

# Coupling model and optimal combination scheme of water, fertilizer, dissolved oxygen and temperature in greenhouse tomato under drip irrigation

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**Abstract:** Water-fertilizer coupling technology has been widely used in the world. Poor soil aeration, low temperature or high temperature can affect the rate of nutrient uptake by crop roots. Aiming at the interaction between water, fertilizer, dissolved oxygen and temperature (WFOT) coupling model and irrigation flux of tomato in greenhouse, using these four factors with a five-level uniform-precision rotatable central composite design, a mathematical model was established among the four factors affecting tomato yield in a greenhouse, and the optimal combination scheme of WFOT was obtained. Within the test range, tomato yields increased with increasing irrigation quotas ( $X_1$ ), fertilization amount ( $X_2$ ), dissolved oxygen ( $X_3$ ) and geothermal pipe water temperature ( $X_4$ ). The magnitude of the effect of each factor of WFOT on tomato yield was in the following order:  $X_1, X_2, X_4, X_3$  (spring and summer), and  $X_1, X_3, X_2, X_4$  (autumn and winter). The interaction between high water-low heat and low water-high heat was beneficial for yield increase (spring and summer), the high fertilizer-low heat and low fertilizer-high heat interactions were beneficial to yield increase (autumn and winter). If WFOT agronomic measures were adopted according to the 95% confidence interval, there was a 95% probability that the spring-summer tomato yield will be higher than 89902 kg/hm<sup>2</sup>. The WFOT coupling scheme was  $X_1$  of 4808-5091 m<sup>3</sup>/hm<sup>2</sup>,  $X_2$  (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) of 171-57-84 to 186-62-89 kg/hm<sup>2</sup>,  $X_3$  of 7.9-8.2 mg/L, and  $X_4$  of 34.9 °C-37.0 °C. There was a 95% probability of tomato yield higher than 85209 kg/hm<sup>2</sup> in autumn and winter, and the WFOT coupling scheme was  $X_1$  of 5270-5416 m<sup>3</sup>/hm<sup>2</sup>,  $X_2$  (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) of 151-50-76 to 167-56-82 kg/hm<sup>2</sup>,  $X_3$  of 8.0-8.2 mg/L, and  $X_4$  of 34.1 °C-36.2 °C. Overall, and the model had a very good simulation effect, with application value. The relative error between spring-summer and autumn-winter yields ranged from 1.12% to 25.34%. The results of the study can provide a theoretical basis for improving the quality and efficiency of greenhouse tomatoes.

**Keywords:** aeration irrigation, soil warming, water-fertilizer-dissolved oxygen-temperature coupling model, optimal combination scheme

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## 1 Introduction

Crops require water, fertilizer, oxygen, and heat to grow. Maintaining a proper temperature along with soil moisture, fertility, and permeability is necessary at any stage of crop growth. Poor soil ventilation leads to excessive carbon dioxide concentrations in the soil, and anaerobic respiration is formed over a longer period, further hindering root water absorption. Low temperature weakens root respiration and affects root water absorption. Therefore, under the premise of the universal application of water and fertilizer coupling technology, it is necessary to study the mechanism of the comprehensive regulation of water, fertilizer, air and heat in the greenhouse under drip irrigation on crops. Tomato

is one of the most consumed vegetable crops in the world<sup>[1,2]</sup>. Tomatoes contain minerals, vitamins, polyphenols and lycopene, which have beneficial effects on human health<sup>[3]</sup>.

**Water-Fertilizer Coupling:** Tian et al.<sup>[4]</sup> determined the optimal water and fertilizer combination scheme for alfalfa under different target yields based on a three-factor quadratic regression general rotation combination design test. Ma et al.<sup>[5]</sup> obtained the optimal combination of water and fertilizer for different yield targets, and the optimal combination of factors under different yield levels of watermelon in sand-pressed land by adopting a three-factor five-level quadratic regression general rotation combination design method. He et al.<sup>[6]</sup> used a universal rotating combination design test method to establish a water-fertilizer coupling model for rice under drip irrigation. It showed that the influencing significance of the three factors on yield increases in a descending order were irrigation amount, nitrogen application amount, and phosphorus application amount. Yin et al.<sup>[7]</sup> used a quadratic orthogonal rotational combination design to obtain the optimal combination scheme for mung beans, which was validated in 2016-2017 using optimal fertilization measures, and the results showed a 19.6% increase in yield over conventional fertilization.

**Water-Air Coupling:** With the same irrigation frequency and amount, Wen et al.<sup>[8]</sup> showed that the plant height, stem diameter,

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and yield of aerated and irrigated plants increased by 1.44%, 3.02%, and 19.49%, respectively. Aerated irrigation has been shown to have significant effects on soil enzyme activity and microbial populations<sup>[9]</sup>. Injecting air into the soil with high volume water content is beneficial to increasing pepper yield<sup>[10]</sup>. Li et al.<sup>[11]</sup> showed that the optimal treatment combination involved the use of a drip irrigation zone at a depth of 25 cm, with ventilation once per day, and the upper limit of irrigation control is 70% of field water holding capacity. Zhu et al.<sup>[12]</sup> showed that aerated irrigation effectively improved soil aeration, while the content of lycopene, vitamin C, soluble sugar, and sugar-to-acid ratio in tomato fruit increased significantly by 73%, 31.43%, 32.30%, and 45.64%, respectively. A three-dimensional greenhouse cultivation of oil and wheat lettuce test demonstrated that 7.4 mg/L dissolved oxygen provided the best combination when using an irrigation amount of 45 m<sup>3</sup>/hm<sup>2</sup><sup>[13]</sup>. Meanwhile, Zhu et al.<sup>[14]</sup> showed that with subsurface drip irrigation, soil microbial respiration increased significantly by 11.5% ( $p < 0.05$ ), while soil oxygen content, soil respiration, temperature, and plant root respiration all increased when compared with above-ground drip irrigation. Infiltration irrigation using aerated water can achieve a high water-conserving yield in greenhouse celery<sup>[15]</sup>. The injection of oxygenated water into the rhizosphere in underground cavities can promote the growth of grapes and improve the photosynthetic efficiency of the leaves<sup>[16]</sup>. In that study, the use of a 15 N tracer indicated that the injection of oxygenated water did not affect the preference of grape roots for nitrate-nitrogen. Therefore, nitrate-nitrogen should be selected as a nitrogen fertilizer in underground cavities. Ben-Noah et al.<sup>[17]</sup> discussed factors affecting aeration and proposed active soil aeration ("oxidation") practices. Chen et al.<sup>[18]</sup> showed that aerated irrigation significantly increased tomato yield by 32.0% and water use efficiency (WUE) by 32.0%. Aerated irrigation was beneficial to increase crop yield and WUE of tomato (average increases of 19.3% and 17.9%, respectively<sup>[19]</sup>). Chen et al.<sup>[20]</sup> showed that when compared with non-aeration, the tomato yield under each irrigation condition increased by 18.8% on average, and the difference after full irrigation was significant ( $p < 0.05$ ). Rhizosphere aeration can increase plant photosynthesis as well as soil urease and nitrate reductase activities but has a negative effect on the absorption of urea, indicating that there is no synergy between rhizosphere aeration and urea application<sup>[21]</sup>. Ouyang et al. studied the influence mechanism of dissolved oxygen in different irrigation water on greenhouse tomatoes and climate box lettuce by micro-nano aeration<sup>[22,23]</sup>. Li et al.<sup>[24]</sup> introduced and analyzes the mechanism of hypoxia stress in the root zone, and provides an overview about characteristics and application on air-jection irrigation. The mechanism of regulating soil environment by aerated water drip irrigation and the fact that aerated water drip irrigation changes soil structure are presented<sup>[25]</sup>. Oxygenated irrigation of rice<sup>[26]</sup>, potatoes<sup>[27,28]</sup>, Komatsu<sup>[29]</sup> and irrigation with treated wastewater<sup>[30]</sup> has been studied, and Two-phase flow problems in aerated subsurface irrigation was studied<sup>[31]</sup>.

**Water-Heat coupling:** The range of temperature for irrigation water of 25 °C-45 °C promoted tomato seedling growth and increased the growth potential of plants to different extents, Warm water irrigation at 35 °C worked best<sup>[32]</sup>. Li et al.<sup>[33]</sup> showed that using warm water to irrigate greenhouse cucumber seedlings can increase stem diameter, leaf area, root coefficient, photosynthetic rate, dry matter quality per unit fresh mass, root-shoot ratio, and the seedling index. The use of heated irrigation water using heated

water alone or with film mulching or with film mulching alone increased yield by 3.9%, 10.6%, and 11.1%, respectively<sup>[34]</sup>. In addition, Zhang et al.<sup>[35]</sup> showed that the effect of integrated irrigation water temperature on the growth, yield, and photosynthesis of leaf lettuce was suitable at 25 °C-30 °C. Deng et al.<sup>[36]</sup> showed that under the same irrigation water temperature, the temperature range of the vegetable root zone was in a descending order at the depths of 10 cm, 20 cm, and 30 cm.

**Water-Fertilizer-Air-Heat coupling:** By using four factors and three levels of orthogonal design to study the effect of water-fertilizer-air-heat coupling on cucumber, Zhang<sup>[37]</sup> obtained the optimal combination for greenhouse cucumber yield: the irrigation, fertilization, and dissolved oxygen amounts, and geothermal heat pipe temperature were 165 m<sup>3</sup>/hm<sup>2</sup>, 120 kg/hm<sup>2</sup>, 8 mg/L, and 35 °C, respectively. Similarly, Ouyang<sup>[38]</sup> used a four-factor five-level quadratic general rotation combination design to obtain a water-fertilizer-air-heat coupling scheme for greenhouse watermelon and found a vitamin C mass fraction greater than 13.6 mg/100 g with the following conditions: irrigation, fertilization, and dissolved oxygen amounts, and geothermal tube water temperature of 5192-5353 m<sup>3</sup>/hm<sup>2</sup>, 76.62-88.44 kg/hm<sup>2</sup>, 7.42-7.58 mg/L, and 29.22 °C-30.78 °C, respectively. The research team of Professor Tian Juncang of Ningxia University carried out water-fertilizer-gas-thermal coupling irrigation research on greenhouse cucumber<sup>[37]</sup>, tomato<sup>[39]</sup>, watermelon<sup>[38]</sup>, melon<sup>[40]</sup> and pepper<sup>[41]</sup>, respectively. The optimal combination schemes were obtained by orthogonal design and quadratic general rotary design, and many fruitful research results were obtained.

In summary, several types of coupling have been studied worldwide including water-fertilizer coupling, water-air coupling, water-heat coupling, and the water-fertilizer-dissolved oxygen-temperature (WFOT) coupling irrigation. However, the mechanism, model, and optimal combination scheme of WFOT coupling irrigation in a greenhouse and the resulting increase in yield remains unclear. Taking WFOT coupling irrigation flux interaction as the scientific problem, the aim is to establish a WFOT coupling model for greenhouse tomato, to obtain a WFOT coupling scheme, to reveal its water, fertilizer, gas and heat demand rules, and thus to provide a theoretical basis for greenhouse tomato quality and efficiency improvement.

## 2 Materials and methods

### 2.1 Experimental site

The experiment was located in a non-cultivated solar-heated greenhouse (7 m×75 m) in Xinrong Village, Hongguang Town, Helan County, Yinchuan City, Ningxia Hua Autonomous Region, China (38°30'N, 106°07'E), at an elevation of 1111.5 m. The test area is in a temperate continental climate, with an average annual temperature of 9.7 °C, a maximum temperature of 36.90 °C, a minimum temperature of -24 °C, annual precipitation of 138.8 mm, an annual evaporation rate of 1111.9 mm, a frost-free period of approximately 185 d, and an air relative humidity of 60%-70%. The total annual sunshine duration was 2935.5 h. climatic variations were monitored by means of a portable meteorological station installed near the experimental area. The experimental field soil was sandy loam with a water holding capacity of 18.88% (based on mass) and the soil bulk density of the 0-40 cm soil layer was 1.413 g/cm<sup>3</sup>. The tested irrigation water was purified by treatment with reverse osmosis equipment independently developed by Ningxia University. Purified water was used as irrigation water. The purified water pH is 6.88, the salinity is 447.10 mg/L,

the total hardness is 16.10 mg/L, the COD is 21.30 mg/L, the permanganate index is 6.10 mg/L, the nitrate 1.83 mg/L, the ammonia nitrogen is 0.06 mg/L. The underground brackish water pH is 8.08, the salinity is 2895.40 mg/L, the total hardness is 441.50 mg/L, the COD is 40.20 mg/L, the permanganate index is

11.50 mg/L, the nitrate 2.83 mg/L, the ammonia nitrogen is 0.21 mg/L. The soil (0-20 cm) pH was 8.53, the total salt was 0.50 g/kg, the organic matter was 17.46 g/kg, the alkali nitrogen was 67.16 mg/kg, the available phosphorus was 96.99 mg/kg, the available potassium was 402.50 mg/kg.

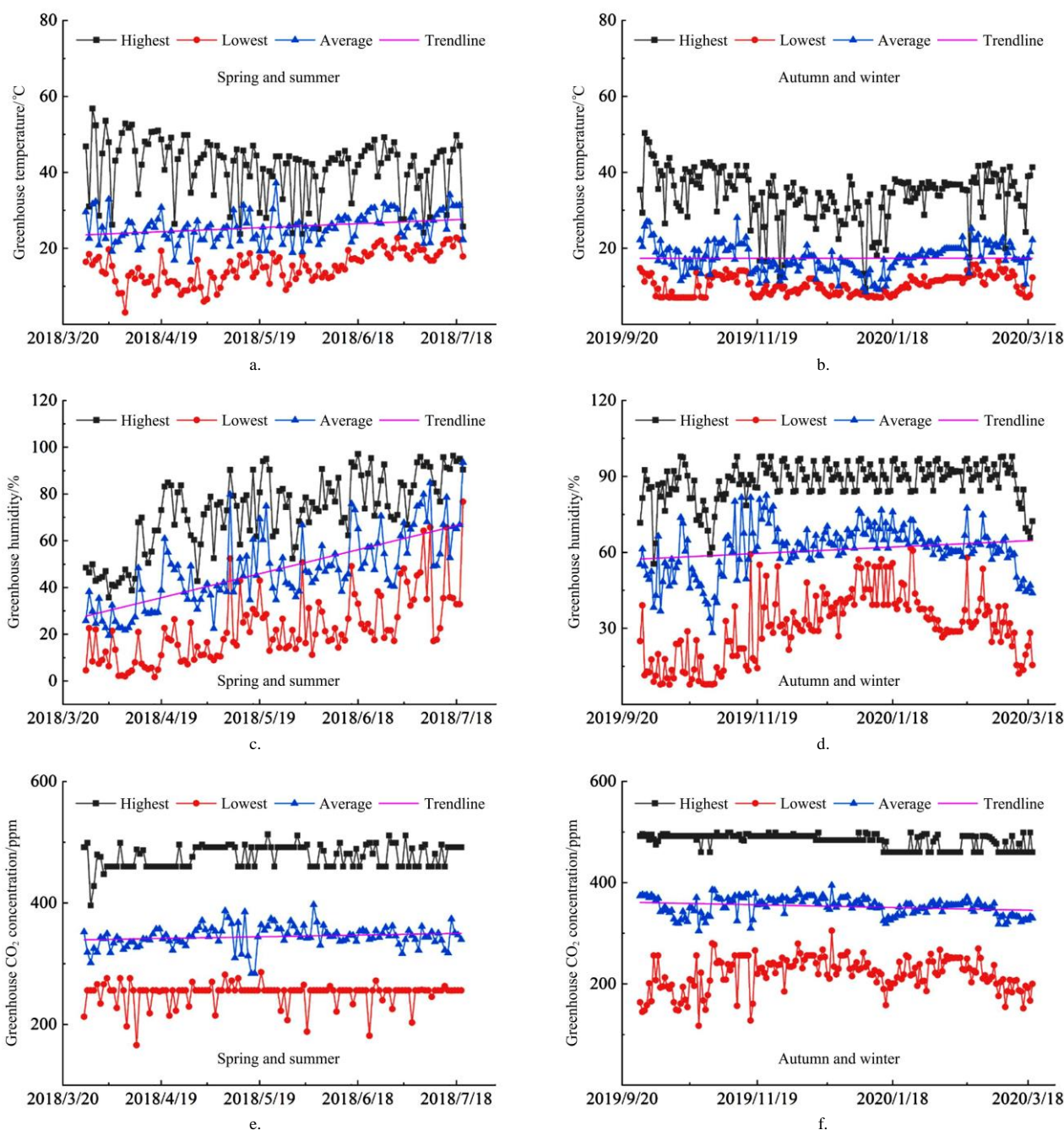


Figure 1 Changes of daily average temperature (a-b), humidity (c-d), and CO<sub>2</sub> concentration (e-f) in the greenhouse with time

## 2.2 Experimental design

The experiment employed drip irrigation conditions under a plastic membrane, using a four-factor five-level uniform-precision rotatable central composite design (1/2 implementation); the four factors were irrigation amount ( $X_1$ ), fertilization amount ( $X_2$ ), dissolved oxygen ( $X_3$ ), and geothermal tube water temperature ( $X_4$ ). For each of these four factors, five levels were used: +1.682, +1, 0, -1, and -1.682. These were repeated three times for each treatment, creating a total of 60 treatments. The control treatment (CK) was T17-T20. The purpose of the experiment was to observe the effects of various treatments on tomato yield by analyzing the effects of the four factors ( $X_1$ ,  $X_2$ ,  $X_3$ , and  $X_4$ ) on tomato yield, and

to establish a mathematical model of the effects of WFOT coupled irrigation. Through the analysis of the model, the factors and characteristics of various factors and interactions that affect greenhouse tomato yield were obtained. By optimizing the model, the optimal WFOT coupling scheme under different target yields was obtained, and the efficiency of use of all four factors listed above was improved. This resulted in increased yield and economic benefits for tomatoes grown in non-cultivated greenhouses.

The  $X_1$ ,  $X_2$ ,  $X_3$ , and  $X_4$  were determined according to the actual amounts typically used during local agricultural production. Table 1 provides the lower and upper limits for all four factors along with the amounts for each level.

**Table 1 Four factor five-level quadratic general rotation combination design test factors and horizontal code**

Level $X_j$ ( $\gamma=1.682$ )	Irrigation amount $X_1$ / $m^3 hm^{-2}$	Fertilization amount $X_2$ ( $N-P_2O_5-K_2O$ ) / $kg hm^{-2}$	Dissolved oxygen $X_3$ / $mg L^{-1}$	Geothermal pipe water temperature $X_4$ / $^{\circ}C$
+ $\gamma$	5760	225-75-105	9	45
+1	5176	195-65-93	8.4	41
0	4320	150-50-75	7.5	35
-1	3464	105-35-57	6.6	29
- $\gamma$	2880	75-25-45	6	25
Change interval ( $\Delta_j$ )	856	45-15-18	0.9	6

The zero level ( $X_{pj}$ ) and the change interval ( $\Delta_j$ ) of each factor were calculated using Equations (1) and (2), respectively:

$$X_{pj} = (X_{1j} + X_{2j}) / 2 \quad (1)$$

$$\Delta_{pj} = (X_{2j} - X_{1j}) / \gamma \quad (2)$$

where,  $X_{1j}$  and  $X_{2j}$  represent the lower and upper limit of each factor, respectively;  $j$  is the number of factors ( $j=1, 2, 3, \text{ or } 4$ );  $m_c = 2^{m-1}$  (1/2 implementation),  $\gamma = 2^{(m-1)/4}$ ,  $m=4$ ,  $m_c=8$ ,  $\gamma=2^{3/4}=1.682$ , and  $\gamma$  is the star arm and  $m$  is the factor number.

### 2.3 Experiment implementation

Tomato cultivar (*Solanum Lycopersicum* L. 'Daier No. 1689') plants were grown in the greenhouse. According to local production practices, the tomato seedlings were transplanted from humus pots when they had 3 to 4 leaves. The two-year experiment of tomato was conducted in spring and summer (from March 26 to July 22, 2018) and autumn and winter (from September 28, 2019 to March 20, 2020), and the whole growth period was 119 days and 177 days, respectively. Each test treatment corresponds to a 5.5 m long  $\times$  1.4 wide ridge, with an area of 7.7 m<sup>2</sup>. The plant spacing, row spacing, and plant density were 0.45 m, 0.30 m, and 31 185 plants/hm<sup>2</sup>, respectively.

A plastic film was installed to a depth of 50 cm between different treatments, and the bottom and both sides were given an anti-seepage treatment. Under the film, two parallel inner-mounted drip irrigation belts were arranged in each plot 0.40 m apart using irrigation tube diameters of 16 mm, a distance

between drip heads of 0.15 m, and a flow rate of 2 L/h.

Irrigation water was applied as follows: 133 m<sup>3</sup>/hm<sup>2</sup> on the day before planting, 267 m<sup>3</sup>/hm<sup>2</sup> at the time of planting, 133 m<sup>3</sup>/hm<sup>2</sup> at the young seedling stage, and six times during the young seedling stage. The experiments were conducted on April 18, 2018. Tomato was irrigated 30 times during the whole growth period (including 6 times at the seedling stage), each irrigation was carried out according to the original test protocol, with irrigation at intervals of 5-7 d.

Base fertilizer and top dressing: The amount of fertilizer was determined based on the nutrient balance method, which is based on the difference between the target yield fertilizer requirement and the amount of fertilizer available in the soil. Nitrogen, phosphorus, and potassium for drip irrigation fertilization were urea (N 46%), diammonium phosphate (N 16%, P<sub>2</sub>O<sub>5</sub> 44%), and potassium sulfate (K<sub>2</sub>O 22%), respectively, and the amount of fertilizer for nitrogen, phosphorus and potassium was as shown in Table 1, and fertilizer was applied five times, and fertilizer was applied during the critical period of tomato fertilizer requirement.

Water with dissolved oxygen was used for irrigation water. The irrigation water was recharged with dissolved oxygen by a combination of a micro-nano bubble generating device and a different gas stone aeration pump, this aerated irrigation occurred 15 times during the entire growth period.

A 20 cm polyethylene geothermal pipe was buried in the middle of each test area. The water tank was heated by solar energy, and the water in the geothermal pipe was heated by electric heating in each cell using an automatic temperature control; the two heating methods were comprehensively controlled to supply the geothermal heat pipe with water at the required temperature. The pipe was connected to a circulating pump near the water tank allowing the geothermal water to circulate. The heating treatment was 96 d and 130 d for the whole experimental cycle of spring-summer and autumn-winter tomatoes, respectively.

Other field management was carried out based on traditional local greenhouse cultivation management techniques.

A schematic of WFOT coupling test setup in greenhouse-grown tomatoes under drip irrigation is presented in Figure 2.

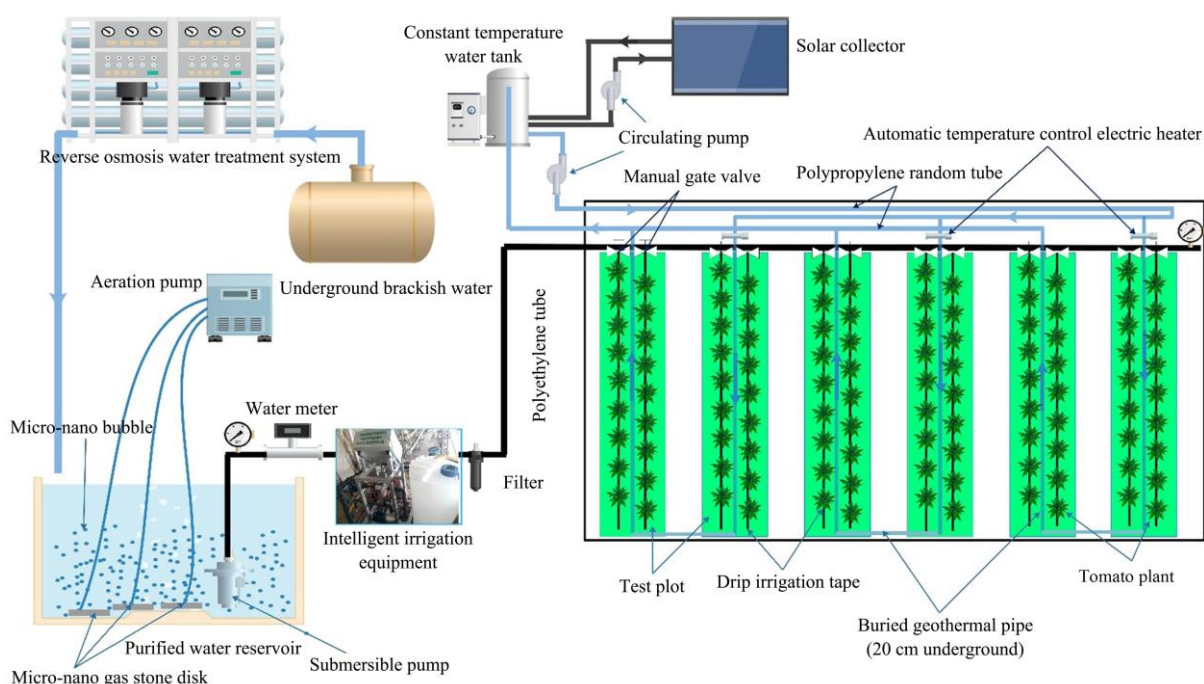


Figure 2 Schematic diagram of greenhouse vegetable water-fertilizer-dissolved oxygen-temperature coupled irrigation test

## 2.4 Measurement items and methods

**Irrigation water:** Purified water treated by a reverse osmosis system independently developed by Ningxia University was placed in a reservoir. This was pressurized by a submersible pump and moved into the main, branch, and capillary drip irrigation pipes using a rotary pipe water meter. A venturi fertilizer applicator and filter were sequentially installed at the head end of the main pipe. The amount of irrigation could be read by a rotary vane.

**Dissolved oxygen:** After aeration, the amount of dissolved oxygen in irrigation water was measured using a JPB-607 dissolved oxygen analyzer.

**Geothermal pipe water temperature:** The water temperature of the geothermal pipes heated by solar energy was controlled by an automatic temperature control mechanism.

**Yield:** Tomatoes were picked at maturity and weighed one by one in the test plots, and the sum of the tomatoes produced in each plot of each crop was the yield of that plot.

**Soil nutrients:** Before the test, the soil was collected for the measurement of the initial soil nutrient levels. For each treatment, soil samples were collected at a depth of 0-20 cm. The indicators mainly included: pH, total salt, organic matter, available phosphorus, available potassium, and alkali nitrogen. The pH was measured by a pH meter and is calibrated according to the manufacturer's guidelines before measurement. Total salt was measured by a conductivity meter. The potassium dichromate

method was used to measure the organic matter content of the soil. Available phosphorus, available potassium, and alkaline nitrogen were measured by the sodium bicarbonate, flame photometry, and diffusion methods, respectively.

**Data processing:** Excel 2019 software was used for data sorting, and Data Processing System (DPS) software 18.10 (Hangzhou Ruifeng Information Technology Co., Ltd., China) was used for variance analysis, single-factor analysis, interaction effect analysis, and simulation optimization. Origin 2021 software (OriginLab Corporation, USA) was used for drawing.

## 3 Results and analysis

### 3.1 Establishment of the model

Using the measured production results in Table 2, The actual yield used to establish the model was the average of three replicates. Data Processing System version 18.10 was used to calculate the WFOT coupled model used for greenhouse-grown tomato using Equation (3) and Equation (4):

$$Y_1 = 78193 + 14314X_1 + 11458X_2 + 5482X_3 + 7170X_4 - 460X_1^2 - 492X_2^2 - 1935X_3^2 - 2195X_4^2 - 6167X_1X_2 + 1508X_1X_3 - 7944X_1X_4 - 806X_2X_3 - 1442X_2X_4 + 591X_3X_4 \quad (3)$$

$$Y_2 = 72588 + 12537X_1 + 6033X_2 + 6351X_3 + 4889X_4 + 2483X_1^2 - 37X_2^2 - 221X_3^2 - 449X_4^2 - 2141X_1X_2 + 3163X_1X_3 - 4615X_1X_4 + 1222X_2X_3 - 6062X_2X_4 + 478X_3X_4 \quad (4)$$

**Table 2 Structure matrix and yield of current rotary composite design method of square regression with four factors and five level**

Treatment	Single item				Interaction term							Quadratic term				Yield/kg hm <sup>-2</sup>		Relative error/%
	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>1</sub> X <sub>2</sub>	X <sub>1</sub> X <sub>3</sub>	X <sub>1</sub> X <sub>4</sub>	X <sub>2</sub> X <sub>3</sub>	X <sub>2</sub> X <sub>4</sub>	X <sub>3</sub> X <sub>4</sub>	X <sub>1</sub> <sup>2</sup>	X <sub>2</sub> <sup>2</sup>	X <sub>3</sub> <sup>2</sup>	X <sub>4</sub> <sup>2</sup>	Y <sub>1</sub>	Y <sub>2</sub>		
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	93 805	95 981	2.32	
2	1	1	-1	1	1	-1	1	-1	1	-1	1	1	1	1	82 783	71 464	13.67	
3	1	-1	1	-1	-1	1	-1	-1	1	-1	1	1	1	1	85 203	84 251	1.12	
4	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	73 318	66 533	9.26	
5	-1	1	1	-1	-1	-1	1	1	-1	-1	1	1	1	1	61 858	70 254	13.57	
6	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	1	1	59 232	60 300	1.80	
7	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	1	1	59 631	71 426	19.78	
8	-1	-1	-1	1	1	1	-1	1	-1	-1	1	1	1	1	51 416	64 447	25.34	
9	-1.682	0	0	0	0	0	0	0	0	0	2.828	0	0	0	55 935	60 339	7.87	
10	1.682	0	0	0	0	0	0	0	0	0	2.828	0	0	0	104 080	102 509	1.51	
11	0	-1.682	0	0	0	0	0	0	0	0	0	2.828	0	0	60 648	64 150	5.77	
12	0	1.682	0	0	0	0	0	0	0	0	0	2.828	0	0	99 187	84 444	14.86	
13	0	0	-1.682	0	0	0	0	0	0	0	0	0	2.828	0	63 610	65 580	3.10	
14	0	0	1.682	0	0	0	0	0	0	0	0	0	2.828	0	88 062	81 971	6.92	
15	0	0	0	-1.682	0	0	0	0	0	0	0	0	0	2.828	63 043	64 910	2.96	
16	0	0	0	1.682	0	0	0	0	0	0	0	0	0	2.828	87 161	81 353	6.66	
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79 280	73 795	6.92	
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	78 842	73 125	7.25	
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	76 589	71 503	6.64	
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70 756	67 679	4.35	

Note: Y<sub>1</sub> and Y<sub>2</sub> are tomato yields in spring-summer and autumn-winter, respectively, kg/hm<sup>2</sup>. Relative error=|Y<sub>1</sub>-Y<sub>2</sub>|/Y<sub>1</sub>.

The yields of the treatments differed, with the yield of treatments T10 and T9 having the largest and smallest yields, respectively. The yield of tomatoes in spring-summer and autumn-winter T10 (optimal treatment) increased by 36.32% and 43.32%, respectively, compared to the control treatment (CK). Shang et al.<sup>[42]</sup> showed that under coupled water-fertilizer-gas conditions, aerated treatment increased tomato yields by an average of 10.4% compared to non-aerated treatment.

### 3.2 Significance test of the model

The significance test of the model showed that the regression term  $p=0.020<0.05$  (spring and summer), the misfit term  $p=0.105>0.05$  (spring and summer), the coefficient of determination  $R^2=0.95$  (spring and summer), the regression term  $p=0.010<0.05$  (autumn and winter), the misfit term  $p=0.130>0.05$  (autumn and winter), and the coefficient of determination  $R^2=0.96$  (autumn and winter), then it showed that the model established based on the experimental

data was reliable and has application value. The results of the significance test of the model coefficients are listed in Table 3.

**Table 3 Coefficient of regression by *t*-test results**

Variables	Spring and summer				Autumn and winter				
	Regression coefficient	<i>t</i> -test value	<i>p</i> -value	Significance	Regression coefficient	<i>t</i> -test value	<i>p</i> -value	Significance	
Primary item	$X_1$	14 314	5.292	0.003	**	12 537	7.125	0.001	**
	$X_2$	11 458	4.236	0.008	**	6033	3.429	0.019	*
	$X_3$	5482	3.149	0.025	*	6351	5.608	0.002	**
	$X_4$	7170	2.651	0.045	*	4889	2.778	0.039	*
Quadratic item	$X_1^2$	-460	0.270	0.798	ns	2483	2.239	0.075	ns
	$X_2^2$	-492	0.289	0.784	ns	-37	0.033	0.975	ns
	$X_3^2$	-1935	1.135	0.308	ns	-221	0.199	0.850	ns
	$X_4^2$	-2195	1.287	0.254	ns	-449	0.405	0.703	ns
Interaction term	$X_1X_2$	-6167	1.745	0.141	ns	-2141	0.931	0.394	ns
	$X_1X_3$	1508	0.663	0.537	ns	3163	2.138	0.086	ns
	$X_1X_4$	-7944	2.248	0.074	ns	-4615	2.008	0.101	ns
	$X_2X_3$	-806	0.355	0.737	ns	1222	0.826	0.447	ns
	$X_2X_4$	-1442	0.408	0.700	ns	-6062	2.637	0.046	*
	$X_3X_4$	591	0.260	0.805	ns	478	0.323	0.760	ns

Note: \* and \*\* represent significant differences at the  $p < 0.05$  and  $p < 0.01$  levels, respectively, and ns indicates no significant difference ( $p > 0.05$ ).

**3.3 Principal factor analysis of the model**

Since all factors in the design were treated by dimensionless linear coding, their regression coefficients were not affected by the size and unit of the factors taken, and the magnitude of the absolute values could directly and effectively reflect the degree of influence of each factor on the index. From Table 3, it can be seen that the magnitude of the effect of each factor on yield was in the following order:  $X_1$ ,  $X_2$ ,  $X_4$ ,  $X_3$  (spring and summer) and  $X_1$ ,  $X_3$ ,  $X_2$ ,  $X_4$

(autumn and winter).

**3.4 Univariate analysis of model**

The dimensionality reduction process was applied to regression equations (Equations (3) and (4)), that is, the three factors of  $X_1$ ,  $X_2$ ,  $X_3$ , along  $X_4$  were fixed at the zero level. A quadratic regression model of single factors for tomato yield can be obtained, and the curve effect diagrams of each factor to yield were obtained separately (Figure 3).

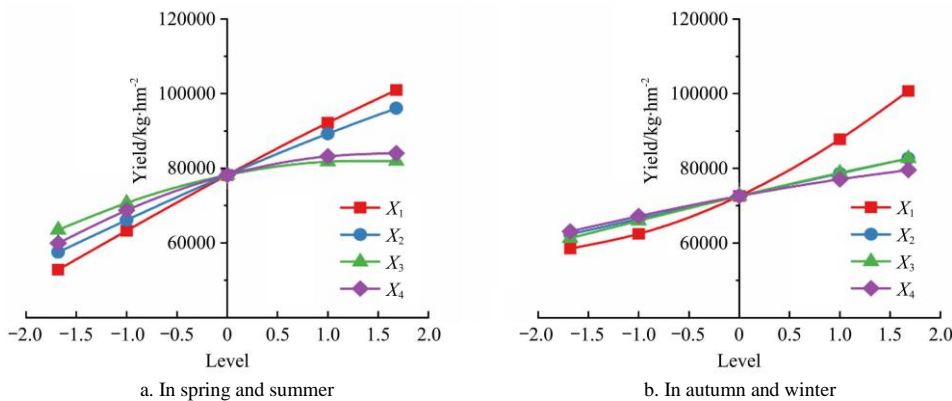


Figure 3 Impact curves of irrigation amount ( $X_1$ ), fertilizer amount ( $X_2$ ), dissolved oxygen ( $X_3$ ), the water temperature of the geothermal heat pipe ( $X_4$ ) and yield of tomato

Figure 3 shows the impact yield curves for the four factors ( $X_1$ ,  $X_2$ ,  $X_3$ , and  $X_4$ ) analyzed in this study. Tomato yields increased with  $X_1$ ,  $X_2$ ,  $X_3$  and  $X_4$  in spring and summer (Figure 3a), and with  $X_1$ ,  $X_2$ ,  $X_3$  and  $X_4$  in autumn and winter (Figure 3b). This occurred because, based on the conditions of this experiment, increasing the  $X_1$  was conducive to promoting tomato growth and metabolism, and can increase production. Increasing the  $X_2$  further increased soil nutrient levels, while increasing  $X_3$  improved soil aeration and promoted nutrient uptake by roots, thereby indirectly increasing tomato yield. Increasing the  $X_3$  was conducive to improving the soil environment and promoting the growth and development of the tomato, thereby increasing the yield. Through the optimized combination of WFOT, these four factors work together to promote the metabolism, growth, and photosynthesis of tomato plants, thereby achieving the goal of high-quality production. However, excessive  $X_2$  and  $X_4$  will cause “burning” of the seedlings, which

was not conducive to increasing production.

**3.5 Interaction analysis of the model**

The absolute value of the coefficient of the  $X_1X_4$  interaction term was the largest in spring and summer, and the  $X_2X_4$  interaction term was significant in autumn and winter; therefore, only the interaction between  $X_1X_4$  in spring and summer and  $X_2X_4$  in autumn and winter was analyzed and used to illustrate how to analyze the interaction between factors.

Figure 4a and Table 4 document the interaction between  $X_1$  and  $X_4$ . The highest yield of 105 166 kg/hm<sup>2</sup> was achieved in spring and summer when the  $X_2$  and  $X_3$  were at 0 level, while the  $X_1$  and  $X_4$  were at 1.682 and -1.682 levels, respectively. Under this test condition, the yield increased with increasing  $X_4$  when the  $X_1$  was -1.682 to 0 level, decreased with increasing  $X_4$  when the  $X_1$  was 0 to 1.682 level and increased with increasing  $X_1$  when the  $X_4$  was -1.682 to 1 level. It indicates that the interaction between

high water-low heat and low water-high heat was beneficial for yield increase.

Figure 4b and Table 5 document the interaction between  $X_2$  and  $X_4$ . The highest yield of 90 286 kg/hm<sup>2</sup> was achieved in autumn and winter when both  $X_1$  and  $X_3$  were at 0 level, while  $X_2$  and  $X_4$  were at 1.682 and -1.682 levels, respectively. Under the conditions of this experiment, yield increased with increasing  $X_4$

when  $X_2$  was -1.682 to 0 level, and when the  $X_2$  was 0 to 1.682 level, the yield decreased when the  $X_4$  increased, and yield decreased with increasing  $X_1$  when  $X_4$  was -1.682 to 0 level, and yield decreased with increasing  $X_1$  when the  $X_4$  was 0 to 1.682 level. It indicates that high fertilizer-low heat and low fertilizer-high heat interactions were beneficial to yield increase.

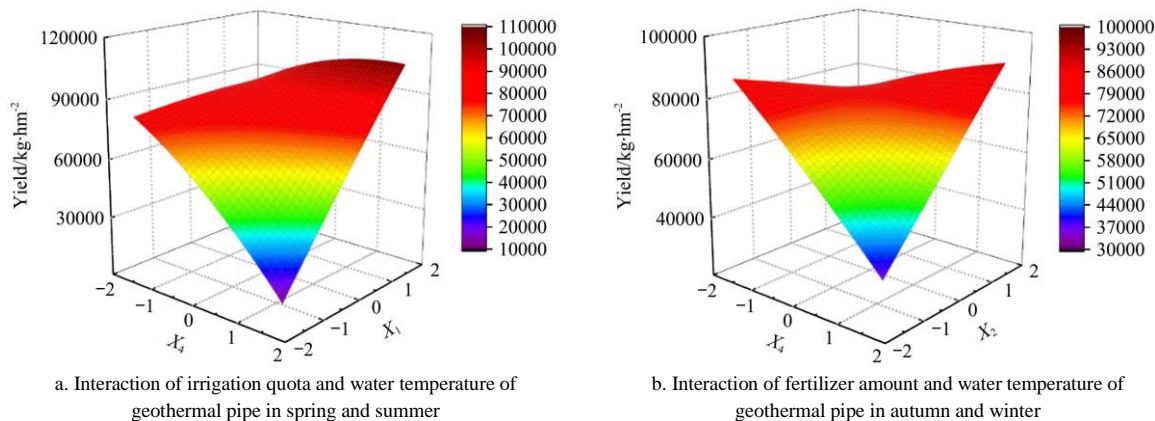


Figure 4 Interaction effects of irrigation quota/fertilizer amount and water temperature of geothermal pipe on yields

Table 4 Interaction between  $X_1$  and  $X_4$  on tomato yield in spring and summer

Item	$X_1$					Statistical parameter		
	-1.682	-1	0	1	1.682	$\bar{X}$	$C_V$	
$X_4$	1.682	105 166	104 975	100 963	92 482	84 344	97 586	0.09
	1	87 382	90 786	92 168	89 079	84 537	88 790	0.03
	0	59 926	68 723	78 193	83 193	84 044	74 816	0.14
	-1	31 532	45 721	63 281	76 370	82 613	59 903	0.35
	-1.682	12 082	29 866	52 818	71 300	81 138	49 441	0.58
Statistical parameter	$\bar{X}$	59 218	68 014	77 485	82 485	83 335		
	$C_V$	0.69	0.45	0.24	0.10	0.02		

Note:  $\bar{X}$  : mean value;  $C_V$ : coefficient of variation.

Table 5 Interaction between  $X_2$  and  $X_4$  on tomato yield in autumn and winter

Item	$X_2$					Statistical parameter		
	-1.682	-1	0	1	1.682	$\bar{X}$	$C_V$	
$X_4$	1.682	90 286	87 528	82 630	76 819	72 437	81 940	0.09
	1	79 435	79 421	78 638	76 942	75 303	77 948	0.02
	0	63 097	67 198	72 588	77 064	79 540	71 897	0.09
	-1	46 684	54 900	66 462	77 111	83 702	65 772	0.23
	-1.682	35 700	46 660	62 337	77 101	86 436	61 647	0.34
Statistical parameter	$\bar{X}$	63 040	67 141	72 531	77 007	79 483		
	$C_V$	0.34	0.23	0.10	0.00	0.06		

Note:  $\bar{X}$  : mean value;  $C_V$ : coefficient of variation.

### 3.6 Optimization of model

The WFOT coupled regression model (spring and summer) established in the present study was analyzed (Table 6). Using DPS software (18.10) for simulation optimization, a total of 191 combined schemes were found to have a yield greater than 89902 kg/hm<sup>2</sup>. The optimal WFOT coupling scheme had an  $X_1$  of 4808-5091 m<sup>3</sup>/hm<sup>2</sup>,  $X_2$  (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) of 171-57-84 to 186-62-89 kg/hm<sup>2</sup>,  $X_3$  of 7.9-8.2 mg/L, and  $X_4$  of 34.9 °C-37.0 °C. At the highest yield (113828 kg/hm<sup>2</sup>), the combination of factors was  $X_1=1.682$ ,  $X_2=1.682$ ,  $X_3=1.682$ , and  $X_4=1.682$ ; that is, irrigation amount, fertilization amount (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O), dissolved oxygen, and the water temperature of geothermal heat pipe were optimal at 5760 m<sup>3</sup>/hm<sup>2</sup>, 225-75-105 kg/hm<sup>2</sup>, 8.8 mg/L, and 25.0 °C, respectively.

The water, fertilizer, dissolved oxygen, and temperature coupled regression model (autumn and winter) established in the present study was analyzed (Table 6). Using DPS software (18.10) for simulation optimization, a total of 188 combined schemes were found to have a yield greater than 85 209 kg/hm<sup>2</sup>. The optimal WFOT coupling scheme had an  $X_1$  of 5270-5416 m<sup>3</sup>/hm<sup>2</sup>,  $X_2$  (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) of 151-50-76 to 167-56-82 kg/hm<sup>2</sup>,  $X_3$  of 8.0-8.2 mg/L, and  $X_4$  of 34.1 °C-36.2 °C. At the highest yield (146 496 kg/hm<sup>2</sup>), the combination of factors was  $X_1=1.682$ ,  $X_2=1.682$ ,  $X_3=1.682$ , and  $X_4=-1.682$ ; that is, irrigation amount, fertilization amount (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O), dissolved oxygen, and water temperature of geothermal heat pipe were optimal at 5760 m<sup>3</sup>/hm<sup>2</sup>, 225-75-105 kg/hm<sup>2</sup>, 9.0 mg/L, and 25.0 °C, respectively.

**Table 6 Optimal yield and frequency of tomato yield more than 89902 kg/hm<sup>2</sup> in spring and summer**

Level	X <sub>1</sub>		X <sub>2</sub>		X <sub>3</sub>		X <sub>4</sub>	
	Times	Frequency	Times	Frequency	Times	Frequency	Times	Frequency
-1.682	17	0.09	16	0.08	8	0.04	30	0.16
-1	20	0.10	22	0.11	23	0.12	33	0.17
0	21	0.11	29	0.15	44	0.23	40	0.21
1	51	0.27	54	0.28	56	0.29	49	0.26
1.682	82	0.43	70	0.37	60	0.31	39	0.20
Total	191	1.00	191	1.00	191	1.00	191	1.00
Mean	0.73		0.64		0.63		0.16	
Standard error	0.08		0.08		0.07		0.09	
95% Confidence interval	0.57-0.90		0.48-0.80		0.47-0.77		-0.01-0.33	
Scope of measures	4808-5091		171-57-84 to 186-62-89		7.9-8.2		34.9-37.0	

**Table 7 Optimal yield and frequency of tomato yield more than 85209 kg/hm<sup>2</sup> in autumn and winter**

Level	X <sub>1</sub>		X <sub>2</sub>		X <sub>3</sub>		X <sub>4</sub>	
	Times	Frequency	Times	Frequency	Times	Frequency	Times	Frequency
-1.682	0	0.00	31	0.16	8	0.04	37	0.20
-1	0	0.00	30	0.16	20	0.10	37	0.20
0	28	0.15	37	0.20	42	0.22	37	0.20
1	65	0.35	44	0.23	56	0.30	37	0.20
1.682	95	0.51	46	0.24	62	0.33	40	0.21
Total	188	1.00	188	1.00	188	1.00	188	1.00
Mean	1.20		0.21		0.69		0.03	
Standard error	0.04		0.09		0.07		0.09	
95% Confidence interval	1.11-1.28		0.03-0.38		0.52-0.82		-0.15-0.20	
Scope of measures	5270-5416		151-50-76 to 167-56-82		8.0-8.2		34.1-36.2	

Tomato yield in this study increased with increasing X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub> and X<sub>4</sub> within the test range, indicating that X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub> and X<sub>4</sub> did not reach their thresholds, while there was a certain antagonistic effect in the actual action of dissolved oxygen and temperature, and both could not reach the optimum at the same time, while the results of Ouyang Zan et al. showed that tomato yield increased with increasing dissolved oxygen in irrigation water<sup>[22,43,44]</sup> and lettuce in the climatic chamber increased with increasing soil temperature<sup>[23]</sup>, which was due to the single-factor comparison test they used, whereas the present study on the effect of WFOT coupling on tomato is also a partial validation and inheritance and innovation of the study by Ouyang et al<sup>[23]</sup>.

Moisture is an important factor affecting crop growth and development, water soluble fertilizer, water to promote fertilization, while fertilizer to regulate water, water to regulate air, irrigation fertilization increases the soil water content and nutrients, oxygenation measures improve soil aeration, improve soil oxygen content and increase the aerated porosity, temperature increase measures improve soil temperature, the higher the soil water content, crowding out the soil air, often leads to a lower soil oxygen content, and soil oxygen content and soil temperature there is a certain antagonistic effect, in fact, the results of this study show that: water, fertilizer, air and heat four factors are to reach the optimal value is only an ideal state, in practice could not be achieved, can only seek the optimal combination of water, fertilizer, air and heat on soil water, fertilizer, air and heat for comprehensive regulation, suitable water, fertilizer, air and heat factors interact, on the one hand, promote the soil microorganisms and root respiration, on the other hand, it increased soil enzyme activity and enhanced the absorption of soil nitrogen, phosphorus and potassium

fertilizers by the tomato root system, thus strengthening the tomato root system and enabling it to draw more water and nutrients from the soil for growth and development, thus providing sufficient substrate for photosynthesis. Previous studies have shown that aerated irrigation effectively improves the soil-crop root zone microenvironment by affecting the air-water ratio of the soil and improving soil aeration conditions, which in turn increases inter-root soil microbial abundance and soil enzyme activity<sup>[45]</sup> and promotes soil respiration<sup>[46]</sup>. While the reduced abscisic acid content and increased chlorophyll content of the leaves enhanced the photosynthetic rate of the tomato plant, which was conducive to the accumulation of dry matter mass, fruit quality and yield of the tomato plant to improve quality and efficiency.

#### 4 Conclusions

Overall, according to the analysis of variance, the missing term was not significant, the F test of the regression equation was significant, indicating that the regression equation established according to the experimental data was reliable, the measured value was highly correlated with the model value, and the model had very good simulation effect, with application value. The relative error between spring-summer and autumn-winter yields ranged from 1.12% to 25.34%.

The highest and lowest yields were observed in treatments T10 and T9, respectively; the yield of tomatoes in spring-summer and autumn-winter T10 (optimal treatment) increased by 36.32% and 43.32%, respectively, compared to the control treatment (CK).

The magnitude of the effect of each factor of WFOT on tomato yield was in the following order: X<sub>1</sub>, X<sub>2</sub>, X<sub>4</sub>, X<sub>3</sub> (spring and summer), and X<sub>1</sub>, X<sub>3</sub>, X<sub>2</sub>, X<sub>4</sub> (autumn and winter). Within the test



range, tomato yields increased with increasing  $X_1$ ,  $X_2$ ,  $X_3$  and  $X_4$ . The interaction between high water-low heat and low water-high heat was beneficial for yield increase (spring and summer), the high fertilizer-low heat and low fertilizer-high heat interactions were beneficial to yield increase (autumn and winter).

If the water-fertilizer-dissolved oxygen-temperature (WFOT) agronomic measures were adopted according to the 95% confidence interval, there was a 95% probability that the spring-summer tomato yield will be higher than 89 902 kg/hm<sup>2</sup>. The WFOT coupling scheme was  $X_1$  of 4808-5091 m<sup>3</sup>/hm<sup>2</sup>,  $X_2$  (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) of 171-57-84 to 186-62-89 kg/hm<sup>2</sup>,  $X_3$  of 7.9-8.2 mg/L, and  $X_4$  of 34.9 °C-37.0 °C. There was a 95% probability of tomato yield higher than 85209 kg/hm<sup>2</sup> in autumn and winter, and the WFOT coupling scheme was  $X_1$  of 5270-5416 m<sup>3</sup>/hm<sup>2</sup>,  $X_2$  (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) of 151-50-76 to 167-56-82 kg/hm<sup>2</sup>,  $X_3$  of 8.0-8.2 mg/L, and  $X_4$  of 34.1 °C-36.2 °C.

Although some fruitful research results were achieved in this study, the model of WFOT coupling of greenhouse tomato under the present experimental conditions was established, but after the experiment, it was found that the regression model established under the present experimental conditions has some limitations due to the complexity of the greenhouse ecosystem, the variability of climatic conditions and the spatial variability of the soil, so that future research should take climatic conditions (temperature and humidity) and soil environment (soil nutrients) into full consideration to establish a dynamic mechanism model of WFOT coupling.

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