northeast China, a vital area for spring maize cultivation, faces challenges due to its dry and rainless climate. Implementing irrigation techniques designed to minimize evaporation and enhance water use efficiency (WUE) and soil nutrient levels is essential. The water-nitrogen coupling technology of Shallow Buried Drip Irrigation (SBDI) offers a strategic solution by facilitating the rational distribution of dry matter, improving the total nitrogen content in the topsoil layer (TN1), and promoting yield increase (Y). In promoting field technology, the necessity for supplementary irrigation can be assessed based on the natural rainfall patterns during the various growth stages of spring maize. This approach ensures that irrigation practices are tailored to meet the specific water requirements of the crop, optimizing both water resource management and crop productivity.

5. Conclusions

Compared to the W1N1 treatment, increasing both the irrigation amount and nitrogen application significantly boosted the dry matter accumulation of spring maize during the tasseling stage, with an increase ranging from 15.17% to 32.70%. The effects of these inputs on photosynthetic performance varied across different times of the day, with irrigation showing a greater impact at 8:00 am and 1:00 pm, while nitrogen application was more influential at 10:00 am and 3:00 pm. These practices led to substantial increases in total nitrogen (TN1 by 20.85%, TN2 by 33.33%) and alkali-hydrolyzable nitrogen (AHN1 by 14.65%, AHN2 by 28.86%). Both irrigation and fertilization positively affected yield (Y), with the optimal combination of inputs bringing Y to its peak when the coded values were close to unity. Diverse irrigation and fertilization strategies were found to enhance yield by 12.02% to 44.09% and water use efficiency (WUE) by 20.08% to 140.07%. Redundancy analysis (RDA) indicated a positive correlation between irrigation volume and yield, photosynthetic rate (Pn), stomatal conductance (Cond), and transpiration rate (Tr). Similarly, nitrogen application was correlated with total nitrogen content, yield, WUE, and the aforementioned photosynthetic traits within the 0-40 cm soil layer. Enhancing photosynthetic traits at 10:00 am, particularly for TN1, contributed to higher yields, AHN2 content, and WUE. Utilizing the TOPSIS entropy weight method for comprehensive analysis, the optimal water and nitrogen coupling mode under Shallow Buried Drip Irrigation (SBDI) was identified. When the irrigation volume was 436.20 mm and nitrogen application was 277.40 kg·hm^{-2}, the conditions were most conducive to spring maize growth. This approach provides a theoretical foundation for the practical application of SBDI water-fertilizer coupling technology in the semi-arid regions.

Author Contributions: Conceptualization, Guanghua Yin and Jian Gu.; methodology, Shijun Sun.; software, Yongqi Liu. and Xue Li; validation, Guanghua Yin., Jian Gu and Ningning Ma.; formal analysis, Yongqi Liu.; investigation, Xue Li and Yongqi Liu.; resources, Guanghua Yin and Jian Gu.; data curation, Xue Li and Ningning Ma.; writing—original draft preparation, Jian Gu and Yongqi Liu.; writing—review and editing, Yongqi Liu, Jian Gu and Shijun Sun; visualization, Jian Gu and Yongqi Liu.; supervision, Guanghua Yin and Shijun Sun; project administration, Guanghua Yin; funding acquisition, Guanghua Yin and Jian Gu. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National "Fourteenth Five-Year Plan" Key R&D Program (grant numbers 2022YFD1500600), the Black Land Protection and Utilization Science and Technology Innovation Project of the Chinese Academy of Sciences (XDA28090200, XDA28120100), the Liaoning Province Applied Basic Research Program (2022JH2/101300195), the Liaoning Provincial Natural Science Foundation General Project (2022-MS-030) and the Liaoning Outstanding Innovation Team (XLYC2008015).

Data Availability Statement: The data presented in this study are available upon request from the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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