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Article

Effects of Water and Fertilizer Coupling on Growth, Fruit Quality, and Yield of the Korla Fragrant Pear

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Abstract: Taking Korla fragrant pear as the research object, single factor testing and water and fertilizer coupling testing were conducted. Under the premise of the drip irrigation mode, the effects of water, nitrogen, and phosphorus on the growth, fruit quality, and yield of Korla Fragrant Pear were studied to provide a theoretical basis for efficient water and fertilizer management. Among them, the single factor test set water, nitrogen and phosphorus as the three factors, and each factor was set at five levels, namely, water (W1, 5460 $m^3{\cdot}hm^{-2}$;W2, 5880 $m^3{\cdot}hm^{-2}$;W3,6300 $m^3{\cdot}hm^{-2}$; W4, 6720 $m^3{\cdot}hm^{-2}$; W5, 7140 $m^3{\cdot}hm^{-2}$), nitrogen (N1, 150 kg $N{\cdot}hm^{-2}$;N2, 225 kg $N{\cdot}hm^{-2}$; N3, 300 kg $N{\cdot}hm^{-2}$; N4, 375 kg $N{\cdot}hm^{-2}$; N5, 450 kg $N{\cdot}hm^{-2}$), phosphorus (P1,75 kg $P2O5{\cdot}hm^{-2}$; P2, 150 kg $P2O5{\cdot}hm^{-2}$; P3, 225 kg $P2O5{\cdot}hm^{-2}$; P4, 300 kg $P2O5{\cdot}hm^{-2}$; P5, 375 kg $P2O5{\cdot}hm^{-2}$). The results showed that the total nitrogen and total phosphorus contents in leaves under the W3, W4, N3, N4, P3, and P4 treatments were significantly higher than those under other treatments, and the fruit quality was better. Therefore, the W3, W4, N3, N4, P3, and P4 treatments were selected as the water and fertilizer inputs for the water–fertilizer coupling test for Korla fragrant pear. Eight treatments were set up in the water and fertilizer coupling test: Treatment 1 (T1, W3N3P3), Treatment 2 (T2, W3N3P4), Treatment 3 (T3, W3N4P3), Treatment 4 (T4,W3N4P4), Treatment 5 (T5, W4N3P3), Treatment 6 (T6, W4N3P4), Treatment 7 (T7, W4N4) P3), and Treatment 8 (T8, W4N4P4). The results showed that the leaf area index of the T1, T2, T3, and T4 treatments was significantly higher than that of the other treatments at maturity. The T3 treatment resulted in the highest fruit yield, single fruit weight, and primary fruit rate. The results of the grey correlation degree analysis of fruit quality showed that T3 treatment had the highest degree of correlation and ranking of each fruit quality index, indicating that T3 treatment had the highest fruit quality. Detailed investigation of pear tree growth and fruit quality showed that the T3 treatment (375 $kg{\cdot}hm^{-2}$ nitrogen application, 225 $kg{\cdot}hm^{-2}$ phosphorus application and 6300 $m^3{\cdot}hm^{-2}$ irrigation) had the best fruit growth and development performance, and the sweet pear fruit quality was the best.

Keywords: water–fertilizer coupling; Korla pear; fruit quality

1. Introduction

Korla pear is one of the most famous fruits in Xinjiang. It belongs to the rose pear family, pear genus middle white pear system [1], and is a cross between an Asian pear and a European pear [2]. Pear trees have strict requirements for temperature and light conditions [3]. However, the requirements for soil conditions are relatively minimal, and the Xinjiang region has unique light and heat resources. Therefore, it is highly suitable for pear tree planting. As of 2017, Xinjiang's pear tree planting area reached 62,800 hm^2, with an output of 1.231 million tons, making it one of the major pear fruit-producing areas in China [4].

Water and fertilizer are the basis of fruit growth, yield, and quality [5]. Among them, nitrogen, phosphorus, and potassium [6] are the three main mineral elements that affect the growth and development of fruit trees. Nitrogen deficiency can affect the synthesis of organic matter in fruit trees, resulting in leaf greening and short branches [7]. As a result, fruit trees such as pears [8], apples [9], and jujube [10] have fewer and smaller fruits, resulting in lower yields. Lack of phosphorus can result in late germination and flowering of plants, resulting in low germination rates and reduced fruit quality [11]. Potassium deficiency disrupts plant metabolism and reduces the stress resistance of plants [12]. Strategic water and fertilizer management are the bases for high yield and quality of pear trees [13]. However, improper cultivation management can occur, resulting in low fruit quality rates, high inputs, and low outputs. In recent years, with the development of science and technology, promoting the use of water with fertilizer, promoting the use of fertilizer with water, and coupling water and fertilizer are key technologies to improve water and fertilizer use efficiency and reduce environmental pollution [14]. Strategic water and fertilizer management can play an important role in improving the quality and yield of fruit trees. This can improve the physical characteristics of orchard soil and increase soil moisture and fertility. It can also provide a favorable environment for the growth and development of fruit trees and enable them to achieve the virtuous cycle of high quality and high yield [15]. However, during the production process, fruit farmers generally implement the management protocols of large quantities of water and fertilizer. Problems from excessive water and fertilizer inputs and unsustainable distribution of water and fertilizer are prominent. Chai et al. [16] investigated the planting of fragrant pear in 15 households and showed that the organic fertilizer of fragrant pear was 15,000 kg ha^{-1} and the input of chemical fertilizer was 2550 kg ha^{-1}. Hongbo et al. (2015) found that the irrigation volume of the Xiangli manglers in Korla reached 14,400 m^3 ha^{-1}, which was substantially higher than the recommended irrigation volume. Unsustainable water and fertilizer management, soil compaction, and permeability can decrease, resulting in a tree nutritional imbalance and affecting fruit quality. Therefore, it is necessary to conduct research on the water and fertilizer regulation of Korla fragrant pears, which has important theoretical and practical importance in maintaining the sustainable development of the Korla fragrant pear industry.

Xinjiang is located inland, with a dry climate and frequent water shortages. Meanwhile, Xinjiang soil is rich in potassium because of the influence of the parent material and climate. Water, nitrogen, and phosphorus management have become the focus of fruit tree water and fertilizer management in Xinjiang. In this study, the effects of water, nitrogen, and phosphorus on the nutrient absorption and fruit quality of Korla fragrant pears were investigated through factor tests to determine the appropriate amounts of water, nitrogen, and phosphorus. A coupling test of water, nitrogen, and phosphorus was used to examine the effects of water and fertilizer coupling on the growth, fruit yield, and fruit quality of Korla fragrant pears to provide theoretical and technical support for strategic water and fertilizer management of Korla fragrant pears.

2. Materials and Methods

2.1. Summary of Experimental Sites

The study was conducted at the 14th company of the 9th Regiment of Alar City of the 1st Agricultural Division of Xinjiang Production and Construction Corps. The study area has a continental arid desert climate with little snow in the winter and strong surface evaporation. The physical and chemical properties of the test sites are listed in Table 8. The soil conductivity is 104.64 $\mu s \cdot cm^{-1}$, pH is 8.45, organic matter is 5.10 $g \cdot kg^{-1}$, salt content is 0.45 $g \cdot kg^{-1}$, alkali-hydrolytic nitrogen, available phosphorus and available potassium are 6.51 $mg \cdot kg^{-1}$, 17.31 $mg \cdot kg^{-1}$, and 70.38 $mg \cdot kg^{-1}$, respectively.

Table 8. Fertility of the test site.

	Soil depth			
Index	**0–20 cm**	**20–40 cm**	**40–60 cm**	**60–80 cm**
Soil bulk density ($g \cdot cm^{-3}$)	1.60	1.56	1.43	1.38

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pH	8.37	8.45	8.48	8.51
Electric conductivity (μs·cm^{-1})	119	117	92.05	90.5
Organic matter (g·kg^{-1})	8.16	6.44	4.36	1.43
Salinity (g·kg^{-1})	0.61	0.68	0.71	0.74
Alkali-hydrolyzed nitrogen (mg·kg^{-1})	12.75	8.05	3.85	1.4
Rapidly available phosphorus (mg·kg^{-1})	27.29	26.86	10.50	4.57
Rapidly available potassium (mg·kg^{-1})	93	81.5	70	37

2.2. Test Materials and Design

The experimental subjects were grafted five-year-old fragrant pear trees with a row spacing of 1.5 m × 4 m. The soil type was sandy loam, and drip irrigation was used. In the first year, a single factor test was conducted to determine the appropriate water, nitrogen, and phosphorus inputs. In the second year, a water and fertilizer coupling test was conducted to determine the coupling model of irrigation and fertilizer application to improve the growth, fruit quality, and yield of Korla fragrant pears.

A single-factor experiment was conducted using a completely random design. A single-factor experiment was set up with three factors and five levels for each (Table 9). Among them, N3 and P3 were the experimental routine fertilizer rates; N1 and P1 were the ultra-low fertilizer rate and 0.5 times the conventional fertilizer rate; N2 and P2 were the low fertilizer rate and 0.75 times the conventional fertilizer rate; N4 and P4 were the high fertilizer rate and 1.25 times the conventional fertilizer rate; and N5 and P5 were the ultra-high fertilizer rate and the conventional fertilizer rate 1.5 times, for a total of 15 processes. Each treatment was repeated three times, and 45 plots were selected. Ten fragrant pear trees, with similar growth rates, were selected from each plot. The water and fertilizer coupling experiment was designed as a three-factor, two-level completely randomized block design, with a total of eight treatments. Each treatment was repeated three times, and 24 plots were divided (Table 10).

Table 9 Single-factor experimental design.

ID	Experimental factor	Factor level	Processing code
1	Irrigation quantity during growth period (m^3·hm^{-2})	5460	W1
2		5880	W2
3		6300	W3
4		6720	W4
5		7140	W5
6	Nitrogen fertilizer application rate (kg N·hm^{-2})	150	N1
7		225	N2
8		300	N3
9		375	N4
10		450	N5
11	Amount of phosphate fertilizer applied (kg P_2O_5·hm^{-2})	75	P1
12		150	P2
13		225	P3
14		300	P4
15		375	P5

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Table 10. Design of water and fertilizer coupling test.

ID	Processing code	Irrigation quantity during growth period ($m^3 \cdot hm^{-2}$)	Nitrogen fertilizer application rate (kg $N \cdot hm^{-2}$)	Amount of phosphate fertilizer applied (kg $P_2O_5 \cdot hm^{-2}$)
1	T1	6300	300	225
2	T2	6300	300	300
3	T3	6300	375	225
4	T4	6300	375	300
5	T5	6720	300	225
6	T6	6720	300	300
7	T7	6720	375	225
8	T8	6720	375	300

2.3. Index Determination Method

2.3.1. Determination of Plant Growth Index

For determination of the leaf area index, three non-adjacent fruit trees were selected from each plot and a canopy analysis instrument (LP-80) was used for five canopy measurements at the flowering (mid–late March to early April), young fruit development (mid–late April to early May), early fruit expansion (mid-May to early June), late fruit expansion (mid-June to late July), and maturity (early August) stages. For assessment of the root growth index, three non-adjacent fruit trees were selected from each plot and root samples were collected before and after fruit harvesting. LA-S was used for scanning, and the WinRHIZO system was used to measure the root density and root surface area.

2.3.2. Leaf Collection and Nutrient Determination

Four fragrant pear trees with similar growth were randomly selected from each plot, and one new branch and one biennial branch were selected from the east, west, south, and north directions, respectively. New branches were collected at the young fruit development stage (mid–late April to early May), early fruit expansion stage (mid-May to early June), late fruit expansion stage (mid-June to late July), and maturity stage (early August). Fifteen leaves were collected from each raw and second-year branch, labeled, and brought back to the laboratory for the determination of total nitrogen and total phosphorus content. The leaves were boiled in H2SO4-H2O2, the total nitrogen content was determined using the Kay nitrogen determination method, and the total phosphorus content was determined using the vanadium molybdenum yellow colorimetric method.

2.3.3. Determination of Fruit Quality Index

For determination of the fruit shape index, during the young fruit growth stage, four non-adjacent fruit trees were selected from each plot, and the fruit trees were divided into upper and lower layers. One disease-free fruit with a uniform shape was selected from each side of the selected fruit trees. Eight healthy young fruits were randomly selected from each plot, and the longitudinal and transverse diameters of the fruits were measured every 15 d using digital Vernier calipers. The pear fruit shape index was calculated as follows:

Fruit shape index = fruit longitudinal diameter/fruit transverse diameter

For determination of pear fruit quality, at the fruit ripening stage, 30 fresh fruits were randomly selected from each plot to determine fruit quality indices. Fruit hardness, stone cell content, soluble solids, soluble sugar content, titratable acid content, vitamin C content, total phenol content, and flavonoid content were determined. Fruit hardness was measured using a fruit hardness tester. Fruit stone cell content was determined using a freezing method. Fruit soluble solids (handheld saccharometer), soluble sugars (concentrated sulfate-anthranone colorimetric method), titratable acids (ethanol extraction-lye-titration method), vitamin C (fluorescence colorimetric method), total phenols, and flavonoids (spectrophotometric colorimetric method) were examined.

2.4 Data Processing and Analysis

Excel 2016 was used to organize, analyze, and calculate the test data. DPS 25 software was used for variance and significance analyses ($p<0.05$). The least squares method was used to draw a nonlinear regression fitting curve to fit the fruit growth trend under different treatments, in which time was the independent variable and fruit shape index was the dependent variable. The fruit quality index was analyzed using the grey correlation degree. The correlation coefficient represented the correlation degree value of the corresponding dimension between the subsequence and the parent sequence, and the larger the number, the stronger the generation correlation. The correlation coefficients under different treatments were compared to obtain the water–fertilizer coupling treatment with a higher degree of correlation and better fruit quality. Origin 2018 software was used to create the relevant charts for the test data.

3. Results

3.1. Effects of the Amount of Water and Fertilizer on Leaf Nutrient Change Change Dynamics in Korla Fragrant Pear

3.1.1. Effects of Water and Fertilizer Dosage on Total Nitrogen in Korla Fragrant Pear Leaves

As shown in Figure 1, with the progress of the growth period, the leaves of both the current and perennial branches showed a trend of first decreasing and then slowly increasing. The main reason for this was that pear trees were in the vegetative growth stage in the early stages and stored substantial amounts of nutrients. However, as the growth period progressed, pear trees shifted from vegetative to reproductive growth, and the nutrients stored in the pear trees migrated to the developing fruits. Therefore, the residual nutrients in the leaves began to decline. By September, the fruits were mature, nutrients in the tree had reached saturation, and parts began to accumulate. The amount of irrigation significantly affected the total nitrogen content of leaves of Korla pears, and the total nitrogen content of leaves of annual branches and perennial branches treated with W3 and W4 was the highest. In September, the total nitrogen content of the leaves of annual and perennial branches treated with W3 and W4 was significantly higher than that of the other treatments. The nitrogen fertilizer application rate significantly affected the total nitrogen content of Korla pear leaves, and the total nitrogen content of Korla pear leaves treated with N3 and N4 was relatively high. In June, July, and September, the total leaf nitrogen content of the annual branches treated with N3 and N4 was significantly higher than that of the other treatments. In July, August, and September, the total nitrogen content of the perennial branches treated with N3 was significantly higher than that of the other treatments.

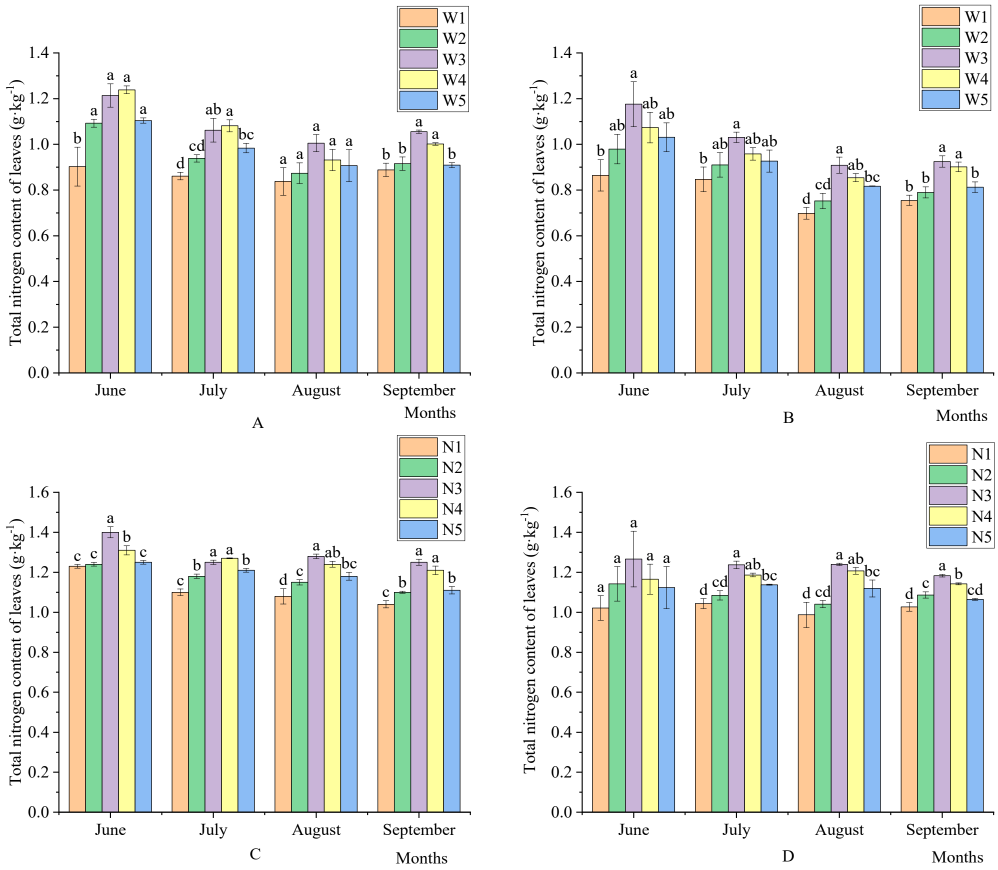

Figure 1. Effects of different amounts of water and fertilizer on total nitrogen content in leaves. Note: (A) Total nitrogen content of leaves of current-year branches under different irrigation levels; (B) total nitrogen content of leaves of perennial branches under different irrigation amounts; (C) total nitrogen content in leaves of current-year branches under different nitrogen application rates); and (D) total nitrogen content of leaves of perennial branches under different nitrogen application rates.

3.1.2. Influence of Water and Fertilizer Dosage on Total Phosphorus of Korla Fragrant Pear Leaves

As shown in Figure 2, the total phosphorus content of the leaves of perennial branches was lower than that of the leaves of current branches. The reason for this phenomenon is that June and July are the periods of more vigorous fruit development, their respiration is significant, and they consume higher quantities of phosphorus compared with the mature stage. The leaves of the current branches have stronger activity than the leaves of the perennial branches. Therefore, the leaves of the current branches have stronger accumulation capacity for phosphorus. In August and September, the growth of the tree body was slow and respiration was weakened and the leaf phosphorus consumption was lower than that of the previous period. Irrigation amount significantly affected the total phosphorus content in leaves of Korla fragrant pear, and the W3 and W4 treatments had the highest total phosphorus content in leaves of annual and perennial branches. The amount of P fertilizer significantly affected the total P content in Korla fragrant pear leaves. In July, August, and September, the total P content of P3 treated perennial branches was significantly higher than that of the other treatments.

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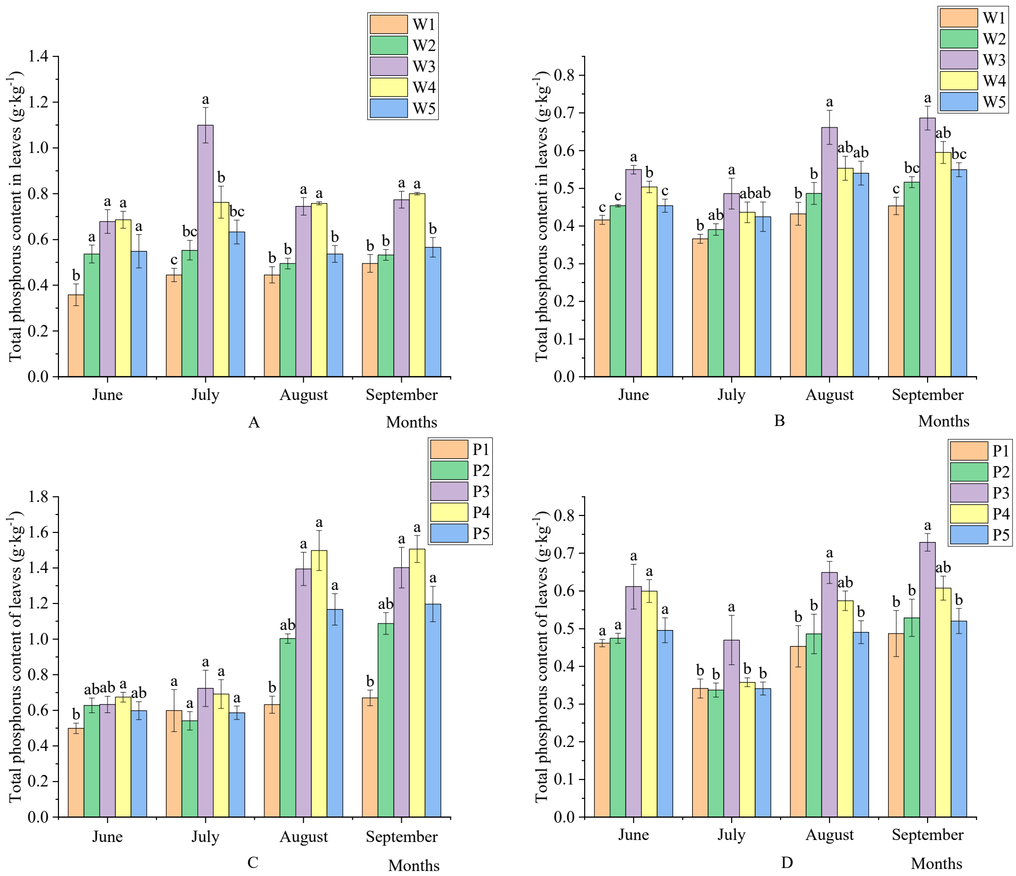

Figure 2. Effects of different amounts of water and fertilizer on total phosphorus content in leaves. Note: (A) Total nitrogen content of leaves of current-year branches under different irrigation levels; (B) total nitrogen content of leaves of perennial branches under different irrigation amounts); (C) total nitrogen content in leaves of current-year branches under different nitrogen application rates); and (D) total nitrogen content of leaves of perennial branches under different nitrogen application rates.

3.2. Influence of Water and Fertilizer Dosage on Fruit Quality of Korla Fragrant Pear

3.2.1. Influence of Irrigation Amount on Fruit Quality of Korla Fragrant Pear

Table 1 shows that the amount of irrigation significantly affected the fruit quality of Korla fragrant pears. Among them, the contents of Vc, soluble solids and soluble sugar were W3>W4>W5>W1>W2. The Vc content of fruits treated with W3 and W4 significantly increased by 5.1–15.8% compared with other treatments. The soluble solids content of fruits treated with W3 and W4 significantly increased by 5.8–11.2% compared with other treatments. The soluble content of fruits treated with W3 and W4 significantly increased by 5.8–11.2% compared with other treatments. Compared with other treatments, the sugar content significantly increased by 6.2–22.9%, and the titratable acid content of fruits treated with W3 and W4 significantly decreased by 2.1–26.3%. However, the stone cell content of fruits treated with W3 and W4 significantly increased compared with other treatments. In conclusion, the fruit quality of Korla fragrant pears under the W3 and W4 treatments was the highest.

Table 1. Effects of irrigation amount on pear fruit quality.

Test treatment	Vc (mg/100g)	Soluble solid content	Stone cell content (%)	Soluble sugar (%)	Titratable acid (%)
W1	8.71 ± 0.13 d	10.43 ± 0.25 c	2.50 ± .033 d	16.17 ± 1.85 c	1.24 ± 0.02 a
W2	9.31 ± 0.07 c	10.78 ± 0.34 b	3.20 ± 0.04 c	16.97 ± 0.76 c	1.17 ± 0.06 b
W3	10.10 ± 0.13 a	11.61 ± 0.26 a	3.66 ± 0.55 ab	19.87 ± 0.11 a	0.95 ± 0.03 d
W4	9.82 ± 0.02 b	11.56 ± 0.24 a	3.82 ± 0.11 a	18.71 ± 0.88 ab	1.00 ± 0.03 c
W5	9.36 ± 0.06 c	10.92 ± 0.41 b	3.18 ± 0.38 bc	17.62 ± 0.64 bc	1.02 ± 0.03 c

3.2.2. Effects of Nitrogen Application Amount on Fruit Quality of Korla Fragrant Pear

As shown in Table 2, the amount of nitrogen applied significantly affected the fruit quality of Korla fragrant pears. Among them, the contents of Vc, soluble solid matter, soluble sugar and stone cell were N3>N4>N5>N1>N2. The Vc content of fruits treated with N3 and N4 significantly increased by 1.9–20.8% compared with other treatments. The soluble sugar content of fruits treated with N3 and N4 significantly increased by 9.9–41.9% compared with other treatments, and the fruit treated with N3 and N4 significantly increased by 9.9–41.9%. The content of solid stone cells significantly increased by 4.5–37.9% compared with other treatments, and the titratable acid content of fruits treated with N3 and N4 significantly decreased by 2.1–25.4% compared with other treatments. In conclusion, the fruit quality of Korla Xiang pears treated with N3 and N4 was the highest.

Table 2. Effects of nitrogen application on pear fruit quality.

Test treatment	Vc (mg/100g)	Soluble solid content	Stone cell content (%)	Soluble sugar (%)	Titratable acid (%)
N1	9.20 ± 0.15e	10.94 ± 0.32 c	2.53 ± 0.46 c	14.44 ± 2.01 c	1.14 ± 0.09 a
N2	9.71 ± 0.11d	11.38 ± 0.39 b	2.81 ± 0.26 bc	15.09 ± 1.05 c	1.03 ± 0.04 b
N3	11.11 ± 0.06a	12.27 ± 0.42 a	3.49 ± 0.03 a	20.49 ± 2.84 a	0.85 ± 0.02 c
N4	10.31 ± 0.13b	12.04 ± 0.09 a	3.25 ± 0.22 a	20.01 ± 2.86 ab	0.95 ± 0.02 b
N5	10.12 ± 0.04c	11.42 ± 0.50 b	3.11 ± 0.07 ab	18.20 ± 2.14 b	0.97 ± 0.03 b

3.2.3. Effects of Phosphorus Application Amount on Fruit Quality of Korla Fragrant Pear

As shown in Table 3, the amount of phosphorus applied significantly affected the fruit quality of Korla fragrant pears. Among them, the contents of Vc, soluble sugar and stone cell were P3>P4>P5>P1>P2. The Vc content of fruits treated with P3 and P4 significantly increased by 6.3–21% compared with other treatments. The soluble solid content of fruits treated with P3 and P4 significantly increased by 1.3–9.8% compared with other treatments, and the soluble sugar content of fruits treated with P3 and P4 significantly increased by 1.3–9.8%. Compared with other treatments, the fruit stone cell content of P3 and P4 treatments significantly increased by 6.1–61.2%, and the titratable acid content of fruits of P3 and P4 treatments significantly decreased by 14.8–28.5%. In conclusion, the fruit quality of Kuerla pears under the P3 and P4 treatments was the highest.

Table 3. Effect of phosphorus application amount on pear fruit quality.

Test treatment	Vc (mg/100g)	Soluble solid content	Stone cell content (%)	Soluble sugar (%)	Titratable acid (%)
P1	8.25 ± 0.04 d	10.37 ± 0.28 c	2.72 ± 0.32 d	12.01 ± 3.01 c	1.23 ± 0.05 a
P2	8.70 ± 0.08 c	10.88 ± 0.35 b	2.93 ± 0.34 cd	13.28 ± 2.47 c	1.19 ± 0.06 a
P3	9.98 ± 0.06 a	11.39 ± 0.32 a	3.56 ± 0.32 a	19.36 ± 1.11 a	0.88 ± 0.06 c
P4	9.92 ± 0.12 a	11.02 ± 0.21 b	3.40 ± 0.07 ab	16.94 ± 1.51 b	0.92 ± 0.09 c
P5	9.33 ± 0.06 b	10.59 ± 0.30 c	3.12 ± 0.19 bc	15.96 ± 1.25 b	1.08 ± 0.02 b

Overall, the W3, W4, N3, N4, P3, and P4 treatments showed the best leaf nutrient use and fruit quality. Therefore, the W3 (6300 $m^3 \cdot hm^{-2}$), W4 (6720 $m^3 \cdot hm^{-2}$), N3 (300 kg N·hm^{-2}), N4 (375 kg N·hm^{-2}), P3 (225 kg P2O5·hm^{-2}), and P4 (300 kg P2O5·hm^{-2}) treatments were applied as the fertilization and irrigation levels used in the coupling test.

3.3. Influence of Water and Fertilizer Coupling on Korla Fragrant Pear Growth

3.3.1. Effects of Water and Fertilizer Coupling on Korla Fragrant Pear Root Density and Root Surface Area

As shown in Table 4, the root density and root surface area of the 40–60 cm soil layer were higher than those of the 20–40 cm soil layer and those of–0–20 cm soil layers. This indicated that the roots were mainly concentrated in the 40–60 cm soil layer. The coupling of water, nitrogen, and phosphorus had no significant effect on the 0–60 cm root density of Korla pears. The coupling of water, nitrogen,

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and phosphorus significantly affected the root surface area of the 0–60 cm soil layer. At the early stages of flowering, the root surface area of 0–20 cm soil layer was T6>T1>T5>T7>T3>T2>T4>T8, and that of 20–40 cm soil layer was T1>T2> T6>T7>T3>T5>T4>T8. In the 40–60 cm layer, the root surface area was T1>T4>T7>T3>T6>T2>T8>T5.

As shown in Table 4, the root change trend was consistent with that of the early flowering period, indicating that the root system was mainly concentrated at soil depths of 40–60 mm. After fruit harvest, the root surface area of the 0–20 cm soil layer was T1>T5>T6>T7>T2>T3>T8>T4. The root surface area of the 20–40 cm soil layer was T1>T5>T7>T4>T6>T3>T2>T8. The root surface area of the 40–60 cm soil layer was T7>T1>T4>T8>T3>T2>T5>T6.

Table 4. Effects of water and fertilizer coupling on root density and root surface area of Korla fragrant pear before flowering.

Test treatment	0~20 root density(cm·cm^{-3})	20~40 root density(cm·cm^{-3})	40~60 root density (cm·cm^{-3})	0~20 root surface area(cm^2)	20~40 root surface area(cm^2)	40~60 root surface area(cm^2)
T1	0.06 ± 0.015a	0.09 ± 0.006a	0.16 ± 0.01a	8.64 ± 1.93ab	17.78 ± 2.23a	22.4 ± 1.22a
T2	0.04 ± 0.012a	0.11 ± 0.006a	0.15 ± 0.01a	5.49 ± 0.51c	13.78 ± 0.99bc	17.52 ± 1.32b
T3	0.05 ± 0.006a	0.10 ± 0.006a	0.15 ± 0.01a	6.22 ± 1.66c	12.02 ± 2.05b	18.66 ± 1.11b
T4	0.04 ± 0.01a	0.07 ± 0.01a	0.12 ± 0.01a	5.35 ± 1.12c	11.03 ± 0.8bc	21.92 ± 1.42a
T5	0.05 ± 0.006a	0.07 ± 0.006a	0.13 ± 0.01a	6.77 ± 0.75bc	12.01 ± 1.63b	17.29 ± 1.3b
T6	0.05 ± 0.006a	0.10 ± 0.01a	0.14 ± 0.03a	9.87 ± 1.09a	13.37 ± 0.64b	18.23 ± 1.44b
T7	0.04 ± 0.006a	0.09 ± 0.006a	0.14 ± 0.01a	6.56 ± 0.94bc	12.76 ± 2.32b	21.62 ± 1.06a
T8	0.04 ± 0.006a	0.07 ± 0.006a	0.11 ± 0.01a	5.28 ± 2.17c	9.05 ± 1.7c	17.44 ± 0.78b

Table 5. Effects of water and fertilizer coupling on root density and root surface area of Korla fragrant pear after harvest. Note: T1 (W3N3P3), T2 (W3N3P4), T3 (W3N4P3), T4 (W3N4P4), T5 (W4N3P3), T6 (W4N3P4), T7 (W4N4P3), T8 (W4N4P4).

Test treatment	0~20 root density(cm·cm^{-3})	20~40 root density(cm·cm^{-3})	40~60 root density(cm·cm^{-3})	0~20 root surface area(cm^2)	20~40root surface area(cm^2)	40~60 root surface area(cm^2)
T1	0.06 ± 0.01a	0.11 ± 0.01a	0.21 ± 0.01a	12.88 ± 0.65a	19.96 ± 0.62a	28.38 ± 1.36a
T2	0.06 ± 0.02a	0.12 ± 0.012a	0.17 ± 0.006a	9.91 ± 0.93bc	14.40 ± 2.15bc	23.37 ± 1.8c
T3	0.05 ± 0.01a	0.12 ± 0.006a	0.19 ± 0.01a	9.66 ± 2.3bc	15.07 ± 1.09bc	24.11 ± 1.56bc
T4	0.06 ± 0.01a	0.12 ± 0.01a	0.16 ± 0.01a	7.79 ± 1.61c	16.58 ± 3.56b	26.41 ± 0.9ab
T5	0.07 ± 0.01a	0.12 ± 0.012a	0.18 ± 0.006a	11.14 ± 1.09ab	16.83 ± 3.52b	20.31 ± 0.89d
T6	0.06 ± 0.01a	0.11 ± 0.006a	0.16 ± 0.006a	11.11 ± 1.69ab	16.36 ± 1.56b	19.37 ± 0.33d
T7	0.07 ± 0.01a	0.13 ± 0.012a	0.16 ± 0.006a	10.38 ± 1.81abc	16.69 ± 0.95b	28.61 ± 1.53a
T8	0.06 ± 0.01a	0.13 ± 0.006a	0.15 ± 0.01a	8.36 ± 2.17bc	12.31 ± 0.94c	24.25 ± 1.92bc

3.3.2. Influence of Water and Fertilizer Coupling on the Change in Leaf Area Index of Korla Fragrant Pear

The results showed that the overall change trend in leaf area index showed a first increase and then slow decrease. At the flowering and young fruit development stages, the leaf area index under the T3 and T7 treatments was significantly higher than that under the other treatments. The leaf area index increased rapidly during the fruit expansion stage. At the strong fruit stage, the LAI began to decrease with dead branches and leaves. The change in leaf area index under the T1 treatment was the largest, decreasing by 0.71 cm^2·cm^3. At maturity, the leaf area index under the T5 treatment showed the largest change, and the leaf area index under the T1, T2, T3, and T4 treatments was significantly higher than that under the other treatments. In general, the leaf area index reached its maximum during the fruit expansion stage and the leaf area index began to decline in the strong fruit stage.

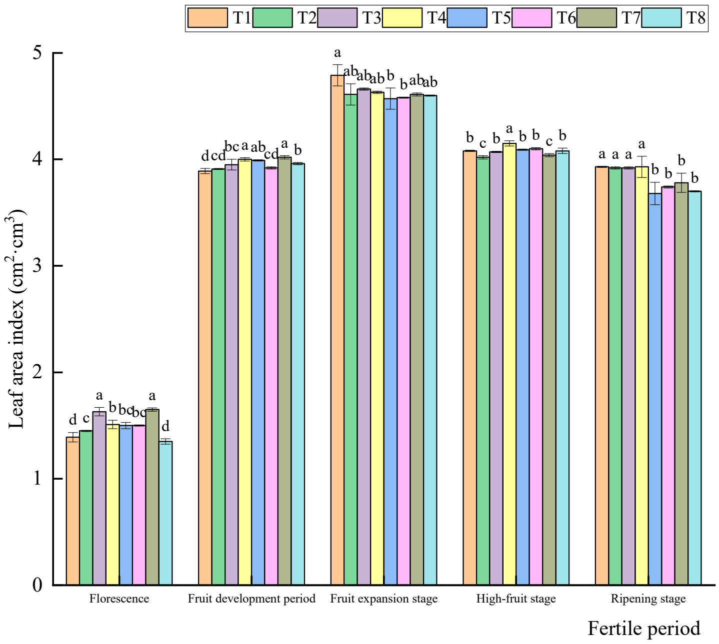

Figure 3. Effects of different water and fertilizer coupling treatments on the leaf area index. Note: T1 (W3N3P3), T2 (W3N3P4), T3 (W3N4P3), T4 (W3N4P4), T5 (W4N3P3), T6 (W4N3P4), T7 (W4N4P3), T8 (W4N4P4).

3.3.3. Influence of Water and Fertilizer Coupling on Yield of Korla Fragrant Pear

As shown in Table 6, there was a significant difference in fruit per fruit weight between different water–fertilizer coupling treatments, with fruit per fruit weight ranging from 137.61 to 114.39 g. Among these, the T3 treatment had the largest fruit per fruit weight (137.61 g). The fruit per fruit weight between different treatments was T3>T1>T5>T8>T4>T3>T7. The total fruit yield differed under the different water and fertilizer combined treatments, and the total fruit yield was T3>T6>T2>T7>T1>T5>T4>T8. The primary fruit production rate for each treatment was in the following order: T3>T7>T2>T6>T8>T1>T5>T4. The primary fruit rate in the T3 treatment was the highest (78.14%), and the fruit rate in the T4 treatment was the lowest (64.44%). The T3 treatment had the highest fruit yield, the largest single fruit weight, and the highest primary fruit rate.

Table 6. Changes in fruit yield and single fruit weight under different water and fertilizer coupling treatments. Note: T1 (W3N3P3), T2 (W3N3P4), T3 (W3N4P3), T4 (W3N4P4), T5 (W4N3P3), T6 (W4N3P4), T7 (W4N4P3), T8 (W4N4P4).

Test treatment	Weight of single fruit (g)	Yield (kg·hm⁻²)	Primary fruit rate (%)	Secondary fruit rate (%)	Tertiary fruit rate (%)
T1	130.28 ± 11.17 ab	4388.89 c	67.09% d	18.38% b	14.53% a
T2	122.50 ± 12.01 ab	4463.89 bc	73.62% bc	12.76% d	13.63% ab
T3	137.61 ± 6.115 a	4916.67 a	78.14% a	9.72% e	12.15% bc
T4	125.40 ± 3.383 ab	4194.44 d	64.44% e	21.85% a	13.71% ab
T5	129.90 ± 5.661 ab	4258.33 d	64.83% e	20.73% a	14.45% a
T6	115.31 ± 7.566 b	4533.33 b	72.43% c	16.30% c	11.27% c
T7	114.39 ± 6.496 b	4447.22 bc	74.29% b	16.21% c	9.49% d
T8	126.38 ± 14.97 ab	4091.67 d	72.03% c	18.86% b	9.10% d

3.3.4. Influence of Water and Fertilizer Coupling on Fruit Shape Index of Korla Fragrant Pear

The least-squares method was used to fit the fruit shape index curve for the different measurement days. Eight processing, according to the results of regression fitting curve

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determination coefficient (R2) shown as T3 (0.541) > T6 (0.408) > T4 (0.407) > T5 (0.375) > T2 (0.340)> T7 has (0.322) >T1 (0.317) > T8 (0.294). From the goodness of fit, the growth trend of the fruit shape under the T3 treatment was closest to the fitting growth curve, and R^2 was closest to 1, which was consistent with the growth law.

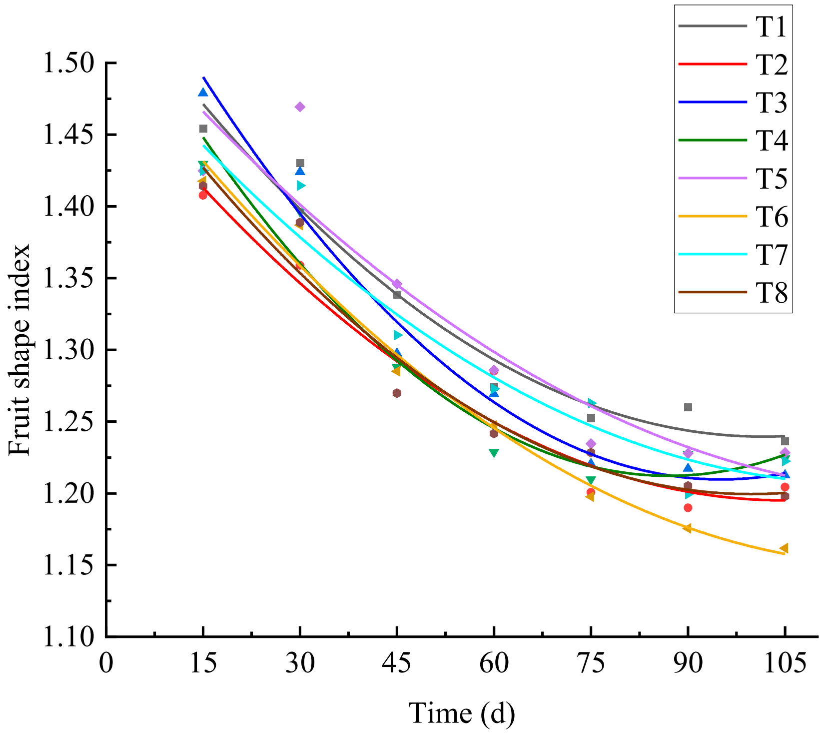

Figure 4. Fitted growth curves of the fruit shape index under different water and fertilizer coupling treatments. Note: T1 (W3N3P3), T2 (W3N3P4), T3 (W3N4P3), T4 (W3N4P4), T5 (W4N3P3), T6 (W4N3P4), T7 (W4N4P3), T8 (W4N4P4).

3.4. Effects of Water and Fertilizer Coupling on Fruit Quality of Korla Fragrant Pear

The results of the grey correlation degree analysis showed that the stone cell content, fruit hardness, Vc content, soluble sugar content, total phenol content, and titratable acid content of fruit had a strong correlation with the fruit quality of Korla fragrant pear and were the key indicators affecting the fruit quality. The results of the gray relational degree analysis showed that the quality of the Korla fragrant pears was T3>T1>T7>T5>T2>T8>T6>T4. The fruit quality of Korla fragrant pears treated with treatment T3 was the highest (Table 7).

Table 7 Grey relational degree analysis. Note: T1 (W3N3P3), T2 (W3N3P4), T3 (W3N4P3), T4 (W3N4P4), T5 (W4N3P3), T6 (W4N3P4), T7 (W4N4P3), T8 (W4N4P4)).

Correlation coefficient results								
Test treatment	T1	T2	T3	T4	T5	T6	T7	T8
Stone cell content	0.9748	0.9532	0.9941	0.9524	0.9511	0.9349	1.0000	0.9653
hardness	0.8212	0.8078	0.8048	0.8043	0.8063	0.7980	0.8049	0.8143
Soluble solid	0.3449	0.3622	0.3505	0.3659	0.3593	0.3662	0.3714	0.3504
Soluble sugar	0.6353	0.5874	0.6395	0.6120	0.6132	0.5997	0.5561	0.5871
Titratable acid	0.5391	0.5332	0.5414	0.5314	0.5448	0.5260	0.5384	0.5385
Vc	0.7382	0.7461	0.7433	0.7408	0.7487	0.7787	0.7449	0.7081
Total phenol	0.5851	0.5640	0.5714	0.5285	0.5622	0.5428	0.5951	0.5869
flavonoid	0.3757	0.3752	0.3762	0.3750	0.3755	0.3753	0.3757	0.3759
sort	2	5	1	8	4	7	3	6

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4. Discussions

4.1. Effects of Water, Nitrogen, and Phosphorus on Korla Fragrant Pear Growth and Fruit Quality

Water is the most important factor in plant growth. Once the water supply stops during the growth process, the plant will not survive. In the case of drought and water shortages, the soil cannot supply water to fruit trees in sufficient time. This weakens the photosynthesis and metabolic capacity of the plants, reduces the use rate of fertilizer, and, therefore, reduces the accumulation of organic matter in plants. When there is sufficient soil water present, fruit trees can obtain a large amount of supplementary water from the soil environment. This, in turn, increases the conversion rate of the applied fertilizer, and improves the fertilizer use rate. In this study, under the drip irrigation mode, the total nitrogen and total phosphorus contents in Korla pear leaves were the highest when the irrigation amount was 6300–6720 m^3 ha^{-1}, and the fruit quality of Korla pears was higher. In line with the results of this study, Liu Xiaogang et al. [18] found that appropriate irrigation promoted the nutrient use efficiency of mango. Chen Lei et al. [19] found that appropriate irrigation reduced reactive oxygen species content in the calyx tube of Korla Fragrant pear and promoted quality improvement of Korla fragrant pear. This is mainly because suitable irrigation promoted the root growth of Korla fragrant pear, improved the water conductivity of Korla fragrant pear, improved the transport efficiency of nutrients absorbed by the root system to the aboveground parts, and improved the fruit quality of Korla fragrant pear using the accumulation of nutrients in leaves [20].

Nitrogen and phosphorus are essential nutrients for plant growth and play irreplaceable roles in the growth and development of fruit trees [21–23]. The synthesis of proteins and chlorophyll in fruit trees requires nitrogen, and the lack of nitrogen affects physiological growth, fruit yield, and fruit quality. Similarly, research results on phosphorus have found that insufficient phosphorus supply severely affects the absorption of nitrogen by plants. Meanwhile, excessive phosphorus application inhibits the normal growth of plants and reduces fruit yield and quality [24]. The results showed that when the nitrogen input was 300–375 kg N ha^{-1} and phosphorus input was 225–300 kg P ha^{-1}, the nitrogen and phosphorus contents in Korla pear leaves were relatively high, and the quality of Korla pears was higher. The results indicated that under the current production conditions, the nitrogen input was 300–375 kg N ha^{-1} and the phosphorus input was 225–300 kg P ha^{-1}, which were the most suitable nitrogen and phosphorus inputs.

4.2. Effects of Water and Fertilizer Coupling on Growth, Fruit Yield, and Quality of Korla Fragrant Pear

Strategic water and fertilizer management can promote fruit tree growth. Root systems are water- and fertilizer-oriented, and root indices, such as root density and root diameter, are highly sensitive to surrounding environmental factors and nutrient supply [25]. The results of this study also showed that under the current production conditions, the appropriate water–fertilizer coupling treatment (T3, T4) was beneficial to the root growth of Korla pear, and the root area and root density at 0–60 cm were the highest. Meanwhile, the coupling of water and fertilizer also significantly affected the leaf growth of Korla fragrant pear, and the leaf area index showed a trend of rapid rise–slow rise–slow decline during the whole growth period. This is because the fruit trees grow rapidly under the influence of water and fertilizer from the flowering stage to the early stage of fruit expansion, as well as with the growth of new branches, and from the late stage of fruit expansion to fruit maturity. The leaf area index slowly declines as nutrients are transferred to the fruit and the tree leaves fall. Compared with other treatments, the leaf area index of the T3 and T4 treatments was always higher, which also indicated that suitable water–fertilizer coupling promoted the leaf growth of Korla fragrant pear.

Strategic water and fertilizer management can promote fruit growth and improve fruit yield and quality. Wang [26] studied the effect of water and fertilizer coupling on the growth and flowering of dwarf Fuji Apple saplings and showed through experiments that an appropriate water and fertilizer combination and management could significantly improve the nutrient status of red Fuji seedlings and promote the development of new shoots so that they could bloom and fruit in advance. According to a study by Yanjie et al. [27] on the effects of irrigation and fertilization mode on the growth, fruit formation process, and yield of longan, strategic water and fertilizer management improved the growth rate of longan trees, as well as the fruit yield and fruit quality. In line with the results of previous studies, the results of this study showed that T3 treatment had the best fit for the Korla fragrant pear fruit shape index. The fruit yield of Korla pears under the T3 treatment was the highest, and the primary fruit rate was as high as 78%. This was significantly higher than that of the other treatments, indicating that suitable water and fertilizer treatments were beneficial to the growth and development of Korla pear fruit. Suitable water and fertilizer promoted root growth, which was conducive to the transport of water and fertilizer to the ground, and, therefore, promoted the growth of Korla fragrant pear fruit. Meanwhile, suitable water and fertilizer application can improve the leaf area index and stomatal conductance of fruit leaves [28]. This means that photosynthesis can be maintained, which is conducive to the formation of photosynthetic products and promotes fruit growth and yield.

A suitable combination of water and fertilizer can improve fruit quality. The results of this study have shown that water and fertilizer control within a suitable range can increase the soluble solid content of Korla pear, increase the soluble sugar content, reduce the titratable acid content, reduce the fruit stone cell content, and improve the fruit quality. However, insufficient or excessive water and fertilizer can reduce the fruit quality. The main reasons were as follows: the lack of water and fertilizer affected the growth of Korla pear fruit, and then affected the accumulation of photosynthetic products and fruit quality; excessive water and fertilizer led to excessive nutrient growth of fruit trees, reduced the distribution of photosynthetic products to fruit, and affected the accumulation of photosynthetic products and fruit quality of Korla Xiangli fruit. In conclusion, under the current production conditions, 6300 $m^3 \cdot hm^{-2}$ irrigation, 375 $kg \cdot hm^{-2}$ nitrogen application and 225 $kg \cdot hm^{-2}$ phosphorus application are the recommended water and fertilizer inputs.

5. Conclusions

The single-factor test of water, nitrogen, and phosphorus showed that the contents of total nitrogen and total phosphorus in the leaves of Korla fragrant pear were significantly higher than those of other irrigation treatments when the irrigation amount was 6300–6720 m^3 ha^{-1}. The contents of soluble sugar and Vc in fruits were significantly higher than those of the other irrigation treatments. The total nitrogen content of Korla pear leaves was significantly higher than that of other nitrogen treatments when the nitrogen application rate was 300–375 kg N ha^{-1}. The soluble sugar and Vc contents of Korla pear fruits were the highest, which were 20.0–20.5% and 10.3–11.1/100g, respectively. The total phosphorus content of Korla pear leaves was significantly higher than that of other phosphorus treatments when the phosphorus application rate was 225–300 kg P ha^{-1}. The soluble sugar and Vc contents of Korla pear fruits were the highest, which were 16.9–19.4% and 9.9–10.0/100 g, respectively. In summary, an irrigation amount of 6300–6720 m^3 ha^{-1}, a nitrogen application amount of 300–375 kg N ha^{-1} and a phosphorus application amount of 225–300 kg P ha^{-1} are suitable water, nitrogen, and phosphorus inputs under the current production conditions.

The coupling test of water and fertilizer showed that the irrigation amount was 6300 m^3 ha^{-1}, the nitrogen application rate was 375 kg N ha^{-1}, and the phosphorus application rate was 225 kg P ha^{-1}, 0–60 cm had higher root density and root surface area, higher leaf area index, the best fit curve of fruit shape index, and the highest gray correlation degree of fruit quality. Therefore, an irrigation amount of 6300 m^3 ha^{-1}, a nitrogen application amount of 375 kg N ha^{-1} and a phosphorus application amount of 225 kg P ha^{-1} are recommended for local water and fertilizer treatment.

Author Contributions: T.L. and S.Y. completed all the experimenal work and model analysis,T.L. and Z.G. participated in the drawing up of the manuscript,designed the experment,and wrote the frist draft of the manuscript.J.Z. supervised the research and reviewed the manuscript.X.B. and Q.Z. depicted and discussed.S.A. conducted an investigation.Z.T. participated in mechanism discussions and provided language editing.All authors have red and agreed to the published version of the manuscript.

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Data Availability Statement: The data are available on request from the authors. The data supporting the findings of this study are available from the corresponding author, Jinhu Zhi, upon request.

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