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Effect of Drip Irrigation, N, K, and Zn Coupling on *Pn* of Densely Cultivated Apple on Dwarf Rootstock in Xinjiang, China

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Abstract: This study aimed to determine the effect of irrigation amount (*W*), nitrogen (*N*), potassium (*K*), and zinc (*Zn*) on the net photosynthetic rate (*Pn*) of closely planted apple trees on dwarf rootstocks in arid areas of Xinjiang. Taking the "Royal Gala" apple as the experimental material, a mathematical model for *Pn* was established using the principle of four-factor five-level quadratic regression with a general rotation combination design. The results show that: (1) The regression equations reached significant levels ($F = 37.06 > F_{0.01}(11.11) = 4.54$). (2) The effect of *W*, *N*, *K*, *Zn* on *Pn* is significant with relative importance $W > N > Zn > K$. (3) The results of single factor analysis showed that with an increase in *W*, *N*, *K*, and *Zn*, *Pn* exhibits an n-shaped parabolic response. (4) The positive coupling between *W* and *N* is significant, and the positive coupling between *W* and *Zn* is also significant. (5) Analysis of the interaction between sets of three factors revealed that *W*, *N*, and *Zn* could be combined to best effect, with the maximum value reaching 12.77 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Compared with $W \times K \times Zn$ and $W \times N \times K$, the combination of $W \times N \times Zn$ reduces *W* by 9.2% and 6.3%, respectively, which indicates its suitability for use in the dry and water deficient planting environment in Xinjiang. (6) Within the 95% confidence level, when *W* is 258–294.75 mm, *N* is 33.44–39.51 kg/hm^2, *K* is 53.82–69.39 kg/hm^2, and *Zn* is 6.46–7.84 kg/hm^2, the net photosynthetic rate reaches 11 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Keywords: irrigation fertilizer coupling; net photosynthetic rate; apple tree; regression analysis

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1. Introduction

Photosynthesis is the basic link between energy absorption, fixation, material transformation, and distribution in terrestrial ecosystems, an important biochemical process of material circulation and energy exchange on the surface, and an important factor affecting crop productivity, providing essential nutrients for crop growth [1–4]. Under natural conditions, in addition to the plant's own physiological characteristics, the main factors affecting any change in *Pn* (net photosynthetic rate) are the amount of irrigation (*W*) and fertilization (F_t), but other environmental factors also play a decisive role, which is more obvious in agricultural crops [5–7]. Therefore, research into the effect of *W* and F_t on *Pn* has always been a hot research issue globally [8].

As an important crop, apple is widely planted, particularly because of its adaptability to the environment and its high nutritional value [9]. According to recent statistics, China has become the largest apple producer in the world, with the planting area and output accounting for about 50% of the global total, and the export volume of apples also ranks among the top in the world [10,11]. Xinjiang is located in an arid area. In this area there is sufficient sunlight and a large temperature difference between day and night, resulting in conditions that are extremely effective for the accumulation of fruit sugar; it has, therefore, become an important high-quality apple production base in China [12]. As a new type of planting mode, dwarfing rootstock combined with close planting has the advantages of high mechanization potential, early bearing, high quality, and high land utilization rate, and has become an important approach in apple cultivation [13]. However, the development of the apple industry in Xinjiang is seriously restricted by limited rainfall, extensive use of irrigation and fertilizer, and serious salinization of the soil [14,15]. Therefore, it is very important to study how the interaction between irrigation and fertilization affects the physiological characteristics of apples during growth and development, in order to build an effective irrigation and fertilization management model, ensuring the efficient production and sustainable development of dwarf, closely planted apples in arid areas of Xinjiang [16–18].

Irrigation and fertilization are important factors affecting crop growth, photosynthetic characteristics, and production efficiency. Controlling the relationship between W and F_t can help to promote crop growth, improve Pn, and enhance crop yield and water and fertilizer use efficiency [19–21]. Of these factors, W is particularly important with respect to photosynthesis [22]. It has been found that a good soil water environment can promote the opening of leaf stomata, increase the absorption of CO_2 by leaves, facilitate the transport of photosynthetic products and reduce inhibition of photosynthesis due to an accumulation of photosynthetic products in leaves [23,24]. Therefore, appropriately increasing W will promote the Pn of plant leaves [23,25,26]. Soil water deficit will induce plant roots to produce abscisic acid, which will send inhibition signals to reduce plant growth, with signals being transmitted to the crown through the xylem under the effect of water transmission, there will be the closure of the crown stomata, leading to a reduction in Pn [27–30]. Too much W will lead to poor soil aeration, and decreased root activity, and will indirectly affect photosynthesis [31]. In addition, the nitrogen concentration in most plant leaves is closely related to carbon fixation via photosynthesis [32,33]. Research shows that increasing N can improve the photosynthetic performance of leaves and increase the Pn, thereby promoting the yield and harvest of crops [34]. However excessive nitrogen will reduce the activity of key enzymes in photosynthesis, which is not conducive to the improvement of photosynthetic performance [35–37].

Although potassium does not directly participate in the synthesis of important organic substances in plants, it is frequently an activator of enzymes, and thus indirectly participates in important metabolic activity in plants and has a significant effect on Pn [38–41]. Topdressing with potassium at the fruit expansion stage can improve Pn quality and yield [42]. Potassium stress will limit transmission, transformation, and other non-stomatal factors associated with light energy, reduce photosynthetic capacity and cause a decline in biomass accumulation [43,44]. Zinc is an essential trace element for crops and has important nutritional and physiological functions playing a role in stabilizing, regulating, or catalyzing various enzymes [45–47]. Increasing Zn can enhance leaf photosynthesis and facilitate the transportation of photosynthetic products [48,49]. During the growth of fruit trees, the loss of Zn will cause IAA synthesis in the plant to cease, and eventually lead to the development of young leaves and stems of the plant being blocked; this is usually referred to as “small leaf disease” and “clump leaf disease” and ultimately affects the photosynthetic ability of leaves [50,51].

In general, the existing research on irrigation and fertilizer regulation has mostly focused on the effects of W and F_t as individual factors or on different fertilizer ratios on plant growth, Research into the combined effects of W, N, K, Zn, on photosynthesis is relatively rare [18,52,53]. Especially in arid areas, it is very important to study the synergistic effect of irrigation and fertilization. In this study, the apple variety “Royal Gala” on dwarf rootstock closely planted in the arid region of Xinjiang was used as the experimental material, in order to determine the effect of irrigation amount (W), nitrogen (N), potassium (K), and zinc (Zn) on net photosynthetic rate (Pn) of apple trees planted closely with dwarf stocks in arid areas of Xinjiang. The field experiment was carried out using a four-factor five-level quadratic regression general rotation combination design [54–56]. The effects of W, N, K, and Zn on Pn were analyzed in order to provide reference data and effective suggestions for extending drip irrigation and the use of closely planted apples on dwarf rootstock in arid areas of Xinjiang.

2. Materials and Methods

2.1. Overview of the Study Area

The study site is located in the Apple Garden of the 10th Regiment of Alar City, the First Division of the Xinjiang Production and Construction Corps (40°39′14″ N, 81°16′21″ E), which belongs to a typical inland extremely arid climate zone. The annual precipitation is about 150 mm, the average annual temperature is about 11 °C, the annual evaporation is about 2100 mm, the annual sunshine hours amount to about 2900, the frost-free period is more than 200 days, and the groundwater depth is more than 3 m. The tested soils were sandy with a field holding capacity of 13.7% from 0 to 120 cm soil depth, an average capacity of 1.52 g/cm^3, organic matter content of 11.05 g/kg, available phosphorus and available boron contents of 3.20 mg/kg and 0.60 mg/kg, rapid potassium content of 33 mg/kg, alkaline nitrogen and total nitrogen contents of 10 mg/kg and 176 mg/kg, ammonium nitrogen and nitrate nitrogen contents of 2.01 mg/kg and 1.00 mg/kg, respectively, PH of 8.71, and EC value of 154.60 μs/cm.

2.2. Experimental Materials

The experiment was conducted from 10 April to 1 September 2022, using "Royal Gala", an early maturing apple variety. The M195 rootstock was the trees grafted and the apple trees used in the experiment were six years old. The total growth period (TGP) was 150 days. The anthesis fruit setting stage (AFS) was from 20 April to 1 May, the young fruit development stage (YFS) from 2 May to 1 June, the fruit expansion stage (FES) from 2 June to 1 August, and the fruit ripeness stage (FRS) from 2 August to 20 August. The planting density 2850 plants/hm^2, the plant spacing 1 m, and the row spacing 3.5 m. The drip pipe was set 60 cm from the ground on each side of the fruit trees; the drop head flow was 4 L/h, the drop head spacing was 50 cm, and the tanks were pressure differential fertilization tanks, which were individually configured for each test plot. The distribution of precipitation and daily average temperature is shown in Figure 1. The total precipitation was 195.3 mm, mainly concentrated in July and August.

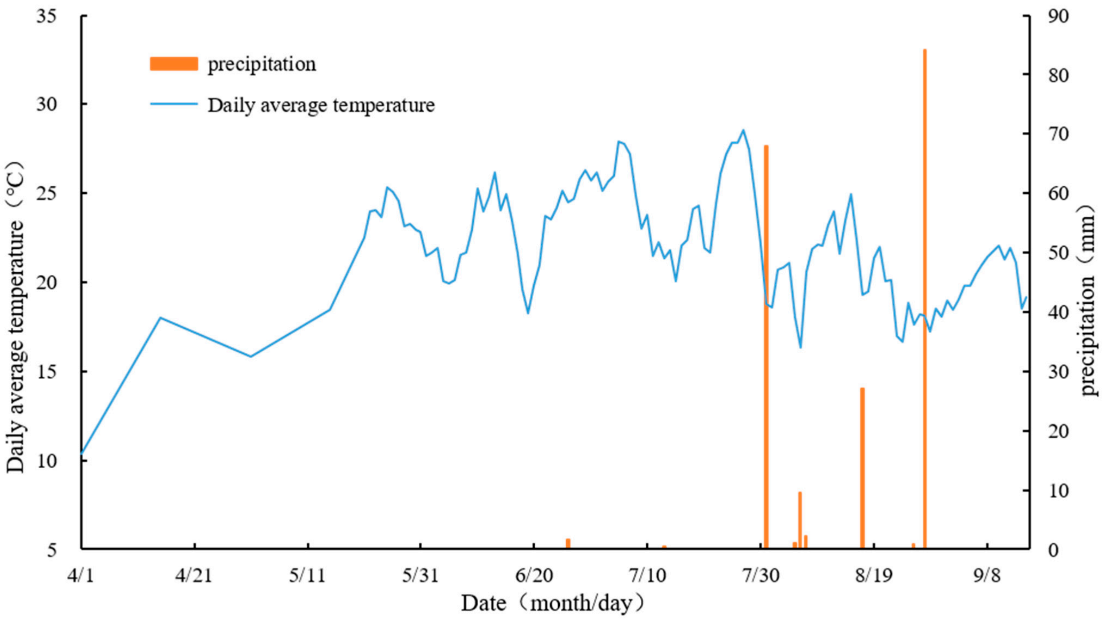

Figure 1. Meteorological data.

2.3. Experimental Design

W, N, K, Zn were treated as independent variables, and net photosynthetic rate (Pn) was used as the dependent variable. A total of 23 treatments were set up using a four-factor five-level quadratic regression general rotation combination design (with 50% implementation) [54–56]. Each treatment was repeated three times with an experimental plot area of 35 m^2 (10 m × 3.5 m) and 10 apple trees were planted in each plot, 690 apple trees in total. The irrigation method is drip irrigation. Irrigation was controlled by a water meter (precision 0.001 m^3) during the test. Since 10 April, the water has been irrigated every 4 days, 30 times. Each test plot was equipped with its own fertilizer tank; fertilizer was dissolved before application. During the experiment, nitrogen was supplied in the form of urea (46%), potassium as potassium sulfate (K_2SO_4 52%) and zinc as zinc sulfate heptahydrate ($ZnSO_4$, 56%) [57,58]. During the total growth period of the apple, a total of 15 times fertilization. Fertilize every 8 days. The level coding for the four factors is presented in Table 1 [56]. Therein, z_t represents the coded formula, and x_1, x_2, x_3, x_4 represent the coded levels of W, N, K, and Zn, respectively [56]. Five levels were assigned to W, N, K, Zn, and the coded levels were $\pm r, \pm 1, 0$. The specific irrigation and fertilization regimes were executed in accordance with Table 2.

Table 1. Factor level code table for the four factors.

z (x_t)	z_1 (W)	z_2 (N)	z_3 (K)	z_4 (Zn)
$z_{2j}(r)$	800.0	150.0	300.0	22.5
$z_{0j} + \Delta_j(1)$	700.0	135.0	270.0	15.8
$z_{0j}(0)$	550.0	112.5	225.0	11.3
$z_{0j} - \Delta_j(-1)$	400.0	90.0	180.0	6.7
$z_{1j}(-r)$	300.0	75.0	150.0	0
$\Delta_j = \frac{z_{2j}-z_{ij}}{2r}$	148.6	22.3	44.6	6.7
$x_j = \left(z_j - z_{0j}\right)/\Delta_j$	$x_1 = \frac{z_1-550}{148.6}$	$x_2 = \frac{z_2-112.5}{22.5}$	$x_3 = \frac{z_3-225}{44.6}$	$x_4 = \frac{z_4}{6.7}$

Table 2. Irrigation and fertilization regimes.

Factors	Stage	Factor Levels				
		−1.682	−1	0	1	1.682
K (g / 35cm^3)	AFS	26.25	31.50	39.25	47.25	52.50
	YFS	105.00	126.00	157.00	189.00	210.00
	FES	288.75	346.50	431.75	519.75	577.50
	FRS	105.00	126.00	157.00	189.00	210.00
	TGP	525.00	630.00	785.00	945.00	1050.00
N (g / 35cm^3)	AFS	26.25	31.50	39.38	47.25	52.50
	YFS	131.25	157.50	196.88	236.25	262.50
	FES	105.00	126.00	157.40	189.00	210.00
	FRS	0	0	0	0	0
	TGP	262.50	315.00	393.75	472.50	525.00
W (m^3 / 35cm^3)	AFS	0.53	0.70	0.96	1.23	1.40
	YFS	1.58	2.10	2.89	3.68	4.20
	FES	6.30	8.40	11.55	14.70	16.80
	FRS	2.10	2.80	3.85	4.90	5.60
	TGP	10.50	14.00	19.25	24.50	28.00

Table 2. *Cont.*

Factors	Stage	Factor Levels				
		−1.682	**−1**	**0**	**1**	**1.682**
Zn ($g/35cm^3$)	AFS	0	7.10	17.50	27.90	35.00
	YFS	0	7.10	17.50	27.90	35.00
	FES	0	7.10	17.50	27.90	35.00
	FRS	0	0	0	0	0
	TGP	0	21.30	52.45	83.70	105.00

Note: TGP represents the total growth period of the apple tree, AFS represents the anthesis fruit setting stage of the apple tree, YFS represents the young fruit development stage of the apple tree, FES represents the fruit expansion stage of the apple tree, FRS represents the fruit ripeness stage of the apple tree.

2.4. Data Acquisition and Analysis

(1) Sample collection

At the FRS, we randomly selected three apple trees in each test plot and selected three leaves from the middle of each tree, east, south, west, and north for the observation of the net photosynthetic rate, and measured the net photosynthetic rate three times for each leaf. The Pn was determined using a $Li - 6800$ portable photosynthesis analysis system (USA) between 9:00 and 11:00 a.m. During the assay, the photometric flux setting was 1800 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and the blade temperature was set to 28 °C.

(2) Construction of regression models

Based on the quadratic regression general rotation combination design, the regression statistics were generated; with p variables, the general formula of the quadratic orthogonal regression model is:

$$\hat{y} = b_0 + \sum_{j=1}^{p} b_j X_j + \sum_{j=1}^{p} b_{jj} X_j^2 + \sum_{i<j}^{p} b_{ij} X_i X_j \quad (1)$$

where $\hat{y}$ is the response variable; b_0 is a constant term; b_j is the coefficient for X_1; b_{jj} is the quadratic term coefficient; b_{ij} is the interaction term coefficient; p is the number of dependent variables; $1 \leq j \leq p$, $1 \leq i \leq p$ and $i < p$.

The corresponding regression coefficients were calculated:

$$b_0 = A\sum_{i=1}^{N_a} y_i + E\sum_{j=1}^{p}\left(\sum_{i=1}^{N_a} x_{ij}^2 y_i\right) \quad (2)$$

$$b_j = e^{-1}\sum_{i=1}^{N_a} x_{ij} y_i = \frac{B_j}{D_j} \quad (3)$$

$$b_{hj} = m_c^{-1}\sum_{\substack{i=1 \\ h>j}}^{N_a} (x_{ih} x_{ij}) y_i = \frac{B_{hj}}{D_{hj}} \quad (4)$$

$$b_{jj} = (F_a - G)\sum_{i=1}^{N_a} x_{ij}^2 y_i + G\sum_{j=1}^{p}\sum_{i=1}^{N_a} x_{ij}^2 y_i + E\sum_{i=1}^{N_a} y_i \quad (5)$$

where $A, E, N_a, F_a, G, m_c, p$ all represent the necessary parameters of quadratic regression general rotation combination design, x and y, respectively, represent coding and the corresponding Pn.

(3) Data processing and mapping

Data were processed using Microsoft Excel 2020 (Microsoft, Redmond, WA, USA); frequency analysis and regression analysis were conducted in SPSS 25.0 (IBM SPSS, Chicago, IL, USA), and one-way effect plots as well as two- and three-factor interac-tion plots were produced by Origin 2021 pro (Northampton, MA, USA) and Matlab 2021 (Natick, MA, USA).

3. Results and Analysis

3.1. Analysis of Pn in Apple Leaves

It can be seen from Table 3 that there are significant differences between T1, T2, T3 T4. The results show that *Pn* is affected only by the *W*. Significant differences were found between T9, T10, and T17, and the *Pn* response is ranked T17 > T10 > T9. It appears that fixing *N*, *K*, and *Zn*, and changing *W* significantly affects *Pn*. As *W* increases, *Pn* first increases and then decreases. These results indicate that the effect of water fertilizer coupling on *Pn* can be altered by changing *W* and F_t individually. Based on the differences between treatments (T15, T16, T17), it can be seen that an appropriate increase in *Zn* can increase the *Pn*, when *W*, *N*, *K* are fixed; however, when the application is excessive, it will inhibit *Pn*. Fixing *N* (T3, T4, T7, T8), P (T1, T3, T5, T7), and Zn (T2, T3, T5, T8), respectively, resulted in the *Pn* differing significantly, indicating that each factor has a significant effect on *Pn*. It follows that an increase in irrigation water and fertilization alone does not necessarily contribute to fruit tree growth, which in turn favors yield increase, and that fruit tree growth can be better enhanced and fruit yield improved only by an appropriate water-to-fertilizer ratio.

Table 3. Net photosynthetic rate (*Pn*) change for different treatment.

No.	Factor Code				Implementation				*Pn* (μmol·m^{-2}·s^{-1})
	x_1	x_2	x_3	x_4	W (mm)	N (kg/hm^2)	K (kg/hm^2)	Zn (kg/hm^2)	
T1	1	1	1	1	700	135.0	270	15.825	12.960 ^{a}
T2	1	1	−1	−1	700	135.0	180	6.675	11.226 ^{ef}
T3	1	−1	1	−1	700	90.0	270	6.675	10.428 ^{hi}
T4	1	−1	−1	1	700	90.0	180	15.825	10.797 ^{gh}
T5	−1	1	1	−1	400	135.0	270	6.675	10.227 ^{ij}
T6	−1	1	−1	1	400	135.0	180	15.825	10.106 ^{ij}
T7	−1	−1	1	1	400	90.0	270	15.825	10.062 ^{ij}
T8	−1	−1	−1	−1	400	90.0	180	6.675	9.517 ^{k}
T9	−1.682	0	0	0	300	112.5	225	11.250	9.900 ^{jk}
T10	1.682	0	0	0	800	112.5	225	11.250	11.692 ^{d}
T11	0	−1.682	0	0	550	75.0	225	11.250	10.119 ^{ij}
T12	0	1.682	0	0	550	150.0	225	11.250	11.168 ^{efg}
T13	0	0	−1.682	0	550	112.5	150	11.250	11.025 ^{ef}
T14	0	0	1.682	0	550	112.5	300	11.250	11.431 ^{de}
T15	0	0	0	−1.682	550	112.5	225	0	10.897 ^{fg}
T16	0	0	0	1.682	550	112.5	225	22.500	11.659 ^{d}
T17	0	0	0	0	550	112.5	225	11.250	12.733 ^{ab}
T18	0	0	0	0	550	112.5	225	750.000	12.580 ^{bc}
T19	0	0	0	0	550	112.5	225	750.000	12.643 ^{abc}
T20	0	0	0	0	550	112.5	225	750.000	12.752 ^{ab}
T21	0	0	0	0	550	112.5	225	750.000	12.677 ^{ab}
T22	0	0	0	0	550	112.5	225	750.000	12.265 ^{c}
T23	0	0	0	0	550	112.5	225	750.000	12.575 ^{bc}

Note: *Pn* is the net photosynthetic rate. T1–T23, respectively, represent 23 treatments set up in the experiment. *Pn* is expressed in average values, and different letters indicate significant difference at $p < 0.05$.

3.2. Regression Analysis

With *Pn* as the response variable (y_{Pn}), and *W* (x_1), *N* (x_2), *K* (x_3), *Zn* (x_4) as independent variables, regression models were constructed according to general rotation combination design and Formula (1) [56]. Coefficients values (b_0, b_j, b_{jj}, b_{hj}) for the regression model were obtained according to Formulas (2)–(5), respectively [56].

$$\begin{gathered} y_{pn} = 12.5517 + 0.6238x_1 + 0.4011x_2 + 0.1988x_3 + 0.2787x_4 - 0.5666x_1^2 \\ -0.62x_2^2 - 0.4134x_3^2 - 0.3955x_4^2 + 0.2759x_1x_2 + 0.0872x_1x_3 + 0.2097x_1x_4 \end{gathered} \tag{6}$$

To determine the validity and reliability of the regression models, the regression coefficients and partial regression coefficients were examined using the F-test. The results are shown in Table 4. Based on these results, a lack-of-fit test was conducted.

$$F_{If} = \frac{S_r/f_{If}}{S_e/f_e} = 4.04 < F_{0.05}(5,6) = 4.36 \tag{7}$$

Table 4. Analysis of variance for the regression relationships.

Source	Df	SS	MS	F Value	*p* Value
x_1	1	5.314	5.314	82.62	0.0001 **
x_2	1	2.197	2.197	34.16	0.0001 **
x_3	1	0.540	0.540	8.39	0.015 *
x_4	1	1.061	1.061	16.49	0.002 **
x_1^2	1	5.103	5.103	79.33	0.0001 **
x_2^2	1	6.109	6.109	94.97	0.0001 **
x_3^2	1	2.717	2.717	42.23	0.0001 **
x_4^2	1	2.486	2.486	38.65	0.0001 **
x_1x_2	1	0.609	0.609	9.47	0.011 *
x_1x_3	1	0.061	0.061	0.95	0.352
x_1x_4	1	0.352	0.352	5.47	0.039 *
Regression	11 (f_r)	26.225 (S_r)	2.384	F_r = 37.06	0.0001 **
Residual error	11 (f_R)	0.708 (S_R)	0.064		
Lack-of-fit	5 (f_{If})	0.546 (S_{If})	0.109	F_{If} = 4.04	0.059
Error	6 (f_e)	0.162 (S_e)	0.027		
Sum	22	26.225			

Notes: * indicates significant at the 0.05 level, ** indicates significant at the 0.01 level; SS indicates stdev square, MS is mean square, Df is degree of freedom.

The lack-of-fit of the regression model was not significant, indicating that the four factors selected in this experiment are meaningful for investigating the change in *Pn* of apple and suitable for estimation. For the regression equations, the test was as follows:

$$F_r = \frac{S_r/f_r}{S_R/f_R} = 37.06 > F_{0.01}(11,11) = 4.54 \tag{8}$$

This indicates that the relationship between four factors (*W*, *N*, *K*, *Zn*) and *Pn* was significant ($P < 0.01$), and the regression model could well reflect the correlation between independent variables and dependent variables. In addition, Table 4 also shows that partial regression coefficients in the model reached significant or extremely significant levels for all but the $x_1x_3(W{\cdot}K)$ interaction term. Further indicating that the single factor variations in *W*, *N*, *K*, and *Zn* were strongly related to the variation in *Pn* and there was a strong correlation between the quadratic term and *Pn*; $W \times N$ coupling and $W \times Zn$ coupling had significant effects on *Pn*.

(1) Main effect analysis

Regression models were subjected to principal factor analysis. There was no correlation between the coefficients of the linear term in the model and the linear term coefficients and the interaction term coefficients were also uncorrelated. Therefore, the effect of the linear term for each factor on *Pn* was determined by comparing the magnitude of the absolute value of the regression coefficients. The results showed that W and N had the greatest important effect on Pn, followed by K and Zn, respectively, and that all factors had a positive effect on Pn. It can be concluded from the linear term coefficient that Pn increased with the increasing application until the maximum tested application was reached.

The quadratic coefficients of W, N, K, and Zn were all negative. With increasing W, Pn showed first an increasing and then decreasing trend, appearing as an n-shaped parabolic curve. We believe that the optimal solution for W, N, K, and Zn is at the highest point of the parabolic curve when Pn reaches its peak value. Because of the correlation between the quadratic term coefficients in the orthogonal trial designs, the absolute value of the coefficients cannot be used directly to compare the magnitude of the quadratic term effect, and therefore, further analysis and validation are required. The coefficients of the $W \times N$ coupling, $W \times K$ coupling, and $W \times Zn$ coupling were all positive, therefore, increasing their combined effect is important to increase net photosynthesis in fruit trees, showing a positive interaction, indicating that the factors can work synergistically to increase Pn.

(2) Single factor effects

The "dimension reduction method" was used to simplify the regression model, coding one factor within the range of investigated values, with the remaining factors all set to zero; this approach eliminates the influence of other factors on the analysis of the target factor. A single-factor model was obtained after dimension reduction elimination:

$$y = 12.5517 + 0.6238x_1 - 0.5666x_1^2 \quad (9)$$

$$y = 12.5517 + 0.401x_2 - 0.62x_2^2 \quad (10)$$

$$y = 12.5517 + 0.1988x_3 - 0.4134x_3^2 \quad (11)$$

$$y = 12.5517 + 0.2787x_4 - 0.3955x_4^2 \quad (12)$$

A single-factor plot of Pn effects was produced from the single-factor model described above (Figure 2). From calculations, we know that the corresponding Pn is 9.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 10.123 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 11.047 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 10.964 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively, when the single-factor minimum coded level for W, N, K, Zn is -1.682 within the experimental design. When the coded level increased to 0, the corresponding Pn values all increased to 12.552 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The corresponding Pn reached its maximum value within the range of the experimental design when the coded values of W, N, K, and Zn increased to 0.799, 0.493, 0.323, and 0.561, the corresponding applications were 669.775 mm, 123.586 kg/hm^2, 236.298 kg/hm^2 and 13.815 kg/hm^2, respectively, and the Pn values were 12.689 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 12.599 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 12.573 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 12.584 $\mu mol \cdot m^{-2} \cdot s^{-1}$. When the coded levels were increased to 1.682, the corresponding Pn for each factor decreased to 11.998 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 11.471 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 11.715 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 11.902 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. It follows that the maximum Pn that can be achieved under a single-factor influence and the coded levels of that single factor are not the same, but the trend of change in Pn is similar under each in-factor influence, showing a gradual increase in Pn with increasing levels for W, N, K, and Zn before the maximum levels are reached, after which the Pn again exhibits a gradually decreasing trend. This indicates that excessive irrigation and fertilization do not promote Pn but rather have an inhibitory effect.

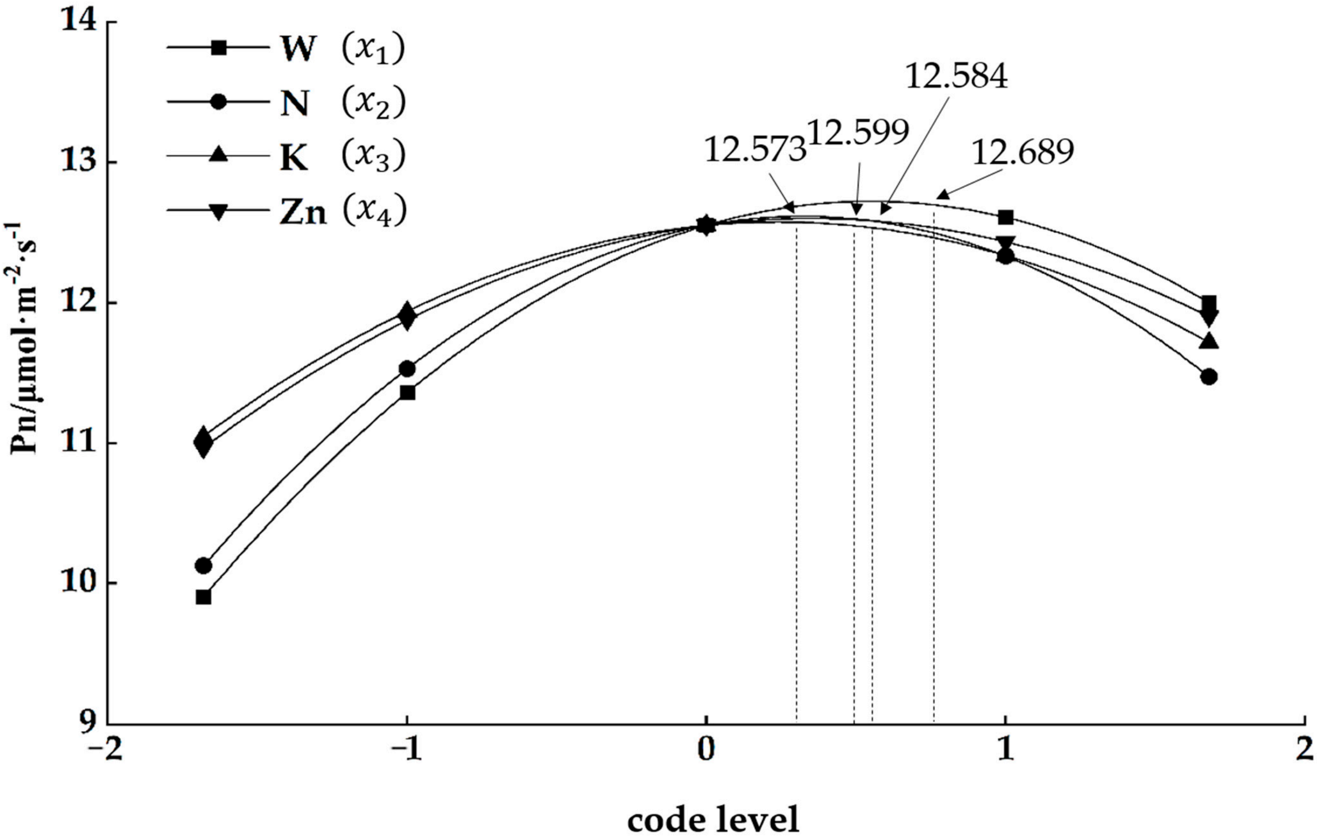

Figure 2. Effect on net photosynthetic rate (*Pn*) of irrigation amount (W), nitrogen application amount (N), potash application amount (*K*), and zinc application amount (Zn).

The sensitivity of individual single factors to *Pn* can be judged by examining the curve of the parabola: the tighter the curve, the more sensitive the *Pn* is to the factor, and the greater the extent to which it is affected. Figure 2 reveals that the single factor effect plots in relation to *Pn* are parabolic and n-shaped, and the sensitivity ranking of the factors to the *Pn* is: $W > N > Zn > K$.

(3) Two-factor interaction effect analysis

Fixing the coding value of two factors to zero, we can model the interaction between the other two factors with respect to the *Pn*:

$$y = 12.5517 + 0.6238x_1 + 0.4011x_2 - 0.5666x_1^2 - 0.62x_2^2 + 0.2759x_1x_2 \tag{13}$$

$$y = 12.5517 + 0.6238x_1 + 0.1988x_3 - 0.5666x_1^2 - 0.4134x_3^2 + 0.0872x_1x_3 \tag{14}$$

$$y = 12.5517 + 0.6238x_1 + 0.2787x_4 - 0.5666x_1^2 - 0.3955x_4^2 + 0.2097x_1x_4 \tag{15}$$

Figure 3 represents the above models. Figure 3a shows that the effects of $W \times N$ coupling can be represented as a domed surface. That is, when other factors are set to zero, *Pn* changes are represented by a parabola as *W* and *N* increase, and the interaction coefficient is 0.2759. This suggests that the interaction between *W* and *N* promotes *Pn*. When the coded levels for *W* and *N* were 0.68 and 0.48, respectively, *Pn* reached its maximum of 12.85 μmol·m^{-2}·s^{-1}. The actual levels for *W* and *N* were 652 mm and 123.3 kg/hm^2, respectively. With a continuing increase in *W* and *N* application, *Pn* began to decline.

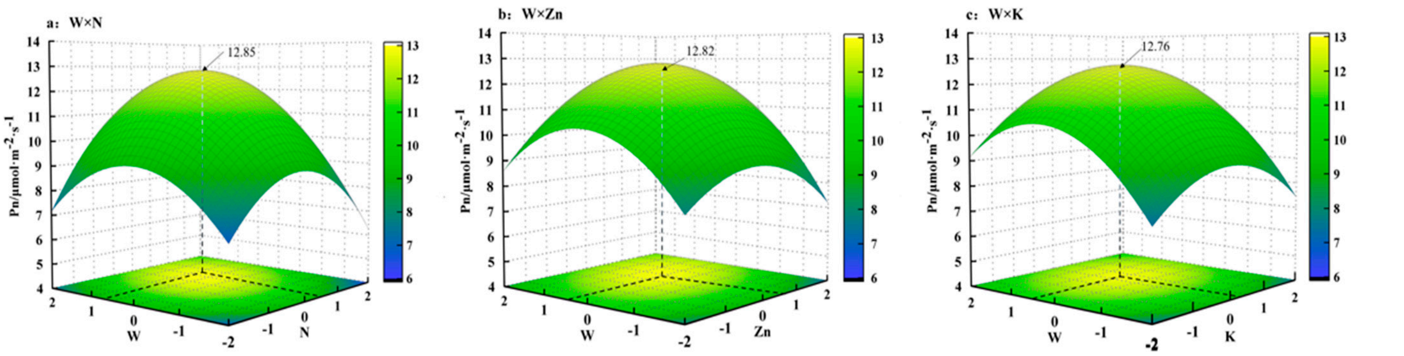

Figure 3. Combined effects of pairs of factors ((**a**): $W \times N$, (**b**): $W \times Zn$, (**c**): $W > K$) on net photosynthetic rate (Pn).

Figure 3b,c show similar effect trends for the $W \times Zn$ coupling and $W \times K$ coupling. With respect to the degree of effect $W > K, Zn$. When the W was at its middle or upper level, the Pn remained at a high level. When the W was at a lower level, increasing the Zn or K had little effect on Pn. The $W \times Zn$ coupling produced a maximum Pn of 12.82 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with coded levels of 0.64 and 0.52, respectively. The corresponding W and Zn actual levels are 646 mm and 13.63 kg/hm^2, respectively. For W and K, Pn reached a maximum value of 12.76 $\mu mol \cdot m^{-2} \cdot s^{-1}$ when the coded levels were 0.56 and 0.28, respectively. The corresponding W and K actual levels are 634 mm and 237.6 kg/hm^2, respectively.

(4) Three-factor interaction effect analysis

By setting the value of one factor in the fixed model to zero, the combined effect of the other three factors on Pn can be examined. The model was, thus, used to derive the relationships shown in Figure 4. Figure 4a. reveals the combined effects of W, K, and Zn on the Pn: when coded levels reach 0.496, 0.187, and 0.221, respectively, the corresponding actual levels are 624.33 mm, 233.42 kg/hm^2, and 12.06 kg/hm^2, and the Pn reaches 12.75 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Figure 4b. reveals that when the Pn reaches its highest value, 12.77 $\mu mol \cdot m^{-2} \cdot s^{-1}$, under the combined effects of W, K, and Zn, the corresponding coded levels are 0.454, 0.222 and 0.231, respectively, and the actual levels are 618.06 mm, 117.5 kg/hm^2 and 12.31 kg/hm^2. Compared with Figure 4a, the maximum Pn exhibits little difference. The Zn is increased by 4.5% and the W is decreased by 9.2%. Figure 4c shows the combined effect of W, N, and K on the Pn. The maximum Pn is 12.76 $\mu mol \cdot m^{-2} \cdot s^{-1}$. When the Pn reaches its maximum, the coded levels for each factor are 0.483, 0.216, and 0.189 respectively; the corresponding actual levels are 622.51 mm, 117.36 kg/hm^2, and 233.51 kg/hm^2. By comparing Figure 4c to Figure 4b, it can be seen that when the Pn reached its maximum, W increased by 6.2%. Contrasting Figure 4a–c, it can be found that the maximum Pn values for the $W \times Zn \times K$ coupling, $W \times K \times N$ coupling, $W \times Zn \times N$ coupling do not differ much, but in the case of $W \times Zn \times N$ coupling, the W required for Pn to reach a maximum is minimal, which is more suitable for the arid conditions in Xinjiang. This demonstrates that the combined effect of $W \times Zn \times N$ coupling can be manipulated to deliver the best results. This may be related to the content of soil nitrogen and zinc in the experimental plot, or it is possible that under the experimental conditions, Pn is more sensitive to the changes in N and Zn in the soil. It may also be that the synergy between soil water and nitrogen and zinc is strong, so the promotion of Pn is more obvious than other water and fertilizer combinations.

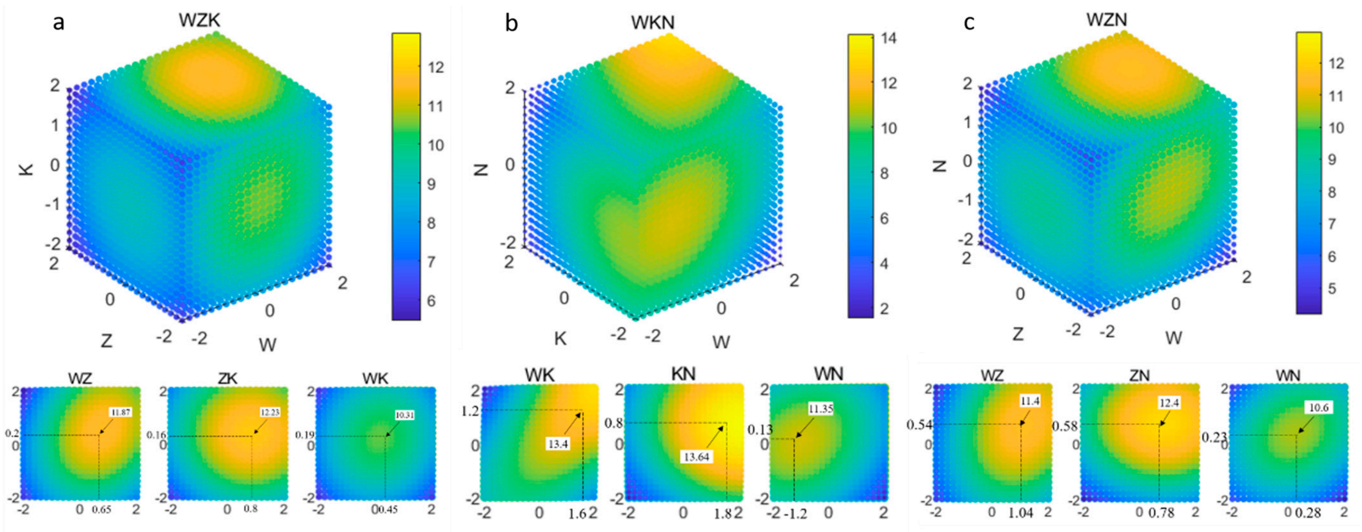

Figure 4. Combined effects of trios of factors ((**a**): $W \times Zn \times K$, (**b**): $W \times K \times N$, (**c**): $W \times Zn \times N$) on net photosynthetic rate (Pn).

(5) Optimal combination scheme

The regression model was based on five levels (−1.682, −1, 0, 1, 1.682) and we used simulation optimization and frequency analysis, resulting in 129 irrigation fertilizer couplings with Pn > 11 µmol·m^{-2}·s^{-1}, accounting for 20.6% of the total test protocol. It can be seen from Table 5 that when the value range for each factor value reflects the 95% confidence interval for W-coded levels (0.72–0.965), N-coded levels (0.486–0.756), K-coded levels (0.196–0.542) and Zn-coded levels (0.411–0.72), the corresponding actual level of W, N, K, and Zn are 658–694.75 mm, 123.44–129.51 kg/hm^2, 233.82–249.39 kg/hm^2 and 13.13–14.54 kg/hm^2, respectively.

Table 5. Optimization scheme and frequency of target output.

Code	x_1		x_2		x_3		x_4	
	t	f	t	f	t	f	t	f
1.682	36	0.279	25	0.194	25	0.194	18	0.140
1	51	0.395	46	0.357	36	0.279	41	0.318
0	39	0.302	49	0.380	39	0.302	41	0.318
−1	3	0.023	9	0.070	25	0.194	18	0.140
−1.682	0	0	0	0	4	0.031	0	0
total	129	1	129	1	129	1	129	1
Weighted average	0.843		0.621		0.369		0.565	
95% Confidence interval	0.720–0.965		0.486–0.756		0.196–0.542		0.411–0.720	
Application rate	658.00–694.75 mm		123.44–129.51 kg/hm^2		233.82–249.39 kg/hm^2		13.13–14.54 kg/hm^2	

Notes: t indicates times, f indicates frequency.

4. Discussion

Photosynthesis is the main driving force affecting dry matter assimilation and organ formation, and it is the basis of plant production [59,60]. Irrigation and fertilizer are important factors affecting crop photosynthesis. Appropriate irrigation and fertilizer management can change the environmental conditions for crop growth and improve crop Pn [61,62].

This study has shown that soil moisture has a significant positive effect on the Pn; that is, with increased W, the Pn first showed an increasing trend. This is consistent with the research results of Liao et al. [63] and Zhen et al. [64]. An increase in soil moisture promotes the synthesis of hormones and related enzymes in plants, enhances the material transport capacity, and accelerates the transport rate of photosynthetic products, whilst, at the same time, the stomata open, the transpiration rate increases, and the Pn increases [65,66]. However, when the W increases beyond a certain threshold, the Pn decreases. This may be because too much soil moisture leads to poor soil ventilation and decreased root activity, thus affecting water transmission in plants, and indirectly inhibiting photosynthesis [67].

Under the conditions of this experiment, the effects of the linear term and quadratic term for N, K, and Zn reached significant levels. Single-factor analysis showed that, with increased applications, Pn first increased and then declined. The effects of the three factors on the Pn were ranked as follows: $N > Zn > K$. This may be because all three factors participate in photosynthesis in plant leaves, but they have different functions. Braun et al. [68] reported that the presence of K^+ helps to maintain the transmembrane proton gradient of chloroplasts and thylakoids under light, keeping the chloroplast interstitium at the higher PH required for CO_2 assimilation, promoting photophosphorylation and CO_2 assimilation, and improving the Pn. Makino et al. [37] and Sperling et al. [69] reported that nitrogen is the main element in chloroplasts, present in chloroplasts, proteins, and lamellar membranes and playing an important role in photosynthesis. Zinc is an important component and activator of many enzymes in photosynthesis, and also an essential nutrient for protein, nucleic acid, and sugar metabolism in chloroplasts [70–72]. After zinc application, the stomatal resistance of plant leaves decreases, stomatal conductance increases, and the transpiration and Pn of leaves increases [48,73]. Wang et al. [70,74] also found that a lack of zinc will lead to a decrease in chlorophyll content, stomatal conductance, intercellular concentration, and Pn, and a reduction in plant photosynthetic performance. These research results support, to some extent, the results of our experiment. However, with the continuous application of nitrogen, potassium, and zinc, the effective content of the three elements in the soil increases, and the plants can also absorb a lot, thus promoting their growth. At the same time, due to the initial content of nitrogen, potassium, and zinc in the soil at the experimental site, the three elements reached the optimum threshold at different application rates, and the activities of photosynthesis-related enzymes were reduced due to non-stomatal factors, which further led to the inhibition of plant photosynthesis with increasing application rates [75].

A large number of studies have shown that the coupling of water and fertilizer indirectly affects the photosynthetic rate of plant leaves by expanding leaf area, increasing leaf transpiration rate, increasing stomatal conductance, increasing intracellular water concentration, and reducing intracellular carbon dioxide concentration [76]. Wang et al. [77] showed that water/nitrogen coupling had a significant positive effect on the Pn of leaves, which is similar to the results of the current study. The reason may be that, with the increase in irrigation and nitrogen fertilizer application, the available nitrogen in the soil increase. Because there is sufficient soil water, the nutrient transport efficiency of the tree is significantly improved. Therefore, the combined effect of the two factors is that the absorption of nitrogen increases, and it is quickly and effectively transported to the leaves, promoting the synthesis of chlorophyll and thus enhancing the Pn [78–80]. With regard to the interaction between W and Zn, we found that when there was limited W, the Pn remained at a low level with increasing Zn, and when there was more W, the Pn increased somewhat with the appropriate increase in Zn. This shows that water plays the dominant role in the interaction between W and Zn. Some studies have shown that the effect of applying zinc fertilizer on plant biomass is better when there is sufficient water. Spraying $ZnSO_4$ on the leaf surface can improve the leaf water conditions [48,49]. Water and potassium are important factors affecting plant photosynthesis [81].

Some studies have shown that when soil moisture content increases, soil mechanical resistance decreases, which facilitates the flow of nutrients, thus promoting the absorption of nutrients by the root system. Potassium itself promotes photosynthesis. Studies by Nieves-Cordones have shown that under the condition of insufficient potassium fertilizer supply, excess energy in plants can induce the production of more reactive oxygen species, destroy chloroplast structure, accelerate chloroplast decomposition, and then inhibit photosynthesis. These negative effects caused by potassium deficiency will be improved with the increase in potassium application. The results of this experiment showed that the photosynthetic rate of apple leaves increased significantly with the increase in irrigation amount under the condition of constant potassium application. The results showed that the increase in irrigation water promoted the absorption of potassium in apple trees. There was a significant coupling effect between irrigation amount and potassium application amount, and it had a positive effect on *Pn* increase. So, the combined effect of *W* and *K* has a somewhat synergistic effect on the *Pn* [43,82–84].

It should be pointed out that due to spatial and temporal differences in the coupling of irrigation and fertilizer, different regions, soil textures, and soil nutrient contents will lead to different conclusions from such testing. Therefore, in both production and application, we must adapt measures to local conditions and consider the prevailing conditions if we are to gain the best effect.

5. Conclusions

With drip irrigation of closely planted dwarf stock in the arid area of Xinjiang, *W*, *N*, *K*, and *Zn*, had significant effects on the *Pn* of apple trees, but the influence of each factor on the *Pn* differed and can be ranked: $W > N > Zn > K$. By examining the interaction between irrigation and each of the fertilizers, we found the following ranking of effects: $W \times N > W \times Zn > W \times K$. Applying zinc can improve the *Pn*, thus enhancing the storage of nutrients in the tree and promoting growth and development, and thus further improving the yield of apple trees.

The test simulation optimization and frequency analysis showed that with *W* in the range 258–294.75 mm, *N* in the range 33.44–39.51 kg/hm^2, *K* in the range 53.82–69.39 kg/hm^2, and *Zn* in the range 6.46–7.84 kg/hm^2, within the 95% confidence level, the net photosynthetic rate reaches 11 μmol·m^{-2}·s^{-1}. This is the best irrigation and fertilizer management plan, under the test conditions.

Based on previous research results and our data, we consider that the indicators and methods targeted by this test have certain limitations. More plant physiological growth indicators are required to establish the relationship between irrigation and fertilizer factors and various growth indicators. Finally, the relationship between yield and economic benefits should be established to better serve the development of commercial agriculture and forestry.

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