Comprehensive evaluation of the optimal rates of irrigation and potassium application for strawberry

Xiaoqing Yang, Rongcheng Du, Mengchi Zhang, Huawei Feng, Ziqing Wang, Zhi Zhang*

(*College of Horticulture, Northwest A&F University, Yangling 712199, Shaanxi, China*)

Abstract: Accurate and effective management of irrigation and fertilization is essential for efficient greenhouse strawberry production. Here, the effects of the combined application of water and potassium on strawberry growth were evaluated by experimenting with 12 treatments, including four transpiration (ET_c)-based irrigation levels (W1: 100% ET_c, W2: 85% ET_c, W3: 70% ET_c, and W4: 55% ET_c) and three potassium levels according to the target yield (K1: 369.5 kg/hm^2, K2: 307.9 kg/hm^2, and K3: 246.3 kg/hm^2). Various indexes of strawberry yield, fruit quality, water and fertilizer utilization efficiency, and soil nutrient residues were measured. Irrigation and potassium application had significant effects on strawberry production. Higher irrigation levels increased yield (Y), and moderate water and potassium application increased single fruit weight (SFW), water utilization efficiency (WUE), total soluble sugar (TSSC), and the sugar-acid ratio (SAR). While low-application of potassium increased the soluble protein content (SP), partial factor productivity of potassium (PFP_K), and reduce nutrient residues in soil effectively. A comprehensive system for evaluating strawberry growth and its benefits to the soil environment was developed. The FAHP and CRITIC methods were used to calculate the subjective weight and objective weight of each index, respectively. The largest subjective weight was observed for$Y$ (0.200), and the largest objective weight was observed for soil-available potassium (0.101). The final weight was determined using Game theory; Y had the highest weight (0.185), and free amino acids (FAA) had the lowest weight (0.047). Grey relational analysis (GRA) was used to evaluate the optimal irrigation and potassium scheme for accomplishing multiple objectives. The response of the comprehensive score of strawberries to irrigation and potassium exhibited a negative parabolic relationship, and the effect of irrigation was greater than the effect of potassium application. There was a significant interaction between irrigation and potassium application, and an irrigation amount of 2053-2525 m^3/hm^2 with a potassium application rate of 288.1-334.2 kg/hm^2 was optimal for promoting strawberry yield, fruit quality, and efficiency and reducing soil nutrient residues. The results of this study provide new insights that could aid the development of sustainable approaches for enhancing agricultural production.

Keywords: strawberry, irrigation, potassium, FAHP, CRITIC, nutrient residues
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1 Introduction

Strawberry (*Fragaria × ananassa* Duch.) is an economically important crop that is popular among consumers for its bright color, taste, and rich nutritional profile[1]. China is the world's largest strawberry producer, while improper management of water and fertilizer still exists, which limited increases in strawberry yield and quality, and also caused soil environment pollution[2,3]. Strawberry plants have a shallow root system and are highly sensitive to soil water content[4]. Water deficiency can reduce strawberry yields, and excessive irrigation can decrease water use efficiency and fruit quality[4,5]. Fertilization is also an important factor affecting the yield and quality of strawberries, and potassium is often referred to as a quality element because of the important role it plays in quality formation[6]. Appropriate potassium application can improve crop yield, total sugar, the sugar-acid ratio, and Vitamin C content, but excessive potassium application inhibits increases in yield and fruit quality[7-10]. Agricultural water resources are in short supply in China, especially in Northwest China[11]. The consumption of potassium fertilizer has also increased annually, and potassium fertilizer use is heavily dependent on imports[12]. The Fourteenth Five-Year Plan of China has made the development of water-saving agriculture and reductions in chemical fertilizer use a priority. Tailoring the joint application of water and fertilizer to the requirements of crops during their growth period is key for improving resource utilization efficiency.

Agricultural indicators such as crop yield and fruit quality, as well as water and fertilizer utilization efficiency and soil nutrient residues, do not respond in the same way to irrigation and potassium application, making evaluating the effects of the combined application of water and potassium a major challenge[4,5,13,14]. Identifying optimal water and potassium application regimes requires using a multi-index evaluation method and carefully considering the relative importance of each indicator. The fuzzy analytic hierarchy process (FAHP) is effective for determining subjective weights, as the construction of a fuzzy judgment matrix overcomes the problems associated with the consistency test of traditional AHP matrices[15]. The CRITIC method

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Biographies: Xiaoqing Yang, MS, research interest: efficient utilization of water and fertilizer, Email: yxqing708@163.com; **Rongcheng Du**, MS, research interest: efficient utilization of water and fertilizer, Email: 286132762@qq.com;**Mengchi Zhang**, MS, research interest: efficient utilization of water and fertilizer, Email: zhangmc0806@163.com; **Huawei Feng**, BD, research interest: controlled environment agriculture, Email: fhw66876@126.com; **Ziqing Wang**, BD, research interest: controlled environment agriculture, Email: w15215694508@163.com.
***Corresponding author: Zhi Zhang**, PhD, Associate Professor, research interest: intelligent regulation in greenhouse environment and water- fertilizer. College of Horticulture, Northwest A&F University, Yangling 712100, Shaanxi, China. Tel: +86-18702945429, Email: zhangzhione@126.com.

is more effective for determining objective weights because it combines the advantages of principal component analysis (PCA) and the entropy weight method (EWM), which take into account the characteristics of the data and the relationships among indicators[16]. These two weighted evaluation methods have been used for safety evaluation, material selection, and so on[17,18].

The aim of this study was to characterize the effects of the combined application of water and potassium on strawberry yield, quality, utilization efficiency of water and potassium, and soil nutrient residues and determine the optimal application regime for balancing economic and ecological needs. The FAHP and CRITIC methods were used to assign subjective and objective weights to different indexes. Grey relational analysis (GRA) based on Game theory was used to evaluate the combined application of water and potassium and identify the optimal irrigation and potassium application regime.

2 Materials and methods

2.1 Test materials and study site

The experiment was conducted in a large asymmetric plastic greenhouse in Yangling, Shaanxi, China (34°16′N, 108°02′E) from September 2020 to March 2021. The greenhouse (55 m×17 m×6 m) was covered with double plastic films and a thermal insulation quilt. The greenhouse was equipped with a small weather station (Hobo Event Logger, Onset Computer Corporation, USA) that automatically recorded the temperature, humidity, and light radiation intensity. The physical and chemical properties of the test soil with an available nitrogen content of 172.42 mg/kg, an available phosphorus content of 51.74 mg/kg, an available potassium content of 262.42 mg/kg, an electrical conductivity of 587.33 μS/cm, and soil pH of 6.50. The strawberry Hongyan variety was used in this experiment.

2.2 Experimental design

The experiment included 12 treatments with four evapotranspiration (ET_c)-based irrigation levels (W1: 100% ET_c, W2: 85% ET_c, W3: 70% ET_c, and W4: 55% ET_c) and three targets yield-based[19] potassium (K_2O) application levels (K1: 369.5 kg/hm^2, K2: 307.9 kg/hm^2, and K3: 246.3 kg/hm^2), and there were three replicates for each treatment (Table 1). ET_c is the actual evapotranspiration and was calculated as follows:

$$ET_c = ET_0 \cdot K_c \tag{1}$$

Table 1 Irrigation and fertilization design

Treatment	Level of irrigation and potassium	Irrigation amount/m^3·hm^{-2}	Potassium rate/kg·hm^{-2}
T1	W1K1	3058	369.5
T2	W1K2	3058	307.9
T3	W1K3	3058	246.3
T4	W2K1	2599	369.5
T5	W2K2	2599	307.9
T6	W2K3	2599	246.3
T7	W3K1	2140	369.5
T8	W3K2	2140	307.9
T9	W3K3	2140	246.3
T10	W4K1	1529	369.5
T11	W4K2	1529	307.9
T12	W4K3	1529	246.3

Note: W: Transpiration (ET_c)-based irrigation level; K: Potassium levels according to the target yield; W1: 100% ET_c; W2: 85% ET_c; W3: 70% ET_c; W4: 55% ET_c; K1: 369.5 kg/hm^2; K2: 307.9 kg/hm^2; K3: 246.3 kg/hm^2. Same below.

where, K_c denotes the strawberry crop coefficient; ET_0 is the evapotranspiration[20] of the reference crop. Each experimental plot was 10 m long and 1 m wide and arranged in random blocks with a planting density of 90 000 plants/hm^2. The ridge height was 0.4 m, with 2 rows of plants per ridge, and the plots were separated by 0.1 mm of black plastic film to prevent interactions between treatments. Slow seedling irrigation was carried out after strawberry plants were transplanted to the field, and combined water and potassium treatments were conducted after reducing the irrigation frequency of seedlings to every 3-5 d. Under-film drip irrigation was used in the experiment because it reduces the transpiration and evaporation of soil and thus conserves water. Fertilizer was applied 10 times according to the requirement of different strawberry growth periods, with water irrigation together through drip irrigation equipment under the film. The application rates of nitrogen (N) and phosphorus (P_2O_5) for all treatments were the same, which were 1596.4 kg/hm^2 and 196.5 kg/hm^2, respectively.

2.3 Measurements

2.3.1 Yield data

In the strawberry harvest period, fruits are harvested every 2-4 d. The single fruit weight (SFW) and total weight were recorded during each harvest. The fruit was weighed using a balance (accuracy of 0.01 g) and a maximum measurable weight of 500 g. After the end of the strawberry harvest period, the SFW and yield per hectare (Y) of each treatment were calculated.

2.3.2 Quality

The quality indexes included total soluble sugar content (TSSC), vitamin C content (VC), soluble protein content (SP), free amino acid content (FAA), and sugar-acid ratio (SAR). The TSSC was determined using an anthrone colorimetry, the SAR was determined using a Bxacid strawberry sugar-acid machine (ATAGO, Japan), the VC content was determined using molybdenum blue colorimetry, the SP content was determined using the Coomassie brilliant blue G-250 staining method, and the FAA content was determined using the ninhydrin hydrate method[21-23].

2.3.3 Efficiency data

Water use efficiency (WUE) was calculated as follows:

$$WUE = Y/W \tag{2}$$

where, Y is strawberry yield per hectare, kg/hm^2; W is the irrigation amount, m^3/hm^2.

The partial factor productivity of potassium fertilizer (PFP_K) was calculated as follows:

$$PFP_K = Y/K \tag{3}$$

where, K is the potassium fertilizer (K_2O) application rate, kg/hm^2.

2.3.4 Soil elements

Soil nutrient indexes included available potassium, available nitrogen, and available phosphorus residues in soil. During the strawberry plants were uprooted after harvest, the soil at depths of 20-30 cm and 40-50 cm near the rhizosphere was collected; the soil samples were then air-dried and sieved. The nitrate nitrogen of the soil was leached with 1 mol/L KCl solution, the available phosphorus of the soil was leached with 0.5 mol/L $NaHCO_3$ solution, and the soil was leached with 1 mol/L CH_3COONH_4 solution. AA3 high-resolution automatic chemical analyzer (Bran & Luebbe Corporation, Germany) was used to determine the content of available nitrogen and available phosphorus in the leaching solution, and the M410 flame spectrophotometer (Sherwood Corporation, UK) was used to determine the content of available potassium in the leaching solution. The available nitrogen, phosphorus, and potassium in the soil at depths of 20-30 cm and 40-

50 cm were referred to as N_{20} and N_{40}, P_{20} and P_{40}, and K_{20} and K_{40}, respectively.

2.4 Comprehensive evaluation using the FAHP and CRITIC methods

2.4.1 Determining the subjective weight based on the FAHP

FAHP decomposes complex problems into several elements with a bottom-up hierarchical structure according to the multiple objectives under consideration. The scale method of 0.1-0.9 can be used to make pairwise comparisons of indexes of the same level with the criteria of the higher-level elements. The fuzzy complementary judgment matrix and the fuzzy consistency judgment matrix are then obtained. After the fuzzy consistency judgment matrix is normalized by row summation, the weight values of each index in this hierarchy are obtained. According to the structure of the multi-layer evaluation system, the subjective weight of each index relative to the overall goal is calculated. The specific calculation process of the FAHP can refer to in Reference [15].

2.4.2 Determining the objective weight based on the CRITIC method

The CRITIC method determines the objective weight of indexes according to the standard deviations and correlations between indexes. The CRITIC method, which is an improvement of the EWM, can reveal differences and conflicts between the indexes. After the original evaluation matrix is established according to the data for each index, the standard deviation of the indexes and the correlation coefficients between indexes are calculated from the standardized original matrix. And the specific calculation process can refer to in Reference [18].

2.4.3 Combined weighting based on game theory

The combined weight was obtained based on the subjective weight and the objective weight through Game theory. The specific calculation methods of Game theory can refer to in Reference [24]

2.4.4 GRA

GRA is based on grey theory and can be used to analyze the similarities and differences between systems to determine the correlation degree between objects. First, the basic evaluation matrix is normalized, and the weighted evaluation matrix is obtained according to the weights of each index. The positive and negative ideal solutions are then determined, which represent the two reference sequences in GRA. The difference values between the data for each treatment and the reference sequence are calculated, and the grey relation coefficient can be calculated refer to Reference [25]. The comprehensive score based on GRA finally was obtained.

2.5 Data analysis

Excel 2019 was used to sort data and carry out the calculations for GRA and the CRITIC and FAHP methods. SPSS 25 was used for variance analysis. DPS 9.50 was used to fit the evaluation model. Matlab 2018b was used to analyze the model and make the graphs. Origin 2021 software was used to make the figures.

3 Results and analysis

3.1 Effects of the combined application of water and potassium on single indexes

3.1.1 Strawberry yield and water and fertilizer utilization efficiency

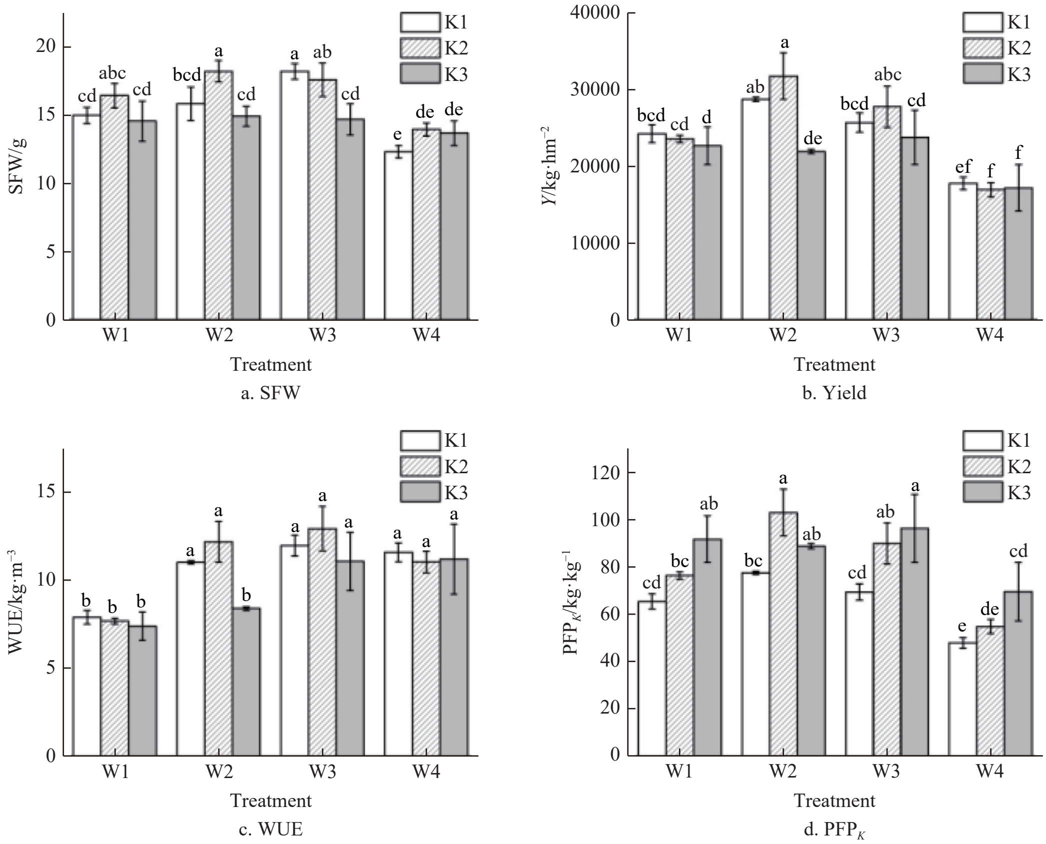
The SFW and *Y* of strawberries were significantly affected by irrigation (Table 2), and both first increased and then decreased as the amount of irrigation increased. SFW was highest under W3, and *Y* was highest under W2. Potassium also had a significant effect on the SFW and *Y* of strawberries (Table 2); SFW was 7.9% and 14.5% higher under K2 than under K1 and K3, respectively. The effect of potassium on *Y* was highest under K2, followed by K1 and K3; however, there was no significant difference in *Y* between K2 and K1. The interaction between irrigation and potassium had a significant effect on the two yield indexes (Table 2). SFW was highest in T5 and T7, with 47.8% higher in these two treatments than the lowest SFW value (T10) (Figure 1a). *Y* was highest in T5 (31704.16 kg/hm^2), followed by T4 and T7, and no significant differences were observed among the three treatments. The lowest *Y* was observed in T11, which was only 53.3% of that in T5 (Figure 1b).

Table 2　Significance analysis of yield of strawberry, efficiency and nutrients residues in the soil under different water and potassium levels based on Two-way ANOVA

Factors	SFW/g	Y/kg·hm^{-2}	WUE/ kg·m^{-3}	PFP_K/kg·kg^{-1}	N_{20}/mg·kg^{-1}	P_{20}/mg·kg^{-1}	K_{20}/mg·kg^{-1}	N_{40}/mg·kg^{-1}	P_{40}/mg·kg^{-1}	K_{40}/mg·kg^{-1}
W1	15.31^{b}	23 438.91^{b}	7.66^{c}	77.88^{b}	130.84^{c}	75.20^{b}	724.89^{a}	117.97^{a}	28.77^{a}	382.99^{a}
W2	16.32^{a}b	27 410.41^{a}	10.55^{b}	89.77^{a}	115.38^{d}	76.12^{b}	659.67^{c}	94.54^{c}	27.49^{ab}	360.26^{b}
W3	16.82^{a}	25 684.96^{ab}	12.00^{a}	85.22^{ab}	154.45^{b}	92.86^{a}	683.43^{b}	104.67^{b}	24.78^{b}	330.55^{c}
W4	13.31^{c}	17 263.15^{c}	11.29^{ab}	57.51^{c}	175.66^{a}	94.94^{a}	683.11^{b}	107.77^{b}	21.09^{c}	385.00^{a}
K1	15.33^{b}	24 057.23^{a}	10.63^{a}	65.11^{b}	147.91^{a}	86.27^{b}	724.42^{a}	114.42^{a}	27.38^{a}	370.52^{a}
K2	16.54^{a}	24 958.78^{a}	10.97^{a}	81.06^{a}	138.67^{b}	75.64^{c}	697.08^{b}	99.62^{c}	27.05^{a}	374.49^{a}
K3	14.45^{b}	21 332.06^{b}	9.52^{b}	86.61^{a}	145.67^{a}	92.44^{a}	641.83^{c}	104.68^{b}	22.17^{b}	349.10^{b}
W	**	**	**	**	**	**	**	**	**	**
K	**	**	*	**	**	**	**	**	**	**
W×K	*	*	NS	NS	**	**	**	**	**	**

Note: Different letters in the same column are significant differences (p<0.05). * Indicates a significant difference (p≤0.05), ** indicates a very significant difference (p≤ 0.01). SFW: Single fruit weigh; Y: Yield; WUE: Water utilization efficiency; PFP_K: Partial factor productivity of potassium. '×' denotes the interaction between W and K. Same below.

Irrigation and potassium application significantly affected both WUE and PFP_K, but the interaction did not have a significant effect on these variables (Table 2). WUE first increased and then decreased as the amount of irrigation applied increased. The highest WUE appeared under W3, although there was no significant difference in WUE between W3 and W4. The effect of potassium application on WUE was consistent with its effect on Y. WUE was significantly higher under K2 and K1 than under K3. PFP_K first increased and then decreased as the irrigation application increased and was highest under W2. According to the different potassium applications, PFP_K was highest under K3, followed by K2 and K1. Among all the treatments, T8 achieved the highest WUE, while T5



Note: SFW: Single fruit weigh; WUE: Water utilization efficiency; PFP_K: Partial factor productivity of potassium.

Figure 1 Effect of water and potassium coupling on strawberry SFW, Yield, WUE, and PFP_K

performed best in PFP_K (Figure 1).

3.1.2 Strawberry quality

Apart from the insignificant effect of irrigation on TSSC, irrigation, potassium, and their interaction had significant effects on all the quality indexes of strawberries (Table 3). From different irrigation levels, SAR was highest under W3, while VC, SP, and FAA were highest under W4. As the potassium application rate increased, TSSC, SAR, VC, and FAA first increased and then decreased, and K2 showed the most promotion for these indexes, although there was no significant difference between K2 and K3 in TSSC. SP decreased gradually as the potassium application rate increased and was highest under K3. TSSC, SAR, and FAA were highest in T8, VC was highest under T11, and SP was highest under T12.

3.1.3 Distribution of soil elements

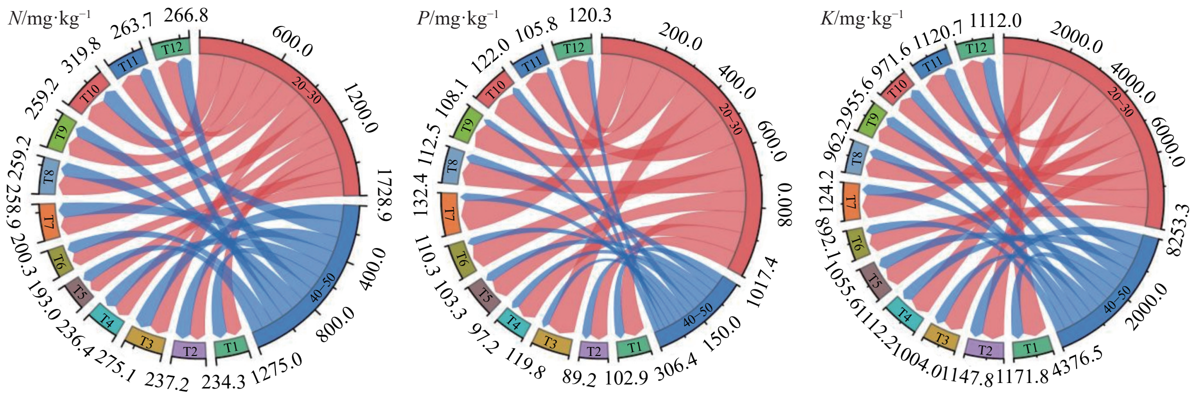
Irrigation and potassium application, as well as their interaction, had significant effects on the nutrient residues of soil (Table 2). From the perspective of irrigation level, both N_{20} and N_{40} were lowest at W2 application. The reduction in P_{20} was most favorable under the action of W1 and W2, while P_{40} appeared to be the lowest with W4 application. For the available K residue, the lowest residues in K_{20} and K_{40} occurred at W2 and W3, respectively. With the effect of potassium application, K2 significantly reduced N residues in both soil layers, while K3 was the most beneficial for reducing K residues in both soil layers. The responses of the P residues in the two soil layers were inconsistent, resulting in that K2 and K3 were the most favorable for the reduction of P_{20} and P_{40}, respectively. The content of soil available elements in different treatments significantly varied under the combined application of potassium and irrigation. N_{20} and N_{40} were lowest in T5 and highest in T10 (Figure 2a). P_{20} and P_{40} were lowest

Table 3 Effect of water and potassium coupling on fruit quality of strawberry

Treatment	TSSC/mg·g^{-1}	SAR	VC/mg·100 g^{-1}	SP/μg·g^{-1}	FAA/μg·g^{-1}
T1	6.96^{e}	14.34^{g}	348.41^{d}	276.29^{d}	410.35^{f}
T2	8.60^{ab}	15.14^{f}	345.90^{d}	287.65^{d}	479.52^{ef}
T3	8.32^{abc}	16.12^{e}	348.94^{d}	349.88^{b}	593.91^{bcd}
T4	7.63^{cde}	16.07^{e}	413.19^{e}	318.93^{c}	661.41^{ab}
T5	8.17^{abc}	16.87^{d}	443.03^{e}	320.88^{c}	562.65^{cde}
T6	8.00^{abcd}	14.35^{g}	437.29^{e}	311.68^{c}	422.98^{f}
T7	8.76^{a}	19.36^{b}	403.87^{e}	322.87^{c}	534.72^{de}
T8	7.93^{abcd}	20.79^{a}	424.57^{e}	330.34^{c}	742.22^{a}
T9	7.81^{bcde}	17.62^{c}	434.07^{e}	320.27^{c}	442.27^{f}
T10	7.24^{de}	15.68^{ef}	504.68^{b}	323.58^{c}	601.89^{bcd}
T11	8.49^{abc}	16.12^{e}	586.58^{a}	322.39^{c}	632.48^{bc}
T12	8.50^{abc}	15.09^{f}	415.25^{e}	380.94^{a}	578.61^{bcd}
W1	7.96^{a}	15.20^{c}	347.75^{c}	304.61^{c}	494.59^{c}
W2	7.93^{a}	15.76^{b}	431.17^{b}	317.16^{b}	549.02^{b}
W3	8.16^{a}	19.26^{a}	420.84^{b}	324.49^{b}	573.07^{ab}
W4	8.08^{a}	15.63^{b}	502.17^{a}	342.31^{a}	604.33^{a}
K1	7.65^{b}	16.36^{b}	417.54^{b}	310.42^{b}	552.09^{b}
K2	8.30^{a}	17.23^{a}	450.02^{a}	315.31^{b}	604.22^{a}
K3	8.15^{a}	15.80^{c}	408.89^{b}	340.69^{a}	509.44^{c}
W	NS	**	**	**	**
K	**	**	**	**	**
W×K	**	**	**	**	**

Note: TSSC: Total soluble sugar content; SAR: Sugar-acid ratio; VC: Vitamin C content; SP: Soluble protein content; FAA: Free amino acid content.

in T2 (Figure 2b); K_{20} and K_{40} were lowest under T6, and K_{20} and K_{40} were 76.1% lower in T6 than in T1, which was the treatment with the highest K_{20} and K_{40} (Figure 2c).



a. N b. P c. K

Figure 2 Effects of water and potassium coupling on nutrients residue in soil

3.2 Comprehensive evaluation of strawberry growth based on the FAHP and CRITIC method

3.2.1 Construction of the comprehensive evaluation hierarchy model

A comprehensive evaluation system of strawberry production was established to balance economic and ecological needs and maximize efficiency. The comprehensive score of strawberry (C) was used as the target layer; yield (C1), fruit quality (C2), water and fertilizer utilization efficiency (C3), and soil nutrient residues (C4) were used as the factor layers. C1 includes SFW (C11) and Y (C12). C2 comprises TSSC (C21), SAR (C22), VC (C23), SP (C24), and FAA (C25). C31 and C32 of C1 denote WUE and PFP_K, respectively. C4 comprises K_{20} (C41), N_{20} (C42), and P_{20} (C43).

3.2.2 Index weight determination

The subjective weight of indexes was determined using the FAHP method, and the fuzzy complementary judgment matrix was obtained as,

$$C=\begin{bmatrix}0.5&0.6&0.8&0.8\\0.4&0.5&0.7&0.7\\0.2&0.3&0.5&0.5\\0.2&0.3&0.5&0.5\end{bmatrix} \tag{4}$$

$$C_1=\begin{bmatrix}0.5&0.2\\0.8&0.5\end{bmatrix} \tag{5}$$

$$C_2=\begin{bmatrix}0.5&0.5&0.6&0.7&0.8\\0.5&0.5&0.6&0.7&0.8\\0.4&0.4&0.5&0.6&0.7\\0.3&0.3&0.4&0.5&0.6\\0.2&0.2&0.3&0.4&0.5\end{bmatrix} \tag{6}$$

$$C_3=\begin{bmatrix}0.5&0.5\\0.5&0.5\end{bmatrix} \tag{7}$$

$$C_4=\begin{bmatrix}0.5&0.5&0.7\\0.5&0.5&0.7\\0.3&0.3&0.5\end{bmatrix} \tag{8}$$

The fuzzy consistency judgment matrix was obtained, which satisfies the fuzzy consistency requirement, and the subjective weights of each index are shown in Table 4. The subjective weight of Y was the largest, followed by SFW and WUE. The subjective weight was lowest for FAA (0.043).

The objective weights of the indexes were determined using the CRITIC method. The objective weight of K_{20} was the highest, followed by P_{20} and VC, and the objective weight of SAR was the lowest. The objective weight of Y, the index with the largest subjective weight, was only 0.075.

The subjective and objective weights were combined using Game theory. The combined weight of Y was the largest (0.185), followed by SFW(0.104) and WUE(0.102). The combined weight of FAA was the smallest (0.047).

Table 4 Subfactor weights based on FAHP, CRITIC, and Game theory

Subfactor	C11	C12	C21	C22	C23	C24	C25	C31	C32	C41	C42	C43
Subjective weight	0.108	0.200	0.063	0.063	0.056	0.050	0.043	0.104	0.104	0.076	0.076	0.056
Objective weight	0.073	0.075	0.086	0.072	0.092	0.075	0.079	0.088	0.074	0.101	0.091	0.095
Comprehensive weight	0.104	0.185	0.066	0.064	0.061	0.053	0.047	0.102	0.100	0.079	0.078	0.060

3.2.3 Evaluation results based on GRA

Based on the combined weight of each subfactor, the comprehensive score of each treatment was calculated using GRA. The correlation degree, comprehensive score, and rankings of each treatment obtained by GRA are shown in Table 5. When strawberry growth benefits and soil environmental benefits were combined, the treatment with the highest score was T5, followed by T8 and T4, and the comprehensive score of T1 was the lowest.

3.3 Determining the optimal amount of water and potassium application

According to the comprehensive score of strawberry with irrigation (X) and potassium application (Y) as independent variables and comprehensive growth score (Z) as a dependent variable, the regression equation of the strawberry comprehensive score response to the combined application of water and potassium was obtained by quadratic polynomial stepwise regression fitting. The equation was as follows:

$$Z=-0.063\,62X^2-0.000\,66X-0.04211Y^2+0.004\,50Y+0.006\,59XY+0.554\,88 \tag{9}$$

The significance of the regression equation was tested, and the correlation coefficient R^2=0.8912 (F=9.8311, p=0.0074).

3.3.1 Effect of water and potassium on the comprehensive growth of strawberry

To analyze the regulatory effect of irrigation and potassium application on the comprehensive growth of strawberry, the dimensions of the regression model (Equations (9)) were reduced, and the following equation was obtained:

$$Z(X)=-0.063\,62X^2-0.000\,66X+0.554\,88 \tag{10}$$

$$Z(Y)=-0.042\,11Y^2+0.004\,50Y+0.554\,88 \tag{11}$$

Table 5 The comprehensive score based on GRA of strawberry

Treatment	P^+	P^-	Score	Rank
T1	0.6948	0.8507	0.4496	12
T2	0.7501	0.7935	0.4859	7
T3	0.7407	0.7956	0.4821	8
T4	0.7934	0.7307	0.5206	3
T5	0.8932	0.6852	0.5659	1
T6	0.7556	0.7831	0.4911	6
T7	0.7766	0.7597	0.5055	4
T8	0.8524	0.6915	0.5521	2
T9	0.7647	0.7597	0.5016	5
T10	0.7099	0.8632	0.4513	11
T11	0.7379	0.8196	0.4738	9
T12	0.7252	0.8219	0.4688	10

Note: P^+ and P^- denote the closeness degree of each treatment with positive and negative ideal solutions respectively by Grey relation analysis (GRA).

Figure 3a shows that the response of the strawberry comprehensive score to irrigation and potassium application exhibited a negative parabolic relationship. The irrigation curve was also steeper than the potassium application curve, which indicates that irrigation has a greater effect than potassium application on the strawberry comprehensive score.

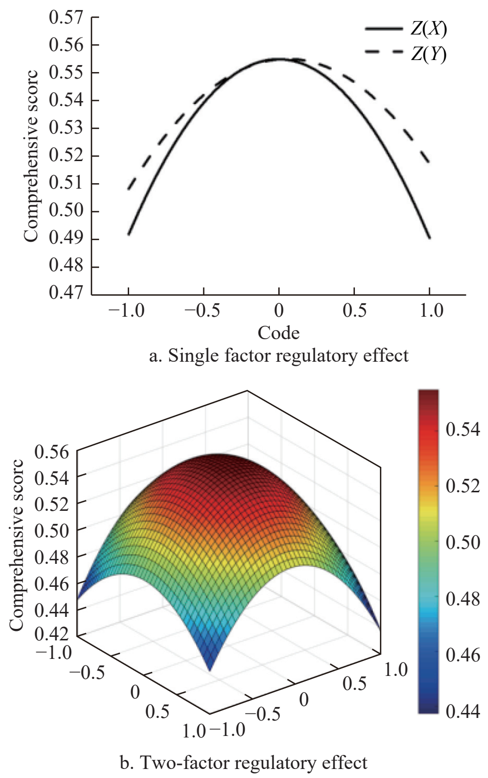


Figure 3 Response model of strawberry comprehensive score to combined application of water and potassium

3.3.2 Optimal water and potassium application rates based on the strawberry comprehensive score

The regression equation was analyzed by Matlab. The optimal interval of irrigation and potassium application was determined using an interval of greater than 95% of the maximum comprehensive score, which corresponded to an irrigation amount of 2053-2525 m^3/hm^2 and potassium application amount of 288.1-334.2 kg/hm^2 (Figure 3b).

4 Discussion

Lower irrigation could reduce strawberry yield but enhances fruit quality, a pattern that has been observed in research on tomato, grape, blueberry, pomegranate, and other crops, as water stress affects several physiological and biochemical factors that affect the yield and quality of plants[4,26-29]. Potassium is an important factor affecting crop yield and quality, but higher potassium application does not always enhance crop yield and quality. Appropriate applications of potassium (K2) can alleviate decreases in strawberry yield caused by water stress because potassium improves the resistance of crops to drought stress by regulating cell osmotic potential, stomatal opening, and cell membrane stability[30]. Appropriate potassium fertilizer application (K2) significantly increased the SFW, *Y*, and quality indexes such as TSSC, SAR, VC, and FAA. This is because potassium can enhance the photosynthesis rate and phloem transport capacity, thus improving fruit yield and quality[31]. Reductions in the amount of irrigation can improve WUE, which was consistent with the conclusion of Zou et al.[32] that WUE was higher under water deficit. A higher rate of potassium application also improves WUE, mainly due to potassium could promote the roots to consume soil water more effectively by increasing the leaf area index, which improves WUE[33]. Moderate irrigation levels (W2, W3) can improve PFP_K, which might originate from the increase in crop yields caused by increases in nutrient absorption under appropriate levels of irrigation. The excess potassium in the high potassium fertilizer treatment (K1) was not fully absorbed and utilized by strawberries, which led to excessive K residues in the soil. The appropriate application of water and potassium reduced nutrient residues in the soil, as most of the soil mineral elements applied were absorbed by strawberries. Xiao et al.[34] also found that the absorption of soil nutrients by crops decreases under drought stress, which increases nutrient residues in the soil.

Given that the responses of the different indexes to irrigation and potassium application in strawberry cultivation vary, the optimally combined application scheme of irrigation rate and potassium application was determined based on indexes of yield, quality, efficiency, and soil elements. The FAHP and CRITIC methods were used to assign subjective and objective weights for the 12 indexes in the four categories, respectively, and the combined weights were obtained based on Game theory. The subjective weight of *Y* was the highest, and research on watermelon and cherry tomatoes has confirmed the importance of these indexes[35,36]. The objective weights of K_{20} and P_{20} were the highest, and they were larger than the objective weight of soil elements determined by the EWM from the experiment of Xiao et al.[34] This is because the CRITIC method considers the relationship between indexes as well as the importance of soil elements in irrigation and fertilization management. The combined weight based on the subjective and objective weights indicates that *Y* is the most important index, followed by SFW and WUE (Table 4). GRA was used to comprehensively evaluate the combined application of water and potassium, and the highest score was observed for T5, which was consistent with the optimally combined application scheme of *Y* and the high-yield goal. The response of the strawberry comprehensive score to irrigation and potassium application exhibited a negative parabolic relationship, which indicates that there is an optimal application interval, and similar results have been obtained in studies of watermelon and cherry tomato[35,36]. The final optimum potassium fertilizer application rate was lower than that of Xing et al.[37], which mainly stems from the fact that the index of soil nutrient residues was included in the comprehensive evaluation system in this study, and reductions in potassium application are more beneficial to the soil ecological environment.

The irrigation and potassium application treatments varied in their effects on different indexes and the comprehensive score of strawberries. A comprehensive evaluation system was established in this study that considers both economic and ecological needs; thus, the conclusions derived from the optimization of the comprehensive model differed from those of previous models. In addition, the greenhouse microclimate and other factors also affect the water and fertilizer demand of crops. Additional studies are needed to explore the interaction between water and fertilizer under different environmental conditions.

5 Conclusions

Irrigation and potassium application vary in their effects on strawberry yield, fruit quality, soil nutrient residues, and water and fertilizer utilization efficiency. Reductions in the amount of irrigation reduce strawberry yields but increase the fruit quality and water and fertilizer utilization efficiency. Appropriate applications of potassium can alleviate the decline of strawberry yield caused by water stress, and significantly improve SFW, WUE, TSSC, SAR, VC, and FAA. While the low application of potassium increased the SP, and PFP_K, and reduce nutrient residues in the soil effectively.

A comprehensive evaluation system was established that optimized strawberry yield and quality, water and fertilizer utilization efficiency, and the content of residual soil elements. Subjective weights were assigned to the 12 indexes in four categories using the FAHP method, and the objective weight of each index was determined using the CRITIC method. The combined weights were determined using Game theory, and *Y* obtained the highest weight of 0.185, followed by SFW, and the combined weight of FAA was the lowest.

A comprehensive evaluation of the combined application of water and potassium was conducted using GRA. The response model of the strawberry comprehensive score to irrigation and potassium application was established. The interaction between irrigation and potassium application significantly affected the comprehensive score. The irrigation amount of 2053–2525 m^3/hm^2 and potassium application of 288.1–334.2 kg/hm^2 was optimal for promoting the growth of strawberry plants, increasing economic benefits, and reducing the content of nutrient residues in soil.

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