Evaluation of tomato fruit quality response to water and nitrogen management under alternate partial root-zone irrigation

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Abstract: A pot experiment was conducted to investigate the effects of different water and nitrogen supply amounts on the comprehensive assessment of tomato fruit quality and root growth parameters under alternate partial root-zone irrigation. Three upper irrigation limitations (i.e. 70% (W1), 80% (W2) and 90% (W3) of field capacity, respectively) and three N-fertilizer levels (i.e. 0.18 (N1), 0.30 (N2) and 0.42 (N3) g/kg soil, respectively) were arranged with a randomized complete block design, and alternate partial root-zone irrigation method was applied. Results showed that fruit yields under deficit irrigation (W1 and W2) were decreased by 6.9% and 2.0% respectively compared with W3 under N1 level. Yields of tomato under W1N1 and W1N2 combinations were also reduced by 10.3% and 7.2%, respectively compared with W1N3 combination. Root dry weight, root length, root surface area and root volume were all increased in W1N2 treatment. According to two-way ANOVA, the root parameters except root dry weight, were extremely sensitive to water, nitrogen and the cross effect of the two factors. TSS (total soluble solids), SS (soluble sugars) and OA (organic acid) in the fruits increased with the decrease in irrigation water, OA and NC reduced with decreasing amount of nitrogen. Moreover, within an appropriate range, as more irrigation water and nitrogen were applied, the higher VC (vitamin C) and lycopene contents were identified in the fruits. Eventually, the combinational evaluation method (i.e. entropy method and gray relational analysis) showed that W2N2 ranked highest in comprehensive fruit quality. Therefore, considering the tradeoff between fruit comprehensive quality and yields, upper irrigation limitation of 80% θ_f and N-fertilizer of 0.30 g/kg soil with alternate partial root-zone irrigation was the optimal cultivation strategy for the greenhouse tomato in autumn-winter season in northwest China.

Keywords: greenhouse tomato, alternate partial root-zone irrigation, water and nitrogen, root growth, comprehensive fruit quality

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1 Introduction

Alternate partial root-zone irrigation (APRI) has caught considerable attention as a water-saving irrigation method in recent two decades. APRI means that halves of the root zone are alternately irrigated or left dry during consecutive irrigations[1,2]. It has been tested and used in some fruit crops, i.e. peach[3], pear[1], grapevine[4] and tomato[5,6]. Previous studies indicated that APRI could significantly reduce transpiration rate while maintaining

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higher photosynthesis rate[7,8]. The mechanism of APRI for reducing transpiration was proposed as that, roots in the drying side could produce abscisic acid (ABA), which might lead to the closure of leaf stomata and therefore reduce the water loss through transpiration, while the wetting side has plentiful supply of water to sustain plant growth[9]. The partial root-zone drying (PRD) experiments on tomato showed significant positive results in terms of increasing water use efficiency and fruit quality[6]. Compared with conventional furrow irrigation (CFI), alternate furrow irrigation (AFI) maintained same photosynthetic rate (Pn) but with a decreased transpiration rate in grape, meanwhile, AFI increased Vitamin C and decreased titrated acidity of berry[10]. Sun et al.[11] indicated that PRD increased fruit juice concentrations of total soluble solid, glucose, fructose and malic acid. Wei et al.[12] used carbon isotope discrimination to show that APRI increased water use efficiency of tomato at leaf and yield scales.

Both irrigation and nitrogen are important factors for tomato growth, fruit quality and yield[13-16]. Although certain degree of irrigation deficit reduced tomato yield, the fruit quality was improved to some extent[17-20]. N fertilizer is also important to tomato yield and fruit quality, and has a positive effect on yield and quality if the amount is suitable. Accompanying with the positive relationships between tomato yield and seasonal water applied, proper deficit irrigation improved the total soluble solids, soluble sugars, organic acid and Vitamin C in tomato fruits[15,16,20] as well as water use efficiency[13]. It had been proved that the tomato relative yield decreased linearly with the decline of relative seasonal evapotranspiration (ET), mainly in fruit development and ripening stage, while the relative fruit quality parameters increased with the decline of relative seasonal ET, mostly because of the increment by ET deficit in fruit ripening stage[21]. Water stress improved dry matter content of the fruit and Brix degree of tomato[22]. Increasing N-fertilizer also increased fruit total sugars and organic acid as well as the water productivity[15]. However, excessive nitrogen supply may also cause NO_3-N leaching and affect nitrate content (NC) in tomato fruits[23-25]. Therefore, it is obvious that an optimal use of water and nitrogen is critical in achieving high yield and quality as well as water/nitrogen use efficiency of tomato.

Yang et al.[2] reported that alternate drip irrigation reduced mean root dry mass and root hydraulic conductance (Kr) in young apple tree, while Kang et al.[1] indicated that partial root-zone drying significantly enhanced Kr and the roots had a greater water uptake capacity than CFI in pear tree. However, more details of effects of alternate partial irrigation on root length, root surface area, root volume of tomato under different water and nitrogen supply should be further investigated.

Tomato fruit quality includes different individual quality attributes[26]. Generally, the fruit quality is classified as external (size, shape and color), taste (TSS, sugar and organic acid), nutritional (lycopene and vitamin C) and healthful (nitrate content) qualities[27] and each single quality parameter has different importance ratings[19]. Therefore, it is crucial to propose a method to calculate the weight of each attribute and determine the comprehensive quality. Among the evaluation methods, entropy method[28] and gray relational analysis (GRA) are two important approaches[16]. The entropy method, effectively adopted for determination of weight of the evaluating indicators, is an objective and powerful weight evaluation process[28,29]. GRA is a useful tool for solving the complicated interrelationship among the designated multiple performance characteristics[16,30].

There are many studies about tomato yield, water use efficiency and fruit quality responses to alternate partial root-zone irrigation and deficit irrigation. But unfortunately, few studies were done on the effects of different amounts of irrigation water and nitrogen applications under alternate partial root-zone irrigation on the comprehensive assessment of fruit quality and root parameters. Our study is aimed to: (1) explore responses of tomato yield, root parameters and comprehensive fruit quality to different water and nitrogen supply under alternate partial root-zone irrigation; (2) find an effective method to assess the comprehensive fruit quality and establish a suitable water and nitrogen combination strategy for greenhouse tomato in northwest China.

2 Materials and methods

2.1 Experimental site and materials

The pot experiment was conducted in a greenhouse at the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Area of Ministry of Education in Northwest A&F University in Yangling, Shaanxi China (latitude 34°18'N, longitude 108°24'E, 521 m altitude) under natural light condition. A local leading variety of fresh tomato, Jinpeng 11, was transplanted on August 11, 2013 and uprooted on November 16, 2013. The experimental site has a semi-humid continental climate with total precipitation of 121.3 mm, mean temperature of 17.3°C and mean relative humidity of 71.3% during the experimental period. Soil in the pot was heavy loam, which was transported from the 20 cm top layer of a field near the experimental station. Soil pH was 7.8, field capacity 25.5%, organic matter content 6.18 g/kg, total N content 0.81 g/kg, available N content 10.93 mg/kg, total P content 0.42 g/kg, available P content 4.18 mg/kg, total K content 13.8 g/kg, available K content 102.3 mg/kg.

2.2 Experimental design

The experimental design was a randomized complete block design with nine replications. There were 9 combinations of three irrigation water levels and three nitrogen levels under APRI (Table 1). The irrigation water levels comprised three irrigation upper limitations (W1, 70%θ_f; W2, 80%θ_f; W3, 90%θ_f), θ_f is the field capacity, and three nitrogen treatments included 0.18 N g/kg (N1), 0.30 N g/kg (N2) and 0.42 N g/kg (N3) (Table 1). Tomato seedlings at 3-4 true leaves stage were transplanted with one plant to each pot at 30 DAT after sowing. For a better establishment, the tomato plant in each pot was irrigated with 4.6 L water to field capacity on the day of transplanting. Alternate partial root-zone drying started at 7 d after transplanting. At 20-30 d after transplanting, the plants stems were staked with plastic string and the flowers were manually pollinated. Other management stages such as pest control and pruning branch were same with local practices. The whole growing season was divided into three stages:

Stage I: vegetative stage (transplant to first fruit set);

Stage II: flowering and fruit development stage (first fruit set to first fruit maturity);

Stage III: fruit ripening stage (first fruit maturity to all fruits harvested).

Table 1 Nitrogen amount and irrigation upper limitation in growth period of tomato

Nitrogen treatment	Nitrogen level /g·(kg soil)$^{-1}$	Total urea amount /g per plant	Water treatment	Upper limitation of irrigation
N1	0.18	7.043	W1	70% θ_f
N2	0.30	11.739	W2	80% θ_f
N3	0.42	16.435	W3	90% θ_f

Note: θ_f means field capacity.

Seven days after transplanting, the tomato plant was irrigated every three days based on the weighing method, and there was no watering on rainy days in order to prevent the development of gray mold. All the treatments were irrigated to respective upper irrigation limitations set up for each irrigation water level (Table 2). Water was applied using measuring glass through the irrigation tube (Figure 1).

Table 2 Irrigation amount (mm) and times of each treatment under alternate partial root-zone irrigation

Treatment		Stage I	Stage II	Stage III	Whole season
T1	W1N1	3.692(3)[a]	9.929(12)	6.070(9)	24.291(25)[b]
T2	W1N2	4.638(3)	10.686(12)	6.143(9)	26.067(25)
T3	W1N3	3.659(3)	9.281(12)	6.008(9)	23.548(25)
T4	W2N1	4.532(3)	10.666(12)	6.217(9)	26.015(25)
T5	W2N2	7.163(3)	11.239(12)	6.429(9)	29.431(25)
T6	W2N3	3.567(3)	11.195(12)	6.139(9)	25.501(25)
T7	W3N1	5.716(3)	12.769(12)	6.466(9)	29.551(25)
T8	W3N2	6.306(3)	11.476(12)	6.153(9)	28.535(25)
T9	W3N3	5.592(3)	12.061(12)	6.270(9)	28.523(25)

Note: [a] Numbers in the brackets represent irrigation times with irrigation interval of 3 d (except rainy days) for the respective growth stage; [b] Irrigation amount and times of the whole season include water applied on the day of transplanting.

Tomatoes were transplanted to the experimental pots (30 cm in diameter at the top edge, 25 cm in diameter at the bottom, 30 cm high) (Figure 1). Each pot was filled with 18 kg soil with a mean bulk density of 1.3 kg/m^3 and vertically installed two PVC tubes (2.5 cm in diameter and 30 cm in depth) at 5 cm from the bottom of the pot for irrigation. Each tube was drilled to have three rows of round holes longitudinal and was twined with two layers of mesh (1 mm in diameter). There were six holes punched at the bottom of the pot and paved with silver sand to provide better aeration. Soil surface was covered with 1 cm thick vermiculite to prevent soil surface hardening and evaporation. Under the alternate partial root-zone irrigation, each experimental pot was evenly divided into two parts with a 24 cm high plastic film to prevent lateral water flow from either side of the root. The plastic film with a V-shaped notch was firmly fixed in the middle of the pot with double sided adhesive tape and each side was installed with one irrigation tube.

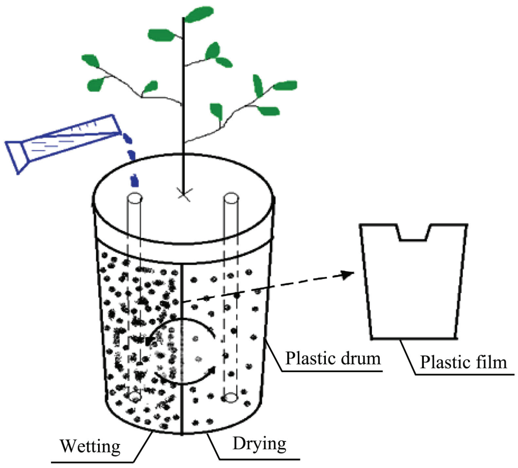


Figure 1 Layout of alternate partial root-zone drying in the pot experiment

N, P, K were supplied as urea (46% N included), calcium superphosphate (15% P_2O_5 included) and potassium sulfate (50% K_2O included) respectively. Organic fertilizer was applied in rotten chicken manure form. Except for urea amount, other fertilizers were the same for all the treatments with P_2O_5 0.264 g/kg soil, K_2O 0.432 g/kg soil and organic fertilizer 30 g/kg soil. Calcium superphosphate and rotten chicken manure were applied entirely as starter fertilizers. One third of urea and potassium sulfate were applied as starter fertilizers, the remaining were applied evenly on each side of the root with irrigation water in the first and second spike fruit enlargement stage respectively.

2.3 Measurements

2.3.1 Yield, water and nitrogen use

Tomato fruits were harvested on 76 d, 83 d, 90 d after transplanting (DAT), and the fresh weight of fruits per plant was recorded with electronic balance on the harvest day.

Irrigation water use efficiency (IWUE, kg/m^3) is calculated as:

$$IWUE = \frac{Y}{I} \tag{1}$$

where, Y is fruit yield per plant (g); I is irrigation amount in whole season per plant (L).

Partial factor productivity of nitrogen (PNP, kg/kg) is calculated by the following equation:

$$PNP = \frac{Y}{N} \tag{2}$$

where, N is the total N amount in whole season for per plant (g).

2.3.2 Root growth parameters

After harvesting all the red ripen fruits, roots and shoots of three tomato plants were collected separately in each treatment in a randomized manner. The roots were flushed with clean water and then scanned with a root scanner (EPSON Perfection V700, Japan). Root length, root surface area and root volume were obtained through image analysis software (WinRHIZO Pro, Canada), plant materials were firstly dried at 105°C for 30 min, and then dried at 70°C to a constant weight.

2.3.3 Fruit quality parameters

Nine tomato fruits with similar maturity and without external defects were picked from three plants for the quality parameters measurement in each treatment. The fruits were squeezed to juice in a blender for measuring the contents of total soluble solids (TSS), soluble sugars (SS), organic acids (OA), vitamin C (VC), lycopene and nitrate content (NC). The average values of the three replicates for each treatment were used for fruit quality parameters.

TSS was measured using the electronic handled refractometer (PR-32, Co., Ltd., Tokyo, Japan). SS was determined with the anthrone colorimetric method[31]. OA was titrated with 0.1 mol/L NaOH and figured as equivalents of citric acid expressed as percentage of fresh mass[32]. VC was measured with the extraction-molybdate blue spectrophotometric method[33]. Lycopene was determined with spectrophotometric method[34]. NC was measured with spectrophotometric method[35].

2.4 Calculating index weight by entropy method

The entropy method was used to assess tomato quality parameters in this study. Procedure of conducting entropy analysis is as follows[28].

Normalization of fruit quality parameters: The normalized values p_{ij} is expressed as:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (3)$$

where, x_{ij} is the j^{th} quality parameter in the i^{th} treatment; in this study, m=9.

The entropy of j^{th} quality parameter, e_j is defined as:

$$e_j = -k\sum_{i=1}^{m} p_{ij}(\ln p_{ij}) \quad (4)$$

where, constant k is related to m, and set as 1/ln (m).

The entropy weight w_j is then defined as:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad (5)$$

where, n=5. The smaller value of entropy for a given indicator indicates that this indicator provides more useful information, and correspondingly the weight of this indicator should be higher.

2.5 Calculating comprehensive quality rank with GRA

Grey relational analysis (GRA) was used to assess the comprehensive quality of tomato fruits in our study. Each treatment is considered as one of the elements in the gray system. The procedure involves the following steps[36-38].

The original parameters are normalized at the range between 0 and 1.0. Y_0 is defined as the maximum value of each single quality parameter. Therefore the normalized values, x_{ij} is expressed as:

$$x_{ij} = \frac{y_{ij}}{y_{oj}} \quad (6)$$

where, y_{ij} is the j^{th} quality parameter in the i^{th} treatment; y_{oj} is the value of ideal treatment.

The gray relational coefficients, ε_{ij} is calculated as:

$$\xi_{ij} = \frac{\min_i \min_j |x_i^o - x_{ij}| + \zeta \max_i \max_j |x_i^o - x_{ij}|}{|x_i^o - x_{ij}| + \zeta \max_i \max_j |x_i^o - x_{ij}|} \quad (7)$$

where, x_i^o is the ideal normalized value for the i^{th} quality parameter; ζ is the distinguishing coefficient, $\zeta \in [0,1]$, ζ=0.5 is generally used.

The grey relational grade is defined and calculated as follows:

$$R_i^* = \sum_{k=1}^{n} w_j \xi_i(k) \quad (8)$$

where, R_i^* is the gray relational grade for the i^{th} treatment; and w_j is the weighting factor for the i^{th} quality parameter, which comes from entropy method.

2.6 Statistical analysis

The experimental data were analyzed by two-way ANOVA using SPSS software. Differences between means were compared for any significant differences using the Duncan's multiple range tests at significant level of p<0.05.

3 Results

3.1 Effects of water and nitrogen management on root growth

As shown in Table 3, tomato root length ranged from 3417.6 cm to 5493.8 cm under APRI. The decline of root dry weight reached 3.7% for W2N3 and 9.3% for W3N3, respectively compared with W1N3. N2 treatments increased root length under the same water level. Root surface area of W1N1 and W2N1 decreased 30.0% and 12.2% in comparison with W3N1. Root volume first increased then decreased with the increasing nitrogen under the same water level. W2N2 treatment had much higher root parameters (root dry weight, root length, root surface area and root volume) than any other treatments under APRI. The two-way ANOVA of water effect, nitrogen effect and cross effect of water and nitrogen were extremely significant except water effect and cross effect on root dry weight.

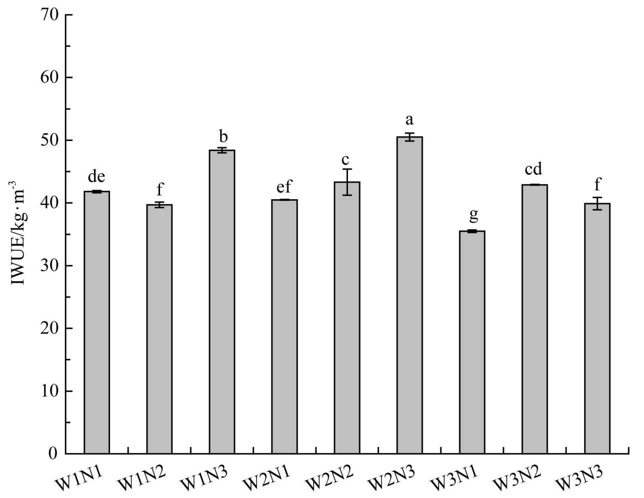
Table 3 Root parameters and yield of tomato as affected by water and nitrogen management under alternate partial root-zone irrigation

Treatment		Root dry weight/g	Root length /cm	Root surface area/cm^2	Root volume /cm^3	Yield /g per plant
T1	W1N1	2.20 bc	3417.6d	277.6g	4.22e	823.7f
T2	W1N2	2.37 bc	3957.2c	418.8e	6.49c	852.3ef
T3	W1N3	2.15 bc	3839.4c	334.1f	4.44e	918.0d
T4	W2N1	2.51 ab	3928.9c	348.2f	4.88d	867.9e
T5	W2N2	3.11 a	5493.8a	732.9a	9.10a	1075.2a
T6	W2N3	2.07 c	5253.9ab	667.1b	8.23b	1056.0ab
T7	W3N1	2.35 bc	3923.4c	396.7e	4.98d	885.2de
T8	W3N2	2.74 ab	5085.1b	589.9c	7.94b	1027.1b
T9	W3N3	1.95 c	4000.5c	553.7d	6.61c	955.1c
W		ns	**	**	**	**
N		**	**	**	**	**
W×N		ns	**	**	**	**

Notes: Different letters in each column indicate significant differences according to the Duncan's multiple range tests at p=0.05 level. W: water regime effect; N: nitrogen regime effect; W×N: water and nitrogen cross effect. * Significant differences for p<0.05; ** Significant differences for p<0.01; ns: no significance.

3.2 Effects of water and nitrogen management on yield, water and nitrogen use

Tomato yields from W1N1 and W1N2 were decreased by 10.3% and 7.2%, respectively compared with W1N3 under APRI. Under the W2 and W3 level, yield was not always increased with the increment of nitrogen, the decline of yield reached 1.8% for W2N3 and 7.0% for W3N3, respectively compared with W2N2 and W3N2. Moreover, the decline of yield reached 6.9% for W1N1 and 2.0% for W2N1 under APRI, respectively compared with W3N1. Under the N2 and N3 level, the yield first increased then decreased with the increment of water, and W2N2 obtained a maximum yield of 1075.2 g/plant under APRI.



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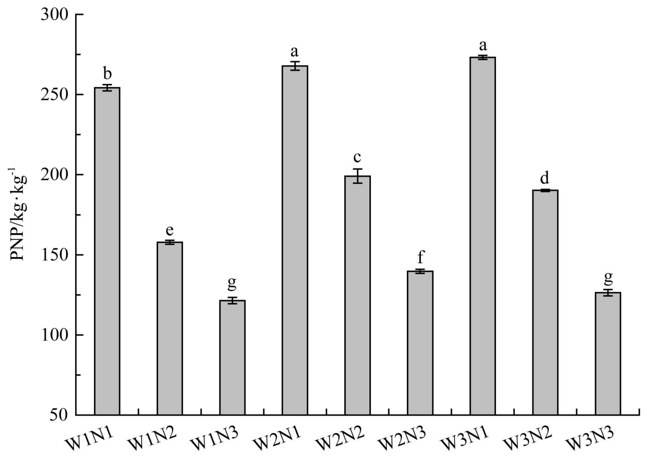

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Figure 2 The irrigation water use efficiency (IWUE) and nitrogen partial productivity (PNP) of each treatment under alternate partial root-zone drying. Letters above the error bars were the significant differences according to the Duncan's multiple range test at p=0.05 level

Irrigation water use efficiency (IWUE) and nitrogen partial productivity (PNP) reflected the economic yield of the tomato crop produced by unit water consumption and unit nitrogen amount, respectively. The IWUE and PNP of APRI ranged from 35.5 kg/m^3 to 50.5 kg/m^3 and from 121.4 kg/kg to 273.3 kg/kg, respectively. Compared with W2N3, the IWUE were decreased ranging from 4.1% (T3) to 29.7% (T7) for different treatments (Figure 2a), respectively. N1 treatments had a much higher PNP than that of any other nitrogen treatments under the same water regime (Figure 2b). The PNP in W2 treatments were higher than those of W1 and W3 treatments under the same nitrogen level.

3.3 Effects of water and nitrogen management on tomato quality

As shown in Table 4, TSS, Vc, lycopene and SS were initially increasing, but decreased with the increment of nitrogen under the same water levels. However, OA and NC continued to increase. This indicated that N2 treatment performed well in achieving optimal fruit quality parameters of tomato. Under the same nitrogen level, the more stressful the irrigation water, the higher the TSS content identified in the fruits. Within an appropriate range, Vc, lycopene and NC increased with the increment in water.

Table 4 Tomato quality parameters as affected by water and nitrogen management under alternate partial root-zone irrigation

Treatment		TSS/%	VC /mg·100 g^{-1}	Lycopene /μg·g	RS/%	OA/%	NC /mg·kg
T1	W1N1	7.87b	15.83e	28.55c	3.79bc	0.59e	73.1bc
T2	W1N2	8.60a	22.63ab	45.55ab	5.92a	0.63de	81.0bc
T3	W1N3	8.57a	20.80bc	28.80c	4.24b	0.79b	123.1a
T4	W2N1	6.60d	18.93cd	35.40bc	3.37bc	0.71c	84.0bc
T5	W2N2	8.33a	23.68a	48.40a	4.65ab	0.86a	120.1a
T6	W2N3	7.94b	21.83ab	44.68ab	4.19bc	0.86a	126.7a
T7	W3N1	5.70e	17.45de	24.75c	2.77c	0.42f	57.3c
T8	W3N2	7.27c	22.15ab	46.95ab	4.58ab	0.64de	105.9ab
T9	W3N3	7.00c	20.77bc	25.65c	3.99bc	0.66cd	123.4a
W		**	ns	ns	ns	**	ns
N		**	**	**	**	**	**
W×N		**	ns	ns	ns	**	ns

Notes: TSS: total soluble solids, Vc: vitamin C, SS: soluble sugars, OA: organic acids, NC: nitrate content. Different letters in each column indicate significant differences according to the Duncan's multiple range tests at p=0.05 level. W: water regime effect; N: nitrogen regime effect; W×N: water and nitrogen cross effect. * Significant differences for p<0.05; ** Significant differences for p<0.01; ns: no significant.

The decline of SS reached 11.1% for W2N1 and 26.9% for W3N1, respectively compared with W1N1. The two-way ANOVA showed that effects of water, nitrogen and cross effect of the two factors on TSS and OA were extremely significant, nitrogen effect on VC, lycopene, RS and NC was also extremely significant.

3.4 Rankings of comprehensive fruit quality

The comprehensive quality rankings using GRA and entropy method were showed in Table 5, W2N2 and W1N2 ranked the first and second, respectively. And W3N1 was the last. Consequently, the high irrigation amount and low nitrogen supply were difficult to obtain the better quality under APRI.

Table 5 Rankings of the comprehensive tomato quality with GRA method

	X_1	X_2	X_3	X_4	X_5	R_i*	The rank of R_i*
ξ_1	0.801	0.467	0.463	0.494	0.482	0.541	8
ξ_2	0.992	0.706	0.857	0.989	0.510	0.811	2
ξ_3	0.981	0.621	0.467	0.553	0.680	0.660	5
ξ_4	0.601	0.553	0.569	0.450	0.585	0.552	6
ξ_5	0.913	0.766	1.000	0.619	0.793	0.818	1
ξ_6	0.818	0.666	0.822	0.545	0.793	0.729	3
ξ_7	0.511	0.508	0.420	0.399	0.389	0.446	9
ξ_8	0.692	0.682	0.922	0.606	0.521	0.685	4
ξ_9	0.653	0.619	0.430	0.519	0.536	0.551	7
w_j	0.089	0.083	0.376	0.227	0.225		

Notes: X_1 means TSS, X_2 means Vc, X_3 means Lycopene, X_4 means SS, X_5 means OA; ξ_1-ξ_9 are the correlation coefficient; w_j is the weight of single quality parameter from entropy method; R_i^* is the weighted correlation.

4 Discussion

Many studies had proved that APRI improved the water use efficiency and fertilizer-N use efficiency[39-42]. Wang et al.[42] pointed out that APRI had no significant influence on tomato yield with 34.3% water saved. Tomato is a water and fertilizer demanding crop. Yield decreased with the drop of irrigation water[20,43], however increasing N rate improved tomato yield[15]. The present experiment proved that tomato yield increased initially and then decreased as the levels of irrigation and nitrogen amounts increased under APRI. Adequate lower irrigation water application and higher nitrogen amounts might achieve high IWUE and PNP as suggested by earlier studies[44,45]. Thus W2N2 treatment was the suitable strategy for water saving and maximizing yield under APRI.

Tomato root, the major organ of water and nitrogen absorption, was significantly affected by the amounts of irrigation water and nitrogen (Table 3). It had been widely reported that APRI regulated the proportion of photosynthetic product in root and shoot, and optimized the root-shoot ratio by promoting root growth[46,47]. This study under APRI showed that increasing the water and nitrogen amounts would initially increase root parameters such as dry weight, length, surface area and volume and then a reduction occurs. This phenomenon proved the conclusion that appropriate irrigation water application and optimized amount of nitrogen applied would result in getting more yield under APRI [48-50].

Previous studies indicated that crop yield under APRI was improved with significant increment of soluble solid content, vitamin C, and soluble protein[10]. Deficit irrigation seemed generally, tend to improve TSS and SS in tomato fruits[19], mostly because water stress increased the activities of sucrose synthase and sucrose phosphate synthase, which enlarged the gradient of sucrose concentration between leaves and fruits[51]. Water deficit was proved to increase Vc content in tomato fruits[17,18], but no significant evidence showed that nitrogen could improve Vc. The study indicated that deficit irrigation increased TSS, SS and OA in tomato fruits, and high nitrogen amount improved OA and NC in fruits (Table 4). Moreover, within an appropriate range, the more irrigation water and nitrogen were applied, the higher the contents of Vc and lycopene would be identified in the fruits (Table 4).

Tomato fruit quality was a crucial factor for the determination of irrigation and nitrogen strategy. But the quality was a comprehensive concept and was difficult to be defined. In this study, the entropy method and GRA were used to assess the comprehensive fruit quality of tomato and to determine the optimal water and nitrogen combination management. The results showed that lycopene, SS and OA had a higher weight than other quality parameters (Table 5), suggesting that the taste and nutritional qualities were important assessment criteria for tomato quality. Moreover, W2N2 and W1N2 were ranked first and second, respectively. W3N1 was the last. In this manner, W2N2 was the appropriate water and nitrogen combination management for greenhouse tomato under alternate partial root-zone irrigation.

5 Conclusions

Appropriate deficit irrigation method and right application of nitrogen could guarantee tomato yield and root growth, and also improved fruit quality. Fruit parameters (TSS, SS, and OA) increased with the decrease in irrigation amount, N-fertilizer had significant influence on NC and OA. The more nitrogen that was applied resulted in higher contents of NC and OA identified in the fruits. High IWUE and PNP were achieved by low irrigation and high nitrogen amounts. Furthermore, the combinational evaluation result showed that W2N2 recorded the best in comprehensive fruit quality. Therefore, deficit irrigation of 80% θ_f and N-fertilizer of 0.30 g/kg soil with alternate partial root-zone irrigation was the best cultivation strategy for the comprehensive fruit quality and yields of greenhouse tomato in northwest China.

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