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Comprehensive Regulation of Water–Nitrogen Coupling in Hybrid Seed Maize in the Hexi Oasis Irrigation Area Based on the Synergy of Multiple Indicators

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Abstract: Water scarcity and the excessive application of nitrogen fertilizer are key factors limiting the sustainable development of the hybrid seed maize industry in the oasis agricultural areas of the Hexi Corridor in China. To determine the optimal water–nitrogen management regime of hybrid seed maize, we established a field experiment in 2020–2021 with three irrigation quotas (W1, W2, and W3 were 60, 80, and 100% of the local conventional irrigation quota, respectively) and four nitrogen application levels (N0, N1, N2, and N3 were 0, 190, 285, 380 kg·hm^{-2}). We analysed the influence of different water–nitrogen combinations on indices of seed vigour, yield, water use efficiency (WUE), irrigation water use efficiency (IUE), the partial productivity of nitrogen fertilizer (NFP), and the nitrogen fertilizer agronomic use efficiency (NFA) of hybrid seed maize. A comprehensive growth evaluation system for hybrid seed maize was established based on the AHP, entropy weight, and TOPSIS methods, and a coupled water–nitrogen response model for hybrid seed maize was established with the objectives of obtaining high-yield, efficient, and high-seed vigour. The results showed that the yield of hybrid seed maize, NFP, and NFA gradually increased with the increase in the irrigation amount, while IUE continuously decreased; the yield of hybrid seed maize, WUE, and NFA increased and then decreased, while NFP continuously decreased with an increase in the amount of nitrogen application. Further, treatment N2W3 had higher water and nitrogen use efficiency and the highest yield and seed viability with a yield of 9209.11 kg·hm^{-2} and germination percentage, germination index, and vigour index of 97.22, 58.91, and 1.55%, respectively. The model of the integrated growth response of hybrid seed maize to water–nitrogen showed that the combined benefits of the hybrid seed maize yield, WUE, and seed viability could be maximised in conjunction with the irrigation rate ranging from 3558.90 to 3971.64 m^3·hm^{-2} and the fertiliser application rate of 262.20 to 320.53 kg·hm^{-2}. This study can provide scientific guidance and act as a decision-making reference for the productive, efficient, and sustainable development of hybrid seed maize in the oasis agricultural area of the Hexi Corridor.

Keywords: hybrid seed maize; water–nitrogen coupling; seed vigour; yield; water–nitrogen use efficiency; comprehensive growth model

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1. Introduction

Maize is a globally important crop for food, animal feed, and energy. China is the second largest producer of maize in the world [1], with 41.26 million hm^2 sown in 2020. Hybrid maize seed production forms the basis of national food security [2], and the area of hybrid maize seed production in China has been expanding in recent times [3].

One of the most important maize production sites is the oasis agricultural area of the Hexi Corridor in Gansu [4], China, producing about 63 t of maize seed per year, which can meet more than half of China's needs for maize seed [5]. However, the high economic value of hybrid seed maize has led growers to apply excessive amounts of nitrogen fertilizer to ensure yields, which can reduce the effectiveness of nitrogen fertilizer [6] and lead to significant nitrogen losses in the environment and potential environmental risks [7]. At the same time, this region experiences water scarcity [8], necessitating crop irrigation, with excessive irrigation resulting in inefficient water use and erratic yields [9]. As a result, disproportionate water and nitrogen inputs severely restrict the sustainable development of the hybrid seed maize industry. With increasing food demand, the optimization of the water–nitrogen management system for hybrid seed maize is the key to achieving productive and efficient hybrid seed maize production in the Hexi Corridor.

Existing studies have explored the effects of water–nitrogen coupling on crop yield, water and nitrogen use efficiency (WNE), and economic benefits [10]. Hou et al. [11] concluded that an appropriate amount of nitrogen fertilizer combined with drip irrigation under mulching could promote nitrogen accumulation in maize plants, reduce the loss of soil nitrogen, and improve WNE and the yield of maize. A study by Cai et al. [12] showed that increased nitrogen fertilizer application could improve the yields of apples when soil moisture is low, but the excessive application of nitrogen caused a reduction in nitrogen fertilizer use efficiency (NFE) and in WUE and was detrimental to yield improvement. Prajapati et al. [13] showed how a suitable water–nitrogen ratio not only improved the yield components of chickpeas in an arid area but also increased the yield and economic benefits. These results show that water–nitrogen optimization synergy can promote water and nutrient uptake by crop roots, promote dry matter accumulation and distribution, improve WNE, and lay the foundations for high crop yields [14–16].

The level of seed vigour directly affects root system development and plant resistance to diseases. Seeds with low vigour exhibit low seedling emergence in the field and produce plants with poor disease resistance, leading to low yields. Previous research has only addressed the effects of single factors of irrigation and nitrogen application on the seed vigour of hybrid seed maize, and these results depended strongly on experimental conditions. Shi et al. [17] concluded that an intermediate level of the soil water deficit could improve hybrid maize seed vigour, while Liu et al. [18] found that the soil water deficit and water excess decreased maize seed vigour. Hao et al. [19] showed that nitrogen levels had no significant effect on seed viability indexes of hybrid seed maize. However, it is still unknown how to optimise water and nitrogen management for multiple objectives of seed vigour, yield, and water and nitrogen use efficiency. Therefore, exploring the effects of water–nitrogen coupling on seed vigour, yield, and the water–nitrogen use efficiency of hybrid seed maize could guide the efficient production of hybrid seed maize in dry production areas.

Multi-criteria decision analysis (MCDA) is used to help stakeholders evaluate decisions with a formal evaluation of several criteria [20]. Currently, there are many types of MCDA methods, such as the Stable Preference Ordering Towards Ideal Solution (SPOTIS), Characteristic Objects Method (COMET), analytic hierarchy process (AHP), principal component analysis (PCA), and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS); different fields of research can choose the best model based on data characteristics.

The advantages of the COMET method include the ability to resist the rank reversal phenomenon, easiness of application, and obtaining an objective and reliable recommendation based on the gathered data. This method, however, has its limitations. At present, the COMET method is widely applied in solving decision problems related to selecting a hydropower plant infrastructure system [21]. The SPOTIS method is very simple to apply and works with any expected solution within the bounds of criteria, but it requires extra information on the bounds of criteria to transform the original ill-defined MCDM into a well-defined MCDM to obtain a solution [22]. The AHP method is a scientific decision-making method that combines qualitative and quantitative analysis. It decomposes the problem to be decided upon into several levels, compares the levels, and calculates the ranking weights of each scheme relative to the total goal of the decision-making system, but it is also subject to randomness with the subjective uncertainty of evaluation experts and ambiguity of knowledge in the evaluation process [23]. The PCA method replaces the original indexes with fewer indexes, which fundamentally solves the problem of overlapping information among indexes and effectively simplifies the index structure of the original index system. Moreover, the weight of each composite factor is determined according to the size of its contribution, which overcomes the defects of artificially determining the weights, making comprehensive evaluation results unique, objective, and reasonable; this method has the most applications and the best results in socio-economic statistics. However, the principal component analysis method assumes that the relationship between the indicators is linear, and when it is not, biased results are produced [24]. The TOPSIS method makes full use of original data, minimizing the loss of information, solving complex optimisation problems, is suitable for multi-indicator decision analysis, and has a high degree of rationality [25]. However, the weights of various parameter indicators are subjectively determined so that the environment, and its conditions change, and the index value also changes, leading to arbitrary rankings and results that are not unique [26]. Due to the different mechanisms of the single assignment method, different weights are assigned in different ways; the use of a single evaluation method for evaluation has certain limitations and it is difficult to accurately describe the advantages and disadvantages of the final results, resulting in the development of optimal programme distortion [27], while the use of a combination of evaluations to overcome the impact of subjective factors and determine the indicator weighting factors has a high degree of scientific rationality [28,29].

The comprehensive measurement of indicators and the establishment of a scientific evaluation system is the basis for obtaining the optimal programme. For example, Liu et al. [30] used the CRITIC method to decide the weights of criteria, and the conventional TOPSIS method was applied to the intuitionistic fuzzy environment to calculate the assessment score of each target. Zhang et al. [31] used the entropy weight method to modify the weights of the original indicators of potato yield, quality, water, and fertilizer use efficiency, and economic benefits and then used TOPSIS to optimize these multiple objectives.

This study aims to find the most appropriate irrigation–nitrogen application rates through a modelling framework and theoretical support to achieve the integrated goals of high-yield, high-seed vigour, and the efficient utilization of water–nitrogen in the production of hybrid seed maize under different scenarios. In this study, an irrigation–nitrogen management framework for sustainable hybrid seed maize production was constructed by combining experimental studies and optimization modelling (Figure 1). First, we generated the response relationships of hybrid seed maize yield, seed vigour, water use efficiency (WUE), irrigation water use efficiency (IUE), nitrogen fertilizer partial productivity (NFP), and nitrogen fertilizer agronomic use efficiency (NFA) to the irrigation–nitrogen application combination. Second, we used the AHP method to subjectively judge and quantitatively describe the relative importance of multiple indicator factors such as seed vigour, yield, the water and nitrogen use efficiency of hybrid seed maize, and the entropy weight method to calculate the variation degree of each indicator and obtain the weight value of each indicator. Finally, the TOPSIS method was used to compare the strengths and weaknesses of each indicator to select the optimal water–nitrogen combination model under the synergistic multi-indicator system.

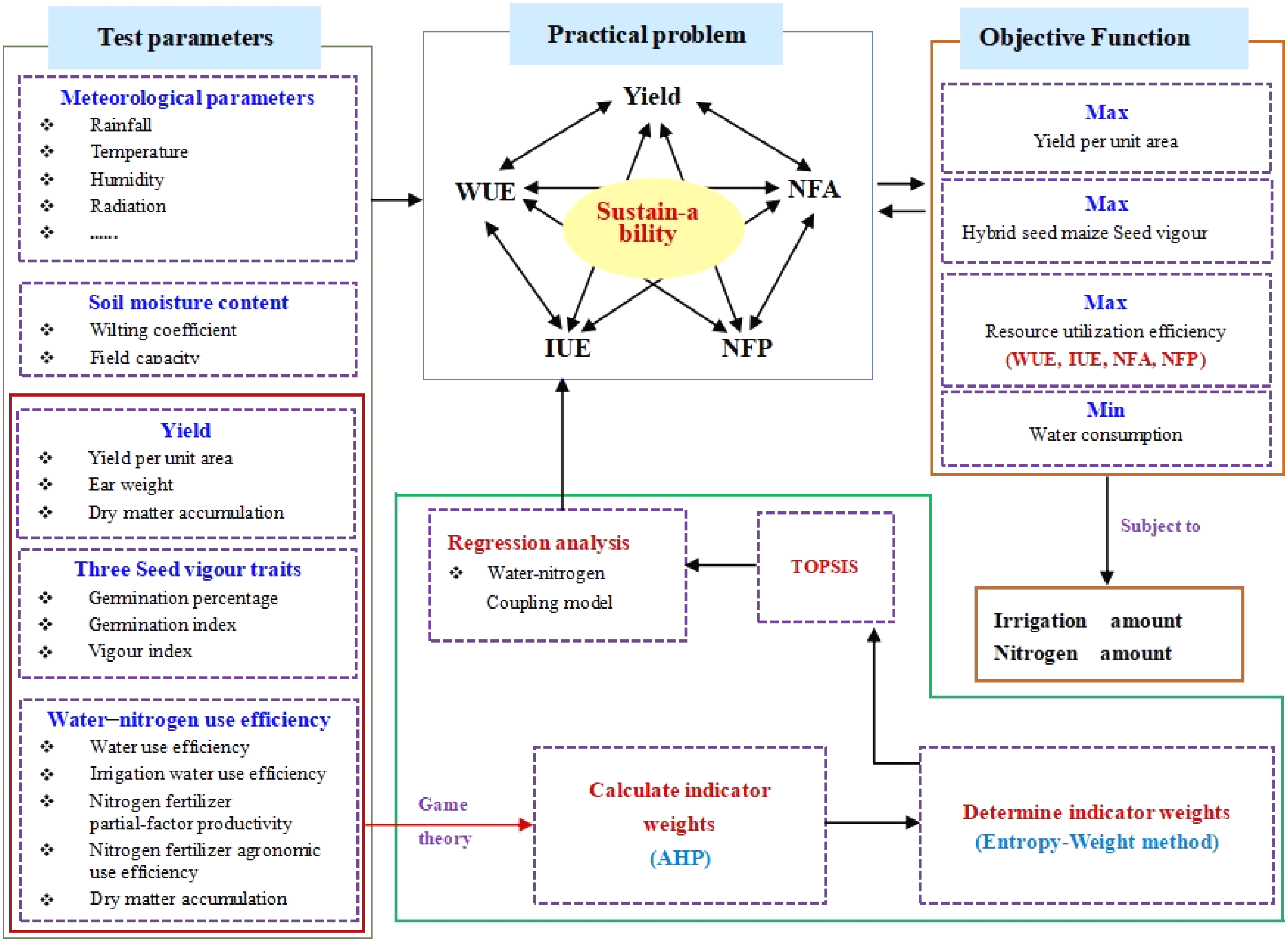

Figure 1. Framework of irrigation–nitrogen regulation for the sustainable production of hybrid seed maize.

2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted in 2020 and 2021 at the demonstration area of water–fertilizer integration for hybrid seed maize in Dangzhai Town, Ganzhou District, Zhangye City (100°29′ E, 38°51′ N, as. 1474 m) (Figure 2). The experimental area is located in the hinterland of the oasis agricultural area of the Hexi Corridor. This area has well-developed irrigated agriculture, and the annual production of maize seeds accounts for more than 50% of the annual use of maize seeds in this country, securing an important role for Gansu Province as a commercial grain-planting and economic crop-production base.

The climate is temperate and continental. The average annual temperature, precipitation, and sunshine duration from 1970 to 2019 were 7.79 °C, 129.38 mm, and 3065 h, respectively, with 80% of rainfall occurring in May–September, in a frost-free period of 145–170 d, and an average annual evaporation of 2047.9 mm. The soil in the experiment area was a sandy loam with a soil bulk density of 1.25 g·cm^{-3}, a maximum field water-holding capacity of 25.8%, a crop-wilting factor of 7.3%, a pH of 8.53, the following contents of organic matter, total nitrogen, total phosphorus, and total potassium at 18.4, 7.87, 0.43 and 11.7 g·kg^{-1}, respectively, a mass ratio of 86.3 mg·g^{-1} for alkaline dissolved nitrogen, 17.7 mg·g^{-1} for fast-acting phosphorus, 177.2 mg·g^{-1} for fast-acting potassium, and electrical conductivity (EC) of 566.80 µS·cm^{-1} [32]. Rainfall during the 2020 and 2021 growing periods was 92.6 and 102.4 mm, respectively, with average temperatures of 20.19

and 20.36 °C (Figure 3), and a reference crop evapotranspiration (ET_0 calculated using the Penman–Monteith formula [33]) of 569.10 and 595.71 mm, respectively.

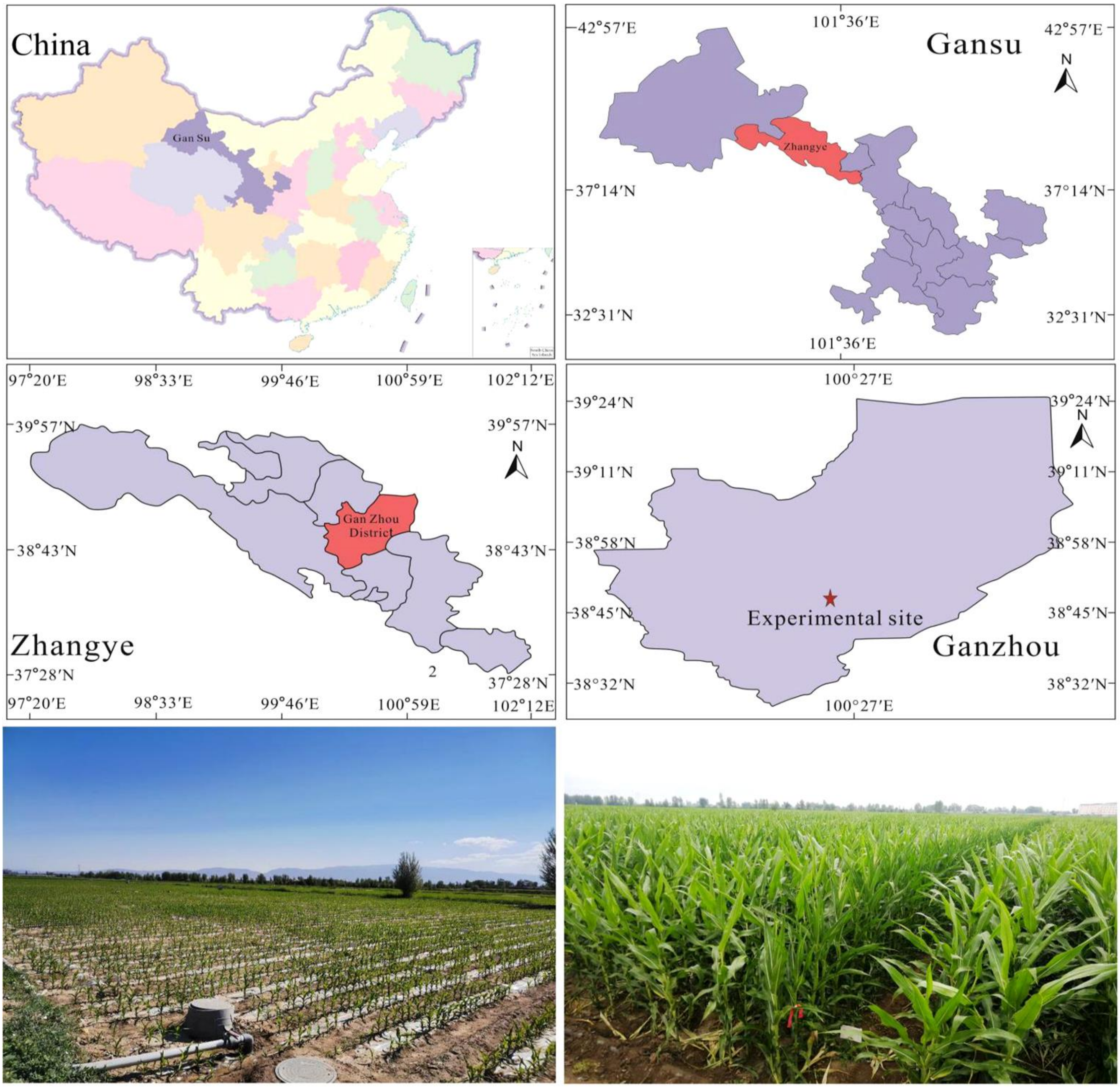

Figure 2. Location of the experimental site.

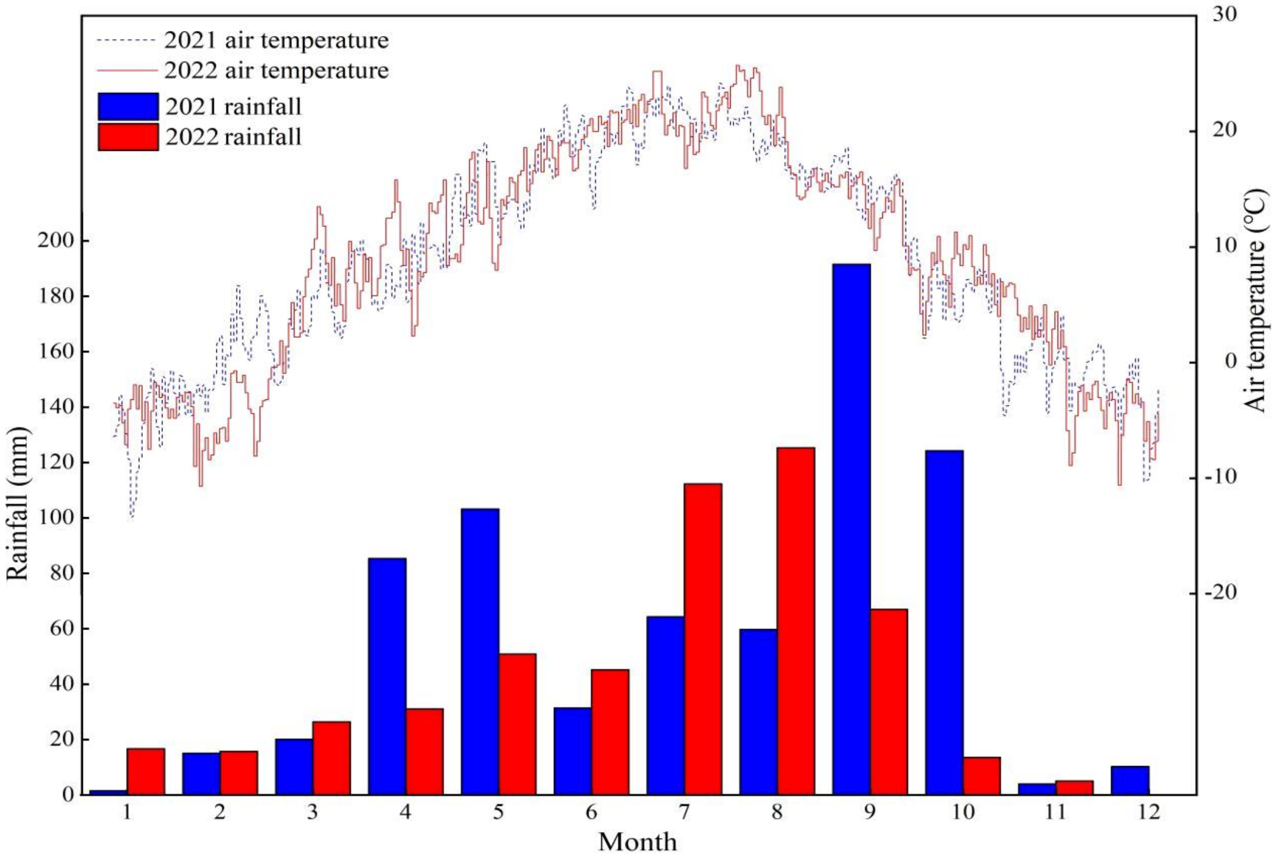

Figure 3. Mean daily temperature and monthly rainfall in the experimental area in 2021 and 2022.

2.2. Experimental Design

The amount of irrigation applied was based on the evapotranspiration (ET_0) of the reference crop and precipitation, and the amount of nitrogen applied was based on the nitrogen uptake of hybrid seed maize and the soil nitrogen content. The experiment was established as a split-plot design with the following two factors: the amount of irrigation water and the amount of nitrogen application, with the main factor being the amount of irrigation water. Three irrigation gradients were used as follows: low (W1, 60% of the local conventional irrigation quota), medium (W2, 80% of the local conventional irrigation quota), and high water (W3, 100% of the local conventional irrigation quota). The following four nitrogen gradients were used: zero (N0, nitrogen level 0 kg·hm^{-2}), low (N1, 190 kg·hm^{-2}), medium (N2, 285 kg·hm^{-2}), and high nitrogen (N3, 380 kg·hm^{-2}). The experiment consisted of 12 treatments, each of which was repeated 3 times and arranged in randomized groups (a total of 36 plots). Plots were 16.0 m long and 5.0 m wide in the east–west direction, for a total area of 80 m^2. Plots were separated from each other in advance of treatments by 1.0 m deep PVC plastic sheeting and 20 cm high ridges to prevent the interaction of water and fertilizer among the plots (Figure 4).

The hybrid seed maize (*Zea mays* L.) used was a new variety, "ZT1011", which was planted by hole-sowing with a mulching seeder, with the female parent sown on 21 April 2020, and the first, second, and third male parent sown on 16, 21, and 26 April, respectively, and harvested on 24 September. The 2–4 unexpanded leaves were removed with the stamens before the female parent stamens were dispersed, and all the male parents were cut down after pollination. The male and female parents were planted in a row ratio of 1:6, i.e., 1 row of the male parent and 6 rows of female parents, planted in east–west rows at equal spacing, with 0.50 m between the rows of female parents and plant spacing of 0.20 m, with a planting density of 85,714 hm^{-2}. The male parent row spacing was 3.5 m, and plant spacing was 0.20 m, with a planting density of 14,285 hm^{-2} (Figure 3).

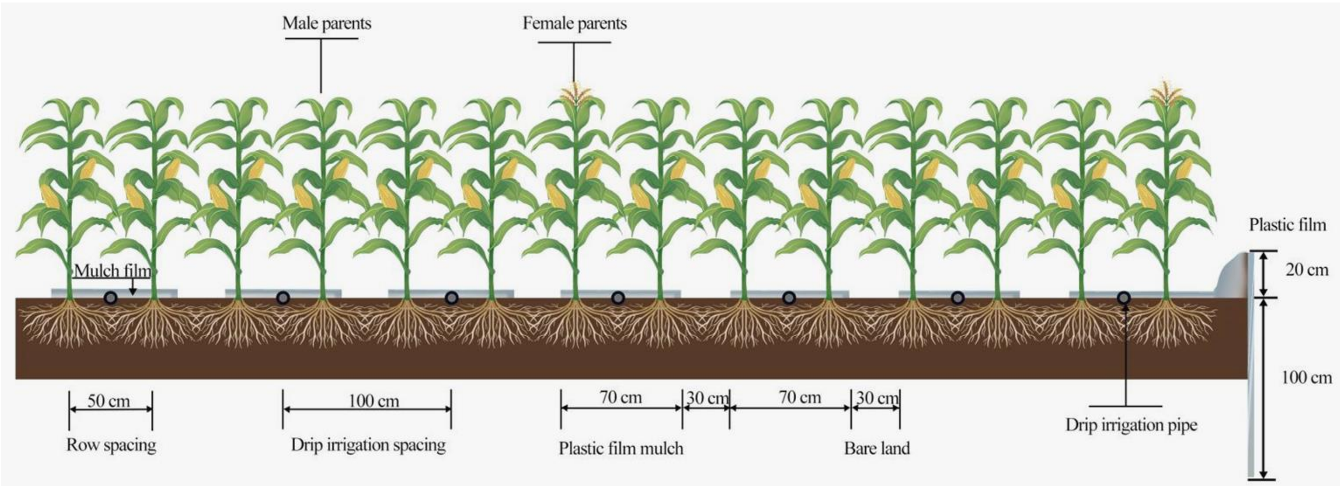

Figure 4. A schematic diagram of the planting arrangement.

All treatments were irrigated nine times during the growing period, with the irrigation dates and irrigation amount shown in Table 1, and each plot was fitted with an individual water meter to control the irrigation amount. Nitrogen (urea, N $\geq$ 46%), phosphorus (diammonium phosphate, $P_2O_5 \geq$ 46%), and potassium (potassium sulphate, $K_2O \geq$ 52%) fertilizers were applied at the same basal rates of 570, 400, and 260 kg·hm^{-2} for each treatment, respectively, with the remaining nitrogen fertilizers applied retrospectively in a 4:3:3 ratio at the jointing stage, late whorl stage, and silking stage. The field application amount for each factor of the experiment, as well as the coded values after normalisation, are shown in Table 2.

Table 1. Irrigation scheduling for different growth stages of hybrid seed maize (m^3·hm^{-2}).

Year	Treatment	Seedling Stage	Jointing Stage	Early Whorl Stage	Late Whorl Stage	Tasseling Stage	Silking Stage	Grouting Stage	Milking Stage	Wax Ripening Stage	Irrigation Quota
2020	W1	180	270	270	315	330	330	315	219	180	2409
	W2	240	360	360	420	440	440	420	292	240	3212
	W3	300	450	450	525	550	550	525	365	300	4015
2021	W1	180	270	270	330	330	330	300	192	180	2382
	W2	240	360	360	440	440	440	400	256	240	3176
	W3	300	450	450	550	550	550	500	320	300	3970

Table 2. The amounts and dates of water and nitrogen application.

Treatment	Irrigation Quota (mm)		Total Nitrogen Application (kg·hm^{-2})	Factor Code Value	
	2020 Year	2021 Year		Irrigation Amount x_1	Nitrogen Application Amount x_2
N0W1	240.9	238.2	0	-	-
N0W2	321.2	317.6	0	-	-
N0W3	401.5	397.0	0	-	-
N1W1	240.9	238.2	160	0.0	0.0
N1W2	321.2	317.6	160	0.5	0.0
N1W3	401.5	397.0	160	1.0	0.0
N2W1	240.9	238.2	280	0.0	0.5
N2W2	321.2	317.6	280	0.5	0.5
N2W3	401.5	397.0	280	1.0	0.5
N3W1	240.9	238.2	400	0.0	1.0
N3W2	321.2	317.6	400	0.5	1.0
N3W3	401.5	397.0	400	1.0	1.0

Note: The nitrogen application amount is the converted pure nitrogen amount.

2.3. Methods and Measured Variables

2.3.1. Meteorological Data

Meteorological data such as precipitation, solar radiation, air temperature, relative air humidity, and wind speed were obtained from a microclimate observer (type MC-NQXZ) installed in the nearby experiment station.

2.3.2. Water Use Efficiency

Soil moisture was measured with TRIME-PICO 64 TDR (made in Germany by IMKO corporation). Measurements were taken at 15 d intervals throughout the hybrid seed maize growing period, with additional measurements before sowing and after harvest, before and after precipitation, 1 day before and 2 days after irrigation, and to a sampling depth of 100 cm and at 10 cm intervals.

Crop water consumption (*ET*) was calculated using the water balance method. The effect of mulching on rainfall infiltration was calculated using the ratio of the increase in soil water before and after a single rainfall event to the current rainfall event; that is,

$$\lambda = \gamma_{\mathrm{i}} \sum \left(w_{if} - w_{ib} \right) d \tag{1}$$

where λ is rainfall infiltration, mm; γ_{i} is the soil bulk density of the i layer, g·cm^3; W_{if} is the soil volumetric water content of the ith layer after rainfall, cm^3·cm^{-3}; W_{ib} is the soil volumetric water content of the ith layer before rainfall, cm^3·cm^{-3}; and d is the thickness of the soil layer, mm.

Water consumption was calculated using the water balance formula as follows:

$$ET = \lambda + I + \Delta W - Q \tag{2}$$

where *ET* is the total water consumption during the growth stage of crops, mm; λ is rainfall infiltration, mm; I is the effective irrigation volume, mm; ΔW is the change in soil water storage, mm; and Q is the amount of recharge and seepage to groundwater, mm.

Since the depth of groundwater in the study area was greater than 10 m, and the irrigation method was drip irrigation, there was no runoff drainage during the growing period, and groundwater recharge and seepage were ignored.

Water use efficiency (*WUE*, kg·m^{-3}) was calculated as follows:

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

where Y is the maize yield, kg·hm^{-2}

Irrigation water utilization efficiency (*IUE*, kg·m^{-3}) was calculated as follows:

$$IUE = Y/I \tag{4}$$

2.3.3. Nitrogen Fertilizer Use Efficiency

Nitrogen fertilizer partial productivity (*NFP*, kg·kg^{-1}) was obtained as follows:

$$NFP = Y/N \tag{5}$$

where N is the nitrogen fertilizer input, kg·hm^{-2}

Nitrogen fertilizer agronomic use efficiency (*NFA*, kg·kg^{-1}) was calculated as follows:

$$NFA = (Y_N - Y_0)/N \tag{6}$$

where Y_N is the grain yield with nitrogen application, kg·hm^{-2}; Y_0 is the grain yield without nitrogen application, kg·hm^{-2}

2.3.4. Above-Ground Dry Weights

At the maturity stage, 6 standard sample plants were randomly selected in each experimental plot, collected, and placed into a plastic bag for transport to the laboratory; there, samples were dried at 105 °C for 30 min and then to a constant weight at 80 °C Samples were weighed with an accuracy of 0.01 g on an electronic balance, and then the average value of six plants was taken.

2.3.5. Yield

After the hybrid seed maize reached maturity, 30 standard sample plants were randomly selected from each experimental plot; the ears were naturally air-dried and the indicators of yield components were determined, threshed for seed counting, and converted to the yield per hectare.

2.3.6. Seed Vigour

Three hundred non-damaged air-dried seeds were selected from each treatment, disinfected with 1.0% sodium hypochlorite, rinsed with deionised water until odourless, and 300 treated seeds were divided into 6 equal parts; 50 treated seeds were placed in Petri dishes with germination paper sterilised at 121 °C, and were then placed in a 25 °C constant temperature incubator. The number of seeds that germinated normally was counted every day. After 7 days, seedlings were taken out, the germination percentage was determined, the fresh weight of individual seedlings was obtained, and the germination index and vigour index were calculated [34].

Germination percentage

$$(GP, \%) = (G_7/T) \times 100\% \tag{7}$$

where G_7 is the number of germinated seeds of hybrid seed maize on day 7 and T is the total number of seeds for testing.

Germination index

$$(GI,\ \%) = \sum (\mathrm{G_i}/\mathrm{i}) \times 100\% \tag{8}$$

where G_i is the number of seeds germinated per day on day 7, i = 1,2,3,4,5,6,7, and i is the day of germination.

Vigour index

$$(VI, \%) = GI \times DW \tag{9}$$

where DW is the seedling dry weight on day 7 (g).

2.3.7. The Water–Nitrogen Coupling Model

We determined the regression relationships between the irrigation amount, nitrogen application amount, and comprehensive growth score of hybrid seed maize under three drip irrigation levels and mulch, with the comprehensive growth score as the target, the amount of irrigation and nitrogen application as independent variables, and the model was expressed using binary quadratic equations. The binary quadratic regression equation is as follows:

$$y = a_0 + a_1x_1 + a_2x_2 + a_{12}x_1x_2 + a_{11}x_1^2 + a_{22}x_2^2 \tag{10}$$

where y is the predicted yield of hybrid seed maize, kg·hm^{-2}; a_0 is the constant term of the regression model; a_1, a_2 are first-order coefficients; a_{12} is the interaction coefficient; and a_{11}, a_{22} is the quadratic coefficient.

2.4. Statistical Analysis Methods

The LSD multiple comparison method in SPSS (Version 22.0, IBM, Inc., New York, NY, USA) software was used for statistical analysis and regression model building, and Origin

(Version 8.0, Origin Lab, Corp., Hampton, MA, USA) software was used for plotting. Yaaph (Meta Decision Software Technology Co., Ltd., Corp., Shanxi, China) software was used to draw the comprehensive analytical hierarchical model of hybrid seed maize and the weight analysis of each index; Microsoft Excel (Version 2010, Microsoft Corp., Raymond, WA, USA) software was used to calculate the comprehensive evaluation values according to the TOPSIS method; DPS was used to establish the mathematical model; and MATLAB (Version R2023b, MathWorks, Corp., MA, USA) software was used to analyse the model.

3. Results

3.1. Effects of Water–Nitrogen Interactions on Seed Vigour of Hybrid Seed Maize

The effect of the irrigation amount on the vigour index was highly significant; the effect of the nitrogen application amount on the germination percentage was significant, and the effect of irrigation amount, nitrogen application amount, and their interaction on the germination index of hybrid seed maize was highly significant (Table 3). Under zero and low nitrogen levels, the germination percentage, germination index, and vigour index of hybrid seed maize exhibited the order of W2, W3, and W1. Under medium and high levels of nitrogen application, the average post-emergence germination percentage, germination index, and vigour index at the same irrigation amount increased by 1.85, 5.88, and 8.71% from low to medium water treatment and by 1.02, 5.42, and 7.42% from medium to high water treatment, indicating that the enhancement of seed vigour with the increase in the irrigation amount under medium and high levels of nitrogen application gradually decreased. Under the same irrigation level, the germination percentage and germination index was highest for N2, N3, N1, and N0 in descending order, but the vigour index increased with the increase in the nitrogen application amount under a low irrigation level. The highest seed vigour of hybrid seed maize was for the water–nitrogen combination of N2W3, and the mean values of the germination percentage, germination index, and vigour index reached 97.22%, 58.91, and 1.55, respectively.

Table 3. The effect of water–nitrogen interactions on the seed vigour of hybrid seed maize.

Treatment	2020			2021		
	GP/(%)	GI	VI	GP/(%)	GI	VI
N0W1	91.94 ± 1.27 d	47.23 ± 0.46 g	1.18 ± 0.08 d	89.17 ± 3.00 c	44.66 ± 1.09 d	1.02 ± 0.06 c
N0W2	94.17 ± 2.50 abcd	53.65 ± 1.74 e	1.37 ± 0.23 bcd	92.22 ± 2.41 abc	51.52 ± 0.07 bc	1.24 ± 0.18 abc
N0W3	93.06 ± 2.92 bcd	50.39 ± 1.41 f	1.28 ± 0.18 cd	91.39 ± 2.68 abc	49.45 ± 1.13 c	1.22 ± 0.09 abc
N1W1	92.22 ± 2.68 cd	48.98 ± 0.41 fg	1.27 ± 0.07 cd	90.83 ± 3.34 bc	46.49 ± 1.31 d	1.12 ± 0.04 bc
N1W2	95.28 ± 1.27 abcd	56.99 ± 1.13 c	1.48 ± 0.12 abc	94.44 ± 3.76 abc	54.30 ± 2.02 ab	1.39 ± 0.19 ab
N1W3	94.72 ± 2.55 abcd	52.93 ± 0.40 e	1.31 ± 0.15 cd	93.06 ± 2.10 abc	50.58 ± 0.53 c	1.24 ± 0.19 abc
N2W1	95.00 ± 2.89 abcd	54.70 ± 0.51 de	1.34 ± 0.11 bcd	93.89 ± 4.19 abc	50.24 ± 2.38 c	1.11 ± 0.17 bc
N2W2	96.39 ± 2.55 abc	57.96 ± 1.70 bc	1.49 ± 0.02 abc	95.56 ± 2.10 ab	55.64 ± 3.33 a	1.35 ± 0.03 ab
N2W3	97.50 ± 1.44 a	60.86 ± 0.97 a	1.61 ± 0.10 a	96.94 ± 1.73 a	56.96 ± 1.27 a	1.49 ± 0.20 a
N3W1	94.44 ± 2.10 abcd	54.10 ± 1.91 e	1.45 ± 0.05 abc	92.78 ± 2.68 abc	50.22 ± 0.90 c	1.29 ± 0.16 abc
N3W2	96.11 ± 1.27 abcd	56.52 ± 0.71 cd	1.48 ± 0.07 abc	95.00 ± 3.00 ab	51.45 ± 1.60 bc	1.31 ± 0.22 ab
N3W3	96.67 ± 1.67 ab	59.48 ± 1.82 ab	1.56 ± 0.04 ab	95.83 ± 2.50 ab	56.29 ± 0.87 a	1.39 ± 0.15 ab
Irrigation (I)	*	***	**	ns	***	**
Fertilization (F)	*	***	*	*	***	ns
I × F	ns	***	ns	ns	**	ns

Note: GP, germination percentage; GI, germination index; VI, vigour index. Different lowercase letters in the same column indicate significant differences among treatments ($p < 0.05$); the same letters indicate no differences; *, ** and *** are significant at the $p < 0.05$, 0.01, and 0.001 levels, respectively; ns, not significant.

3.2. Effects of Water–Nitrogen Interactions on Hybrid Seed Maize Yield and Its Components

Water–nitrogen coupling effects on hybrid seed maize yield and its components in 2020 and 2021 show a similar influence. Both the irrigation amount and nitrogen application amount had highly significant effects on hybrid seed maize yield, but the coupling effect was not significant (Table 4). The changes in the longitudinal ear diameter, 100-grain weight, and above-ground dry matter accumulation were similar and increased with the increase in irrigation inputs and were highest for the N2W3 treatment, with mean values of 16.02 cm, 32.48 g, and 262.27 g/plant, respectively; they increased by 1.07 to 39.87%, 3.01 to 55.42%, and 2.55 to 110.59%, respectively, compared with the other treatments. Under the same nitrogen application level, the yield increased with the increase in the irrigation amount, and after averaging across plots with the same irrigation amount, the yield of hybrid seed maize increased by an average of 25.72% between low and medium water and by only 9.06% between medium and high water, indicating that adequate irrigation was conducive to an improvement in yield, but higher irrigation amounts had a weaker effect on the yield of hybrid seed maize.

Table 4. Effects of water–nitrogen interactions on hybrid seed maize yield and its components.

Year	Treatment	Ear Longitudinal Diameter /(cm)	Ear Diameter /(mm)	Kernel Number per Ear /(a)	Ear Weight /(g)	100-Grain Weight /(g)	Yield /(kg·hm^{-2})	Above-Ground Dry Matter Accumulation /(g·Plant^{-1})
2020	N0W1	11.65 ± 0.72 d	33.50 ± 1.03 c	226 ± 7.00 g	55.17 ± 2.67 g	21.65 ± 0.95 g	4038.52 ± 179.83 g	134.81 ± 6.87 g
	N0W2	13.28 ± 0.76 c	36.22 ± 2.18 bc	242 ± 4.58 g	76.64 ± 4.61 f	25.01 ± 1.27 f	5542.79 ± 229.63 ef	153.13 ± 6.15 fg
	N0W3	14.49 ± 0.64 ab	37.14 ± 1.11 ab	278 ± 12.12 e	84.41 ± 5.01 f	26.19 ± 0.88 ef	5974.41 ± 253.64 e	164.86 ± 8.92 ef
	N1W1	14.15 ± 0.38 bc	36.03 ± 1.66 bc	260 ± 7.23 f	78.09 ± 3.59 f	24.44 ± 0.51 f	5389.27 ± 173.67 f	157.62 ± 9.51 f
	N1W2	14.71 ± 0.66 ab	37.86 ± 2.28 ab	322 ± 10.82 d	101.53 ± 6.10 de	27.61 ± 1.43 de	7120.90 ± 316.68 d	187.98 ± 11.54 d
	N1W3	15.02 ± 0.92 ab	38.28 ± 0.41 ab	354 ± 7.09 c	119.18 ± 5.35 c	28.79 ± 0.95 cd	7839.85 ± 239.16 c	209.53 ± 6.59 c
	N2W1	14.84 ± 0.55 ab	37.69 ± 0.39 ab	318 ± 13.32 d	97.79 ± 4.01 e	27.13 ± 0.98 de	7002.66 ± 308.88 d	180.91 ± 11.99 de
	N2W2	15.33 ± 0.49 ab	39.03 ± 0.89 ab	376 ± 15.59 b	123.25 ± 5.11 c	30.16 ± 1.08 bc	8627.19 ± 210.33 b	223.55 ± 15.02 bc
	N2W3	15.49 ± 0.60 a	39.94 ± 2.60 a	416 ± 7.00 a	144.94 ± 6.46 a	31.96 ± 1.60 ab	9162.43 ± 267.70 a	253.14 ± 17.11 a
	N3W1	15.17 ± 0.52 ab	37.27 ± 1.74 ab	328 ± 5.69 d	108.51 ± 4.10 d	27.40 ± 0.55 de	7203.38 ± 270.99 d	188.17 ± 12.49 d
	N3W2	15.68 ± 0.81 a	38.75 ± 0.61 ab	402 ± 8.89 a	132.28 ± 6.63 b	30.57 ± 0.95 bc	8744.75 ± 329.33 ab	240.09 ± 13.04 ab
	N3W3	15.73 ± 0.51 a	39.42 ± 2.25 a	414 ± 17.35 a	139.37 ± 4.95 ab	32.89 ± 1.44 a	9012.50 ± 282.92 ab	259.61 ± 11.78 a
	Irrigation (I)	***	**	***	***	***	***	**
	Fertilization (F)	***	**	***	***	***	***	***
	I × F	ns	ns	**	*	ns	ns	*
2021	N0W1	11.25 ± 0.35 f	33.13 ± 1.23 d	212 ± 11.53 f	50.09 ± 3.05 g	20.14 ± 0.67 g	3753.81 ± 176.04 h	114.27 ± 8.07 h
	N0W2	12.92 ± 0.51 e	35.28 ± 0.57 cd	230 ± 13.11 ef	71.65 ± 3.89 f	24.14 ± 1.34 f	5180.37 ± 262.93 g	139.58 ± 4.06 g
	N0W3	14.54 ± 0.28 cd	36.62 ± 0.37 bc	268 ± 14.11 d	79.19 ± 4.64 f	25.37 ± 0.91 ef	6149.22 ± 207.47 f	157.77 ± 5.57 f
	N1W1	14.09 ± 0.47 d	35.64 ± 1.60 c	248 ± 15.04 de	74.53 ± 4.47 f	23.46 ± 0.54 f	5572.94 ± 117.16 g	145.36 ± 4.87 fg
	N1W2	15.11 ± 0.29 bc	37.10 ± 1.65 bc	314 ± 17.00 c	97.96 ± 5.49 de	26.92 ± 1.23 de	6754.88 ± 307.87 e	177.15 ± 7.76 e
	N1W3	15.73 ± 0.20 ab	37.47 ± 1.69 bc	346 ± 15.50 b	112.75 ± 3.00 c	28.04 ± 0.56 cd	7991.36 ± 262.22 d	200.84 ± 10.68 d
	N2W1	14.93 ± 0.33 c	36.99 ± 1.51 bc	308 ± 10.97 c	92.38 ± 5.68 e	26.35 ± 1.89 de	7248.52 ± 309.55 e	183.66 ± 12.25 de
	N2W2	15.86 ± 0.19 ab	38.56 ± 0.97 ab	368 ± 10.58 b	118.12 ± 7.33 c	29.51 ± 0.80 bc	8730.10 ± 312.44 bc	219.08 ± 8.05 c
	N2W3	16.19 ± 0.70 a	40.34 ± 1.73 a	412 ± 15.52 a	140.64 ± 4.66 a	31.09 ± 1.59 ab	9255.79 ± 319.94 a	258.37 ± 15.22 ab
	N3W1	15.23 ± 0.41 bc	37.35 ± 1.22 bc	316 ± 18.58 c	101.58 ± 3.48 d	26.72 ± 1.26 de	6812.90 ± 393.42 e	185.30 ± 9.75 de
	N3W2	16.01 ± 0.60 a	39.02 ± 0.41 ab	396 ± 15.72 a	129.17 ± 4.99 b	29.83 ± 1.23 bc	8413.85 ± 260.92 cd	246.78 ± 14.67 b
	N3W3	16.30 ± 0.31 a	40.11 ± 1.50 a	408 ± 19.16 a	135.06 ± 7.17 ab	32.06 ± 1.38 a	9085.36 ± 401.21 ab	264.93 ± 13.50 a
	Irrigation (I)	***	***	***	***	***	***	***
	Fertilization (F)	***	***	***	***	***	***	***
	I × F	**	ns	*	*	ns	ns	*

Note: Different lowercase letters in the same column indicate significant differences among treatments ($p < 0.05$); the same letters indicate no differences; *, ** and *** are significant at the $p < 0.05$, 0.01, and 0.001 levels, respectively; ns, not significant.

The effect that the amount of nitrogen application had on hybrid seed maize yield was also significant; thus, the yield increased by 32.74% between zero and low nitrogen, by 23.01% between low and medium nitrogen, and by only 0.68% between medium and high nitrogen in 2020, while it decreased by 3.65% in 2021. These results show that an appropriate amount of nitrogen application is conducive to improving the yield, but excessive nitrogen application diminishes any further increase and may have a negative effect on the yield of hybrid seed maize.

The combined effect of water–nitrogen resulted in the highest yield with N2W3 and yields of 9162.4 and 9255.8 kg·hm^{-2} in 2020 and 2021, respectively, which indicated that either an insufficient or excessive amount of nitrogen application under high-water treatments inhibit the growth of hybrid seed maize. Trends in ear diameter, kernel number per ear, ear weight, and above-ground dry matter accumulation were similar to those of the yield, with the N2W3 treatment showing significant advantages.

3.3. Effects of Water–Nitrogen Interactions on Water–Nitrogen Use Efficiency in Hybrid Seed Maize

Irrigation quota and nitrogen fertilizer application amount were the primary factors affecting the water consumption and water–nitrogen use efficiency of hybrid seed maize (Table 5). Water consumption exhibited an increasing trend with the increase in water and nitrogen usage, in which the N3W3 treatment had the highest water consumption of 516.0–547.3 mm, followed by the N2W3 treatment at 484.0 to 534.0 mm, with 8.1–69.4% and 1.4–65.9%, respectively, for higher water consumption in these compared to other treatments. There was no significant difference between the N2W3 and N3W3 treatments. These results indicate that, with adequate irrigation, the water consumption of hybrid seed maize increased with increasing nitrogen application, but this increase was small. Water use efficiency increased by 12.4 to 14.4% and 5.2 to 11.9% between low (W1) and medium water (W2) treatments with zero- (N0) and low-nitrogen (N1) application levels, respectively, whereas this increase was smaller between medium- (W2) and high-water (W3) treatments. When the nitrogen application amount was increased to medium (N2) and high (N3) nitrogen levels, water use efficiency increased only by 2.7 to 3.2% and 4.0 to 6.0% between W1 to W2 treatments, respectively. The differences between W2 and W3 treatments varied within the two experimental years, with a significant decrease in water use efficiency of 12.8 and 10.3% in 2020, respectively, and no significant changes in 2021.

Table 5. Effects of water–nitrogen interactions on WNE in hybrid seed maize.

Year	Treatment	ET /(mm)	WUE /(kg·m^{-3})	IUE /(kg·m^{-3})	NFP /(kg·kg^{-1})	NFA /(kg·kg^{-1})
2020	N0W1	323.02 ± 15.64 h	1.25 ± 0.01 h	1.68 ± 0.07 e	—	—
	N0W2	386.24 ± 9.07 ef	1.43 ± 0.04 fg	1.73 ± 0.08 e	—	—
	N0W3	434.61 ± 10.59 c	1.37 ± 0.03 g	1.49 ± 0.06 f	—	—
	N1W1	358.06 ± 5.66 g	1.51 ± 0.06 f	2.24 ± 0.07 c	28.36 ± 0.92 e	7.11 ± 0.96 c
	N1W2	420.95 ± 17.81 cd	1.69 ± 0.09 de	2.22 ± 0.10 c	37.48 ± 1.67 b	8.31 ± 1.95 bc
	N1W3	474.60 ± 13.68 b	1.65 ± 0.08 e	1.95 ± 0.06 d	41.26 ± 1.26 a	9.82 ± 1.27 ab
	N2W1	368.76 ± 17.42 fg	1.90 ± 0.01 ab	2.91 ± 0.13 a	24.57 ± 1.08 f	10.40 ± 0.89 a
	N2W2	440.19 ± 16.93 c	1.96 ± 0.06 a	2.69 ± 0.07 b	30.27 ± 0.74 d	10.82 ± 0.30 a
	N2W3	535.97 ± 12.93 a	1.71 ± 0.03 de	2.28 ± 0.07 c	32.15 ± 0.94 c	11.19 ± 0.49 a
	N3W1	407.62 ± 15.92 de	1.77 ± 0.04 cd	2.99 ± 0.11 a	18.96 ± 0.72 g	8.33 ± 0.38 bc
	N3W2	474.58 ± 22.01 b	1.84 ± 0.02 bc	2.72 ± 0.10 b	23.01 ± 0.87 f	8.43 ± 0.51 bc
	N3W3	547.25 ± 17.28 a	1.65 ± 0.09 e	2.24 ± 0.07 c	23.72 ± 0.74 f	7.99 ± 0.56 c
	Irrigation (I)	***	***	***	***	ns
	Fertilization (F)	***	***	***	***	***
	I × F	ns	***	***	***	ns
2021	N0W1	331.64 ± 12.98 f	1.13 ± 0.06 i	1.58 ± 0.07 g	—	—
	N0W2	408.61 ± 11.88 d	1.27 ± 0.07 h	1.63 ± 0.09 g	—	—
	N0W3	436.55 ± 6.49 c	1.41 ± 0.07 g	1.55 ± 0.05 g	—	—
	N1W1	358.73 ± 12.94 e	1.55 ± 0.03 f	2.34 ± 0.05 d	29.33 ± 0.61 d	9.57 ± 0.39 bcd
	N1W2	414.85 ± 10.56 cd	1.63 ± 0.11 ef	2.13 ± 0.10 ef	35.55 ± 1.62 b	8.29 ± 0.50 de
	N1W3	477.22 ± 8.73 b	1.67 ± 0.03 de	2.01 ± 0.06 f	42.06 ± 1.38 a	9.70 ± 0.96 bc
	N2W1	393.48 ± 5.99 d	1.84 ± 0.07 abc	3.04 ± 0.13 a	25.43 ± 1.09 e	12.26 ± 1.02 a
	N2W2	461.36 ± 20.27 b	1.89 ± 0.06 ab	2.75 ± 0.10 bc	30.63 ± 1.10 cd	12.46 ± 0.74 a
	N2W3	483.99 ± 17.65 b	1.90 ± 0.06 a	2.33 ± 0.08 d	32.48 ± 1.13 c	10.90 ± 0.56 b
	N3W1	404.72 ± 15.47 d	1.68 ± 0.09 de	2.86 ± 0.17 b	17.93 ± 1.03 g	8.05 ± 0.63 e
	N3W2	472.59 ± 19.34 b	1.78 ± 0.03 bcd	2.65 ± 0.08 c	22.14 ± 0.68 f	8.51 ± 0.67 cde
	N3W3	515.98 ± 13.89 a	1.76 ± 0.04 cd	2.29 ± 0.10 de	23.91 ± 1.06 ef	7.73 ± 0.97 e
	Irrigation (I)	***	***	***	***	ns
	Fertilization (F)	***	***	***	***	***
	I × F	ns	ns	***	***	*

Note: Different lowercase letters in the same column indicate significant differences among treatments ($p < 0.05$); the same letters indicate no differences; * and *** are significant at the $p < 0.05$, 0.01, and 0.001 levels, respectively; ns, not significant.

At the same irrigation level, water use efficiency decreased for different nitrogen application amounts in the order of N2, N3, N1, and N0. Nitrogen application treatments (N1, N2, N3) exhibited high-to-low irrigation water use efficiency in the order of W1, W2, and W3, with a decrease in irrigation water use efficiency between W2 and W3 greater than that between W1 and W2.

An analysis of the NFP and NFA of different water–nitrogen combinations revealed that the maximum value of NFP in both 2020 and 2021 was in N1W3 at 41.26 and 42.06 $kg \cdot kg^{-1}$, respectively, and the minimum was in N3W1 at 18.96 and 17.93 $kg \cdot kg^{-1}$, respectively. NFP was negatively correlated with the amount of nitrogen application at the same irrigation level and was significantly different between experimental years for different nitrogen application treatments. NFP was positively correlated with the irrigation amount at the same nitrogen application level and was significantly lower in W1 than W2 and W3; a significant increase in NFP from 20.5 to 32.2%, between W1 and W2, and between W2 and W3 was observed only in N1, with an increase of 10.2 to 18.3%, and a smaller increase in N2 and N3 conditions, with no significant difference. The NFA showed an increasing and then decreasing trend with increasing nitrogen application under the same irrigation level. In the range of N1 to N2, NFA increased with the increase in the irrigation amount, and in the range of N2 to N3, NFA decreased with an increase in the irrigation amount, indicating that increasing the irrigation amount could improve the NFA of hybrid seed maize in a moderate nitrogen fertilizer environment, but not with an excessive amount of irrigation.

3.4. Establishment of a Comprehensive Growth Evaluation System for Hybrid Seed Maize

3.4.1. Comprehensive Evaluation Hierarchy Model (IHM)

A hierarchical model for the comprehensive evaluation of hybrid seed maize was established using Yaaph software (Figure 5). The comprehensive growth index (C) was divided into three guideline layers: yield index (C_1), seed vigour index (C_2), and water–nitrogen use efficiency (C_3). The yield index included the following three components: ear weight (C_{11}), yield (C_{12}), and dry matter accumulation (C_{13}). The seed vigour index included the following three components: germination percentage (C_{21}), germination index (C_{22}), and vigour index (C_{23}). Water–nitrogen use efficiency included water use efficiency (C_{31}), irrigation water use efficiency (C_{32}), nitrogen fertilizer partial-factor productivity (C_{33}), and nitrogen fertilizer agronomic use efficiency (C_{34}).

3.4.2. Indicator Weights

(1) Determination of weights based on the AHP method

After determining the weight hierarchical model based on the AHP method, the judgement matrix was built using a proportion of 1 to 10 and the consistency of the matrix was tested; the comprehensive growth indicators, yield indicators, seed vigour indicators, water–nitrogen use efficiency judgement matrix were, respectively, as follows:

$$C = \begin{bmatrix} 1 & 1 & 5 \\ 1 & 1 & 3 \\ 0.2 & 0.3333 & 1 \end{bmatrix} C_1 = \begin{bmatrix} 1 & 3 & 0.3333 \\ 0.3333 & 1 & 0.2 \\ 3 & 5 & 1 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} 1 & 0.5 & 4 \\ 2 & 1 & 6 \\ 0.25 & 0.1667 & 1 \end{bmatrix} C_3 = \begin{bmatrix} 1 & 3 & 3 & 2 \\ 0.3333 & 1 & 3 & 1 \\ 0.3333 & 0.3333 & 1 & 0.25 \\ 0.5 & 1 & 4 & 1 \end{bmatrix}$$

The consistency test coefficients CR of the comprehensive growth index, yield index, seed vigour index, and WNE were less than 0.10, the consistency test results were acceptable, and the established judgment matrix was reliable and reasonable (Table 6, where λmax is the maximum eigenvalue). The results show that the weights of the best indicators of hybrid seed maize were, in descending order, as follows: yield, germination index, germination percentage, ear weight, water use efficiency, dry matter accumulation, vigour index, nitrogen fertilizer agronomic use efficiency, irrigation water use efficiency, and nitrogen fertilizer partial-factor productivity.

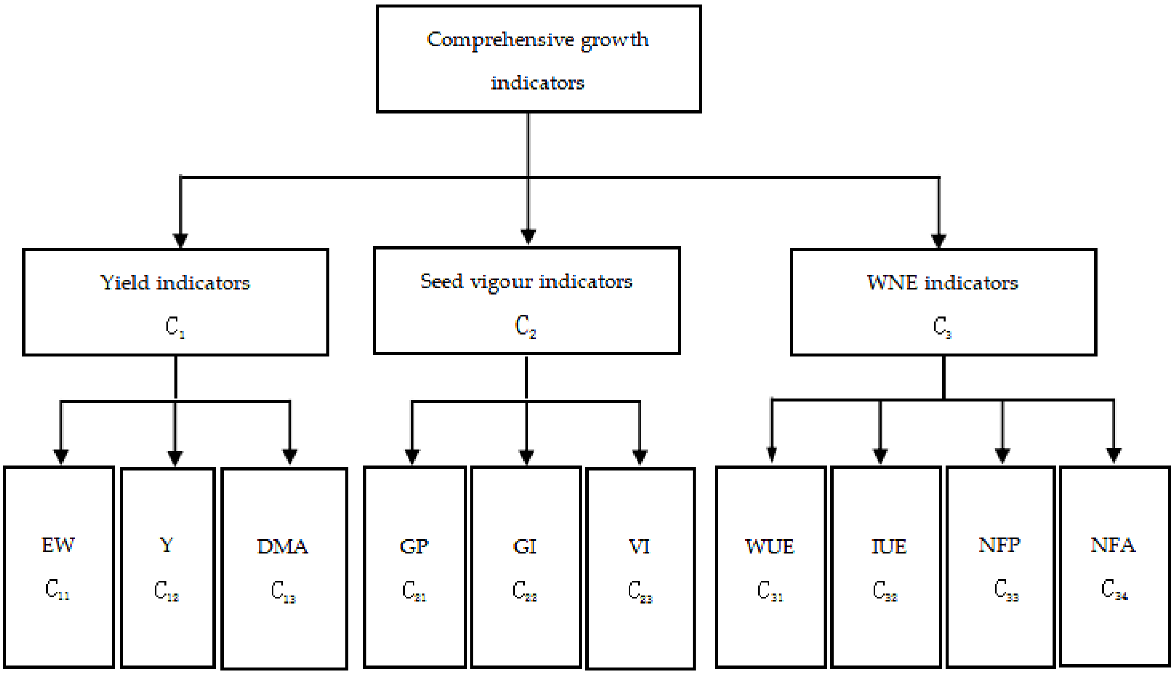

Figure 5. A hierarchical model of comprehensive growth indicators of hybrid seed maize. Note: WNE is the water and nitrogen use efficiency; EW is the ear weight; Y is the yield; DMA is the dry matter accumulation; GP is the germination percentage; GI is the germination index; VI is the vigour index; WUE is the water use efficiency; IUE is the irrigation water use efficiency; NFP is the nitrogen fertilizer partial-factor productivity; NFA is the nitrogen fertilizer agronomic use efficiency.

Table 6. Results of AHP hierarchical analysis for calculating weights.

Hierarchical Structure	Local Weight	Final Weight	Consistency Test Parameter
Target layer C	0.4806 0.4054 0.1140	0.4806 0.4054 0.1140	$C_R = 0.0279 < 0.1$ $\lambda_{max} = 3.0291$
Criterion layer C_1	0.2583 0.1047 0.6370	0.3062 0.2382 0.1311	$C_R = 0.0370 < 0.1$ $\lambda_{max} = 3.0385$
Criterion layer C_2	0.3234 0.5876 0.0890	0.1241 0.0509 0.0503	$C_R = 0.0088 < 0.1$ $\lambda_{max} = 3.0092$
Criterion layer C_3	0.4466 0.2122 0.0896 0.2517	0.0361 0.0287 0.0242 0.0102	$C_R = 0.0577 < 0.1$ $\lambda_{max} = 4.1541$

(2) Determination of weights based on entropy weighting

The entropy weight method was used to assign weights to the single indicators of the success of hybrid seed maize, and the weights decreased in the following order: nitrogen fertilizer agronomic use efficiency, irrigation water use efficiency, nitrogen fertilizer partial-factor productivity, dry matter accumulation, vigour index, germination percentage, water use efficiency, yield, germination index, and ear weight (Table 7).

Table 7. Weights of single indicators of hybrid seed maize determined by the entropy weight method.

Indicators	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{34}
Weights	0.0708	0.0770	0.1062	0.0834	0.0752	0.0974	0.0812	0.1110	0.1077	0.1901

(3) Based on Game Theory

To improve the reliability of the weight assignment values and to avoid the influence of subjective factors on the evaluation, a weight set was constructed on the basis of the two assignment values obtained with the AHP method and the entropy weight method. $w = \sum_{k=1}^{l} \alpha_k \times w_k^T (\alpha_k > 0)$ where a_k is the AHP method; w_k is the entropy weight method.

We obtained a game theory-based weight set model to derive a response model $Min\| \sum_{j=1}^{i} a_j \times u_j^T - u_i^T \|$ i =1, 2. The optimal combination coefficients of the above equation could be obtained using Matlab: a_1 = 0.8391, a_2 = 0.3674, after normalisation a_1^*= 0.6955, a_2^*= 0.3045, This yielded a vector of combined weights as follows: $w^* = \sum_{k=1}^{2} a_k^* \times u_k^T$ (Table 8). The weights of the indicators of hybrid seed maize decreased in the order of ear weight, yield, dry matter accumulation, germination percentage, nitrogen fertilizer agronomic use efficiency, vigour index, germination index, irrigation water use efficiency, water use efficiency, and nitrogen fertilizer partial-factor productivity.

Table 8. Single indicator weights for hybrid seed maize assigned based on game theory.

Indicators	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{34}
Weights	0.2345	0.1891	0.1235	0.1117	0.0583	0.0646	0.0498	0.0538	0.0496	0.0650

3.4.3. Comprehensive Evaluation of Hybrid Seed Maize Based on the TOPSIS Method

The decision matrix was normalised, and the weighting matrix was established based on the TOPSIS comprehensive model with a combined assignment, while the ideal solution and fit (Ci) of the judging indexes were calculated later (Table 9). The Ci value was between 0 and 1, and the larger the value, the stronger the correlation between it and the ideal variety. The results show that the N2W3 (high water and medium nitrogen) treatment had the highest degree of fit for the comprehensive indexes of hybrid seed maize, and the comprehensive evaluation of hybrid seed maize was optimal, followed by the N2W2 (medium water and medium nitrogen) treatment and the N3W3 (high water and high nitrogen); the N1W1 treatment had the smallest degree of fit, indicating that the comprehensive performance of hybrid seed maize was the worst under the conditions of low water and low nitrogen.

3.5. Coupled Water–Nitrogen Response Modelling for Comprehensive Growth of Hybrid Seed Maize

A binary quadratic regression simulation based on the comprehensive growth score of hybrid seed maize and water–nitrogen inputs resulted in a regression model of the comprehensive growth score (y) with the coded values of irrigation amount (x_1) and nitrogen application amount (x_2) as follows:

$$y = 0.194 + 0.707x_1 + 0.803x_2 - 0.324x_1^2 - 0.639x_2^2 - 0.130x_1x_2 \quad (11)$$

The regression equation was tested for significance, and the correlation coefficient, R^2 = 0.998, showed a high degree of fit; F = 158.895, p = 0.001, indicating that the regression relationship reached a highly significant level.

Table 9. Comprehensive indicators of hybrid seed maize based on the TOPSIS method and their ranking.

Treatment	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{34}	D^+	D^-	C_i	Sorted
N1W1	0.3217	0.2933	0.2883	0.2201	0.2324	0.2369	0.2917	0.3049	0.3243	0.2912	0.1098	0.0281	0.2038	9
N1W2	0.3334	0.3419	0.3465	0.2877	0.2941	0.2855	0.3165	0.2889	0.4105	0.2898	0.0725	0.0625	0.4632	6
N1W3	0.3300	0.3180	0.3077	0.3345	0.3356	0.3209	0.3165	0.2636	0.4683	0.3408	0.0606	0.0801	0.5693	4
N2W1	0.3320	0.3224	0.2980	0.2743	0.3021	0.2851	0.3565	0.3955	0.2810	0.3957	0.0800	0.0577	0.4189	7
N2W2	0.3373	0.3490	0.3441	0.3481	0.3679	0.3461	0.3680	0.3622	0.3423	0.4065	0.0419	0.0869	0.6747	2
N2W3	0.3417	0.3620	0.3756	0.4119	0.3904	0.4000	0.3451	0.3076	0.3632	0.3855	0.0320	0.1071	0.7698	1
N3W1	0.3291	0.3205	0.3320	0.3030	0.2971	0.2920	0.3298	0.3901	0.2073	0.2860	0.0879	0.0504	0.3642	8
N3W2	0.3359	0.3317	0.3392	0.3771	0.3637	0.3807	0.3451	0.3582	0.2538	0.2958	0.0613	0.0806	0.5681	5
N3W3	0.3383	0.3556	0.3586	0.3958	0.3836	0.4101	0.3241	0.3023	0.2676	0.2745	0.0614	0.0919	0.5994	3
S^+	0.3417	0.3620	0.3756	0.4119	0.3904	0.4101	0.3680	0.3955	0.4683	0.4065				
S^-	0.3217	0.2933	0.2883	0.2201	0.2324	0.2369	0.2917	0.2636	0.2073	0.2745				

Note: S^+ is the ideal solution, S^- is the inverse ideal solution; D^+ is the distance of each treatment from the ideal solution, D^- is the distance of each treatment from the inverse ideal solution.

3.5.1. Single Factor Effect of Water–Nitrogen

In order to further investigate the effects of single factors on the comprehensive growth of the hybrid seed maize, the established binary quadratic regression model was downscaled to obtain the single-factor equations for the irrigation amount (y_w) and nitrogen application amount (y_n) as follows:

$$y_w = 0.194 + 0.707x_1 - 0.324x_1^2 \quad (12)$$

$$y_N = 0.194 + 0.803x_1 - 0.639x_1^2 \quad (13)$$

The comprehensive score of hybrid seed maize increased with the increasing irrigation amount within the design range of irrigation levels, and the effect of the nitrogen application amount on the comprehensive score of hybrid seed maize was a downward parabola (Figure 6). Overall, the combined scores of hybrid seed maize showed an increasing and then decreasing trend with increasing an irrigation amount or fertilizer application amount, which is consistent with the diminishing reward effect, i.e., the comprehensive scores showed a decreasing trend if the irrigation amount or nitrogen application amount exceeded a certain range. Comprehensive growth scores changed slowly with an increasing irrigation amount while producing more drastic changes with an increasing fertilizer application amount, indicating that the comprehensive growth scores were more sensitive to changes in nitrogen application amount.

3.5.2. Analysis of the Water–Nitrogen Interaction

The growth of hybrid seed maize is influenced by the coupled effects of the irrigation amount and nitrogen application amount. Based on the established regression equations, a three-dimensional plot of the reciprocal effect of irrigation amount and nitrogen application amount on the comprehensive growth indicators of hybrid seed maize was constructed (Figure 7). Based on the regression equation, the highest comprehensive score y = 0.7561 was 0.9851 for x_1 and 0.5281 for x_2, i.e., 3991.07 $m^3 \cdot hm^{-2}$ of the irrigation amount and 290.34 $kg \cdot hm^{-2}$ of the nitrogen application amount.

We divided the closed area of water–nitrogen coupling based on 90% of the maximum comprehensive score, and this closed area appeared at medium to high irrigation levels and medium fertilization levels, indicating that the optimal irrigation and fertilizer intervals for agricultural production were between 3558.90 and 3971.64 $m^3 \cdot hm^{-2}$ of the irrigation amount and 262.20 and 320.53 $kg \cdot hm^{-2}$ of the nitrogen application amount, respectively, and this water–nitrogen combination was the most favourable for achieving the high yield and high efficiency of hybrid seed maize.

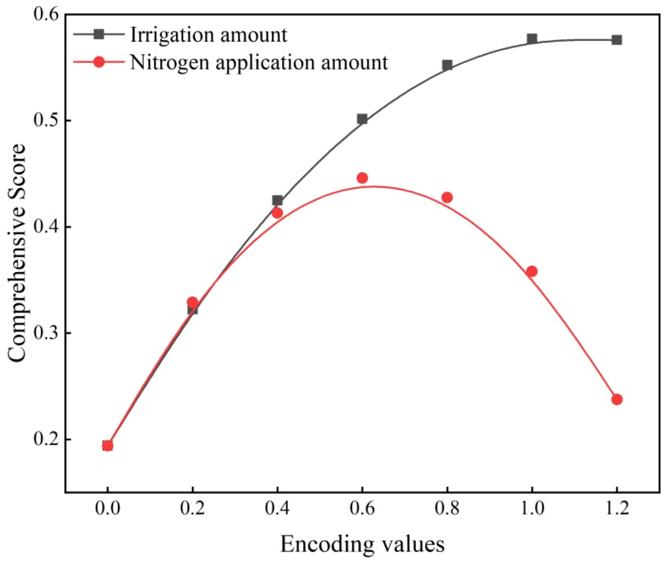

Figure 6. The effect of single factors on the comprehensive score of hybrid seed maize.

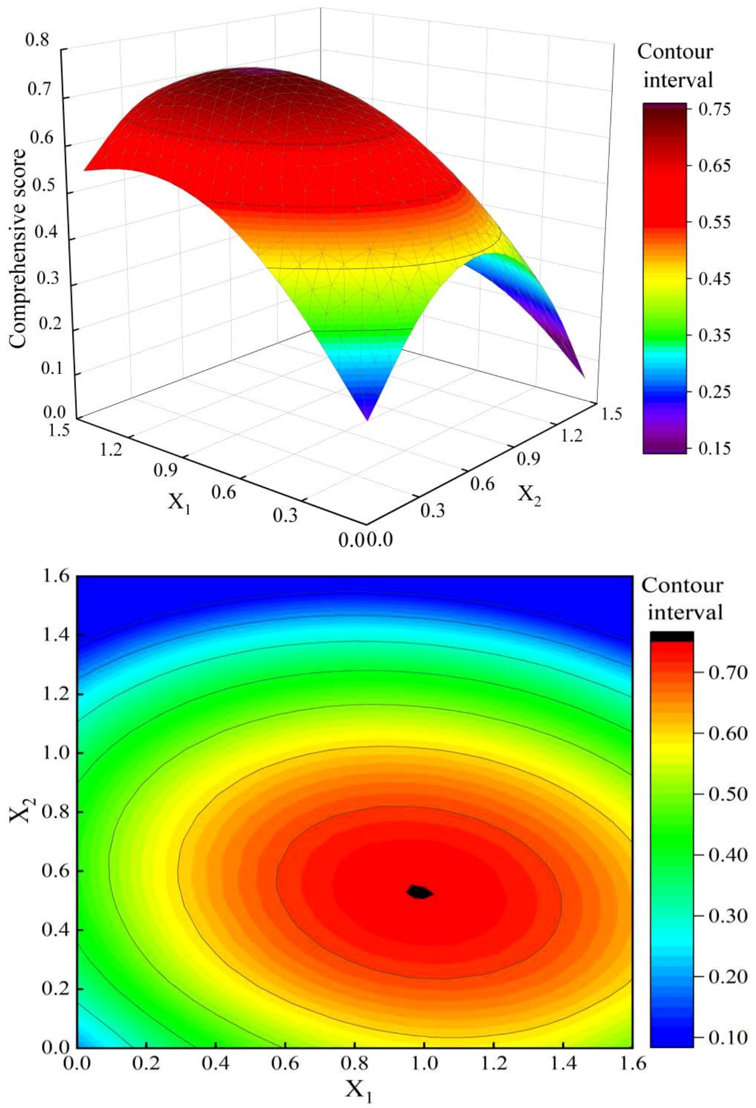

Figure 7. The effect of water–nitrogen coupling on the comprehensive growth of hybrid seed maize.

4. Discussion

Seed vigour is one of the most important indicators of seed quality and is closely related to crop yield [35,36]. The optimisation of water and nitrogen supply can maintain a high vigour of maize seeds, which is a prerequisite for high yield and the quality of hybrid seed maize. Shi et al. [18] showed, however, that higher soil moisture could reduce hybrid maize seed vigour. Lian et al. [36], showed that the germination percentage and vigour index of hybrid seed maize in the medium water treatment (irrigation quota of 480 $m^3 \cdot hm^{-2}$) increased by 0.27–2.22% and 8.62–41.52%, respectively, compared with other irrigation treatments, and the germination percentage and vigour index of the medium nitrogen treatment (nitrogen application amount of 240 $kg \cdot hm^{-2}$) increased by 2.88~3.61%, and 13.50~19.60%, respectively, compared with other nitrogen application treatments; the excessive irrigation amount and nitrogen application amount inhibited seed vigour. The results of this study reflect the findings of the above studies [18,36], indicating that both the irrigation amount and nitrogen application amount had significant effects on the seed vigour of hybrid seed maize and that the optimum water–nitrogen combination was N2W3, in which the germination percentage, germination index, and vigour index increased compared with the other treatments.

Water and nitrogen are involved in most plant metabolic processes and are two essential elements for plant growth and development [37,38]. Appropriate water and nitrogen supply is the basis and key to achieving increased maize yield [39]; both the irrigation amount and nitrogen application amount can significantly increase maize kernel yield, and there is a significant interaction between the two [40]. Mamdouh et al. [41] showed that nitrogen application compensated for the effects of reduced maize yields due to water deficits, and the optimum water–nitrogen combination treatment could also increase yields by 14.9 to 92.3% over other irrigation and nitrogen application combinations. Wang et al. [9] confirmed that the coupled effect of water–nitrogen could significantly increase maize yield in the arid area of northwestern China.

The results of this study show that reasonable irrigation and nitrogen application can significantly increase the yield of hybrid seed maize, and this yield increased with the increase in the irrigation amount under the same level of nitrogen application except when the irrigation amount exceeded the optimal irrigation quota as the increase in yield gradually decreased. The results of this study are similar to those of a previous study [42,43], which further confirmed that the coupling effect of water and nitrogen can significantly increase the yield of hybrid seed maize, with variability due to the differences in climate, water–nitrogen management measures, and crop varieties. This study also showed that different water–nitrogen combination treatments could optimise the ear components of hybrid seed maize, promote dry matter mass accumulation, and improve the weight of 100 kernels, with maximum values obtained in high water and medium nitrogen combinations, consistent with the findings of Lakshmi [44]. Qi [45] et al. reported that water–nitrogen improves maize ear components, enhances kernel weight, and promotes dry matter accumulation.

Improving crop yield and water–nitrogen use efficiency is a common goal of agricultural producers and researchers, and it is also an important method to ensure food security and sustainable development of agriculture, especially in the Hexi Corridor area, where water scarcity and the inefficient use of agricultural resources limit seed and food production [5]. Water–nitrogen use efficiency is an important index that is directly related to high yield and the efficiency of maize [46,47], and appropriate water–nitrogen ratios can improve it greatly [48]. The results of this study show that the water consumption of hybrid seed maize increases with the increase in the irrigation and nitrogen application level, which is consistent with the findings of Qi et al. [49]. The results of this experiment showed that both excessive irrigation and nitrogen application reduced the WNE of maize, which is in agreement with the findings of Rudnick [50] and Yang [51]. At the same irrigation level, IUE gradually increased with increasing nitrogen application; nitrogen fertilizer application promoted maize growth and development and increased WUE but also reduced NFP, while excessive nitrogen application led to a reduction in WUE and NFA as well: a finding that was confirmed in the study by Momen et al. [52].

Most of the studies on water–nitrogen coupling in maize have focused on grain-feeding maize or subjective or objective evaluations only for one or more indicators [53–55]; however, the field management process for hybrid seed maize is complex and cumbersome, and it is unclear whether hybrid seed maize responds to optimal nitrogen fertilizer management in the same way as ordinary maize. In this study, we used the AHP method, entropy weight method, and a hierarchical combination assignment method based on the combinatory game theory in TOPSIS evaluation to achieve the high yield and high efficiency of the comprehensive indexes of hybrid seed maize. The results show that the best water and nitrogen combination for the highest comprehensive growth score of hybrid seed maize was N2W3. At the same time, we concluded, based on the fit for a regression equation of water–nitrogen coupling for hybrid seed maize, that the comprehensive growth of hybrid seed maize with an increase in water–nitrogen inputs was a parabola with a downward opening, and it illustrated that the hybrid seed maize reached the best comprehensive growth under the conditions of a medium–high level of irrigation and a medium level of nitrogen application; furthermore, excessive water–nitrogen inputs were detrimental to the comprehensive growth of hybrid seed maize, which is in line with the results of previous studies [56,57]. Critical irrigation quotas and nitrogen application amounts are important guides for determining comprehensive maize growth and predicting yield.

5. Conclusions

Irrigation and nitrogen application rates had significant interaction effects on the yield, seed vigour, and water and nitrogen use efficiency of hybrid seed maize. The water demand of hybrid seed maize could be satisfied as the irrigation quota was 100% of the local traditional irrigation quota, the nitrogen application rate of 285 $kg \cdot hm^{-2}$ was conducive to the promotion of the nitrogen accumulation of hybrid seed maize, with the higher partial productivity of the nitrogen fertilizer and nitrogen fertilizer agronomic use efficiency, including the better number of grains in the ears of a single plant and the single weight of an ear compared with other nitrogen application treatments. Considering the three evaluation indexes of yield, seed vigour, and water and nitrogen use efficiency, the N2W3 treatment is the most suitable water and nitrogen combination model for hybrid seed maize in this study area. However, this study only determined a different irrigation amount and nitrogen application amount level treatments, and no in-depth study on the effects of irrigation amount and N, P, and K application ratios on the growth of hybrid seed maize. Further studies need to quantify irrigation and fertiliser application ratios in the future and provide more scientific and reasonable irrigation and fertiliser application regimes for hybrid seed maize in the oasis agricultural areas of the Hexi Corridor in China.

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