Agricultural Water Management 98 (2011) 1228–1238

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Determination of comprehensive quality index for tomato and its response to different irrigation treatments

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ARTICLE INFO

Article history:
Received 31 December 2010
Accepted 13 March 2011
Available online 7 April 2011

Keywords:
Tomato
Comprehensive quality index
AHP
TOPSIS
Greenhouse
Irrigation scheduling

ABSTRACT

In order to investigate better irrigation scheduling with the compromise between yield and quality of greenhouse-grown tomato under limit water supply, two experiments of different irrigation treatments were conducted in the arid region of northwest China during spring to summer in 2008 (2008 season) and winter in 2008 to summer in 2009 (2008–2009 season). After measuring single quality attributes, the analysis hierarchy process (AHP) and technique for order preference by similarity to an ideal solution (TOPSIS) were used to determine the weight of single quality attributes and comprehensive quality index, respectively. The results show that the rank of comprehensive quality index had good fitness to that of single quality attributes, indicating that the comprehensive quality index was reliable. Compared to full irrigation, applying 1/3 or 2/3 of full irrigation amount at the seedling stage had slight improvement of comprehensive quality and limit water saving. Applying 1/3 or 2/3 of full irrigation amount at the fruit maturation and harvesting stage decreased the yield by 23.0–40.9%, but had the best comprehensive quality. However, applying 1/3 of full irrigation amount at the flowering and fruit development stage significantly reduced crop water consumption and had obvious improvement of comprehensive quality, but did not decrease the yield significantly and water use efficiency in the 2008 season. And applying 2/3 of full irrigation amount at the flowering and fruit development stage significantly decreased crop water consumption and slightly improved the comprehensive quality, but did not decrease the yield significantly in the 2008–2009 season. Considering the water saving amount, yield and comprehensive quality, applying 1/3 or 2/3 of full irrigation amount at the flowering and fruit development stage and no water stress in other growth stages appears to be a better irrigation scheduling with the compromise between yield and quality of greenhouse-grown tomato, which can be recommended for the spring to summer and winter to summer seasons in the arid region of northwest China.

1. Introduction

As the market for fresh vegetable is growing steadily, the need for higher quality is increasing (Ruiz-Altisent et al., 2006). Tomato is one of popular vegetables and it is an important source of antioxidants such as lycopene, phenolics, and vitamin C in human diet (Toor et al., 2006). The quality of fresh tomato is affected by both genetic factor and growing condition (Viskelis et al., 2008). Among the environmental factors, water is one of the important factors affecting fruit growth and production of tomato, so irrigation scheduling is critical to increase tomato yield and quality. The nutritional quality, fruit acceptance and market grade of tomato are assured by appropriate water and fertilization management (Dorais et al., 2001). Pulupol et al. (1996) observes that after two weeks following transplant, applying appropriate deficit irrigation increases fruit colour intensity, lowers water content and improves the contents of sucrose, glucose and fructose of greenhouse-grown tomato. In red and pink large-fruited tomato cultivar, water deficit tends to increase lycopene content in outer pericarp region (Zushi and Matsuzoe, 1998). Mingchi and Diankui (2002) shows that after the first three trusses fruit set, reducing proper irrigation times increases the contents of soluble solid content, titration acidity, vitamin C and soluble solid/acid ratio of cherry tomato and also improves water use efficiency. Johnstone et al. (2005) shows that deficit irrigation at early fruit ripening stage can effectively increase total soluble solids (TSS) of processing tomato. Appropriate deficit irrigation also lowers colour hue angle, increases fruit reddish, contents of vitamin C, lycopene and beta-carotenoid in processing tomato (Favati et al., 2009; Patane and Cosentino, 2010). However, these studies only investigated the relationship between single quality attributes and water condition in different growth stages and such relationships are difficult to establish an efficient irriga-

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doi:10.1016/j.agwat.2011.03.004

tion scheduling for the compromise between yield and quality in tomato planting.

Tomato quality is a comprehensive concept and a sum of the interaction among different single quality attributes. It not only includes the external (size, uniformity, shape and colour) and taste (TSS, sugar, organic acid) qualities but also involves nutritional (lycopene, vitamin C) and storage (fruit firmness, fruit water content) qualities (Davies and Hobson, 1981; Kader et al., 1978; Labate et al., 2007; Salunkhe et al., 1974; Viskelis et al., 2008). Each quality attribute has different importance ratings, and the priority for quality also depends on consumer's preference. The determination of tomato comprehensive quality index needs to consider not only the measured values of single quality attribute but also consumer's preference and demand for the tomato quality, which is a quantitative and qualitative, subjective and objective complex process. At present, the comprehensive quality of tomato is mainly determined by the taste and smell evaluation (Chaïb et al., 2007; Thybo et al., 2005), but this method is quite complicated and tedious and the results are affected by the evaluators and their personal background, so the results are difficult to be used in other cases. Therefore, it is necessary to propose a new method to determine the comprehensive quality index and study its response to different irrigation managements, which is important in obtaining a better irrigation scheduling for the compromise between yield and quality in tomato planting (Kang, 2009).

Multiple attribute decision making (MADM) is an effective approach to evaluate and/or rank a set of alternatives, which are characterized in terms of their attributes. The principle of the method is to combine all the single variables to a comprehensive index based on the attribute ratings and preferences across the existing attributes, and the aim is to obtain the optimal alternative that has the highest degree of satisfaction for all of the relevant attributes. In this process, the decision maker may be required to calculate or define the attributes weight in terms of importance with respect to the overall objective (Mahdavi et al., 2008; Yang and Hung, 2007). Among the MADM methods, analytic hierarchy process (AHP) and technique for order preference by similarity to an ideal solution (TOPSIS) are two important approaches. The AHP, developed by Saaty (1980), addresses how to determine the relative importance of a set of factors in a multi-criteria decision problem. The process makes it possible to incorporate judgments on intangible qualitative criteria alongside tangible quantitative measure, and is based on three principles, i.e. the structure of the hierarchy model, the pairwise comparative judgment of elements in the same level and the synthesis of the priorities (Dagdeviren et al., 2009; Saaty, 2008). TOPSIS, known as another classical MADM method, has been developed by Hwang and Yoon (1981). The underlying logic of TOPSIS is to define the positive and negative ideal solutions, and the ranking of alternatives in TOPSIS is based on the relative similarity to the positive ideal solution, which avoids the situation of having same similarity to both positive and negative ideal solutions (Chamodrakas et al., 2009; Wang et al., 2010). The positive ideal solution is the solution that maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria. The optimal alternative is closest to the positive ideal solution and farthest to the negative ideal solution. Since the AHP and TOPSIS methods are simple and the result is easy to understand, they have been used to solve many complicated decision making problems in the past few years (Al-Harbi, 2001; Amiri, 2010; Vaidya and Sushil, 2006). However, they have not been applied in evaluating tomato quality.

In this study, two experiments of different irrigation treatments for greenhouse-grown tomato were conducted in the arid region of northwest China. After measuring single quality attributes, this study was to (1) establish the comprehensive quality index using the AHP and TOPSIS methods, (2) analyze the rationality of the comprehensive quality index, and (3) investigate the response of comprehensive quality to different irrigation treatments and then determine a better irrigation scheduling with the compromise between yield and quality under limit water supply in the regions.

2. Materials and methods

2.1. Experimental site

The two experiments were conducted in the 1# and 2# solar greenhouses at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University during spring to summer in 2008 (2008 season) and winter in 2008 to summer in 2009 (2008–2009 season), respectively. Experimental site is located in Wuwei, Gansu, northwest China (latitude 37°52′N, longitude 102°51′E, altitude 1581 m). The site is in a typical continental temperate climate zone with annual precipitation of 164.4 mm and pan evaporation of 2000 mm. It is rich in solar radiation with mean temperature of 8.8 °C, mean sunshine duration of 3000 h and frost-free days of 150 days. The solar greenhouse is built with soil-brick wall and has no heating system, and the inside environment is controlled by straw mulching at the top of greenhouse and narrow ventilation system near the door. The greenhouse is 76 m long and 8 m wide with planting area of 405 m^2. Soil inside the greenhouse is irrigated desert soil (Siltigic-Orthic Anthrosols) and soil texture is sandy loam. In the 1# greenhouse, the mean dry bulk density and soil volumetric water content at field capacity was 1.49 g/cm^3 and 0.28 (cm^3/cm^3) for the upper 0–50 cm soil layer in the 2008 season. Similarly, in the 2# greenhouse, the bulk density and field soil water capacity was 1.45 g/cm^3 and 0.34 (cm^3/cm^3) for the upper 0–50 cm soil layer in the 2008–2009 season.

2.2. Experimental design

The experiment had seven irrigation treatments (Table 1) and each treatment was replicated three times, totally 21 plots. Since 3–4 days after transplanting, tomato crops were irrigated to 90% of field capacity (θ_f) once average soil volumetric water content at the 0–50 cm layer in CK treatment (full irrigation) decreased to 75% of θ_f. At each irrigation event, the amount of irrigation water in a CK treatment plot can be calculated by

$$Q = (\theta_1 - \theta_2) \times H \times S \quad (1)$$

where Q is the amount of irrigation water in each irrigation event (m^3); θ_1 is the upper irrigation limit ($cm^3\ cm^{-3}$), i.e. 90% of θ_f; θ_2 is the actual soil moisture content before irrigation ($cm^3\ cm^{-3}$); H is planned moisture layer, i.e. 0.5 m; S is plot area, i.e. 19.32 m^2 (5.6 m long × 3.45 m wide).

Deficit irrigation treatments received 1/3 or 2/3 of full irrigation amount at seedling stage (transplant to first fruit set), flowering and fruit development stage (first fruit set to first harvest), fruit maturation and harvesting stage (first harvest to the end of cropping season), respectively, and had the same irrigation times as CK (Table 1). At 20 days before the end of harvest, all treatments ceased watering. Tomato crops were furrow-irrigated under mulch. In order to prevent water exchange across plots, a plastic sheet was embedded in the soil with 1 m depth to separate the plot. The irrigation amount was recorded using a water gauge.

2.3. Crop management

In the 2008 season, tomato (*CV. Lycopersicon esculentum Mill, Caihong-1*) seeds were sown on January 10 and transplanted on February 22. In the 2008–2009 season, tomato (*CV. Lycopersicon*

Table 1
Irrigation amount (mm) and times of greenhouse-grown tomato for different irrigation treatments in both seasons. The numbers in the brackets indicate total irrigation times for the respective growth stage. 2008 season means spring–summer in 2008, 2008–2009 season means winter in 2008 to summer in 2009.

Cropping season	Treatment	Transplanting 2008.2.22	Seedling stage 2008.2.23–3.15	Flowering and fruit development stage 2008.3.16–5.10	Fruit maturation and harvesting stage 2008.5.11–7.19	Total 148 days
2008 season	T1	21.0(1)	7.0(1)	84.0(4)	126.0(6)	238.0(12)
	T2	21.0(1)	14.0(1)	84.0(4)	126.0(6)	245.0(12)
	T3	21.0(1)	21.0(1)	28.0(4)	126.0(6)	196.0(12)
	T4	21.0(1)	21.0(1)	56.0(4)	126.0(6)	224.0(12)
	T5	21.0(1)	21.0(1)	84.0(4)	42.0(6)	168.0(12)
	T6	21.0(1)	21.0(1)	84.0(4)	84.0(6)	210.0(12)
	CK	21.0(1)	21.0(1)	84.0(4)	126.0(6)	252.0(12)
Cropping season	Treatment	Transplanting 2008.10.5	Seedling stage 2008.10.6–11.10	Flowering and fruit development stage 2008.11.11–2009.1.23	Fruit maturation and harvesting stage 2009.1.24–7.14	Total 283 days
2008–2009 season	T1	25.5(1)	8.5(1)	76.5(3)	382.5(15)	493.0(20)
	T2	25.5(1)	17.0(1)	76.5(3)	382.5(15)	501.5(20)
	T3	25.5(1)	25.5(1)	25.5(3)	382.5(15)	459.0(20)
	T4	25.5(1)	25.5(1)	51.0(3)	382.5(15)	484.5(20)
	T5	25.5(1)	25.5(1)	76.5(3)	127.5(15)	255.0(20)
	T6	25.5(1)	25.5(1)	76.5(3)	255.0(15)	382.5(20)
	CK	25.5(1)	25.5(1)	76.5(3)	382.5(15)	510.0(20)

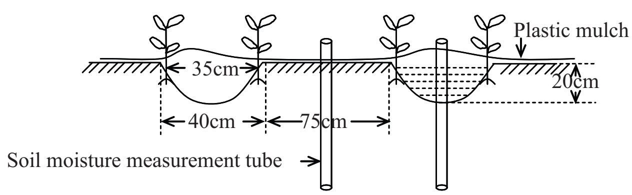

Fig. 1. Plant spacing of tomato and tube layout for soil moisture measurement in solar greenhouse.

esculentum Mill, Jinzuan-3) seeds were sown on August 15, 2008 and transplanted on October 5. Each plot had six rows and 102 plants. Before the transplanting, soils were rototilled and the beds were manually raised as Fig. 1. 110 t hm^{-2} of decomposed organic manure (pig and sheep manure), 1200 kg hm^{-2} of diammonium phosphate (N 18%, P_2O_5 46%) and 350 kg hm^{-2} of compound fertilizer (N 18%, P_2O_5 15%, K_2O 12%) were broadcasted uniformly as basal in the beds.

Tomato seedlings were transplanted to the furrow side with row spacing across the furrow of 0.35 m and interplant spacing of 0.35 m. After transplanting, all plots were irrigated (Table 1). At 4 days after transplanting, crop field was covered with polyethylene film to reduce soil evaporation and enhance soil temperature. At 30–40 days after transplanting (flowering and fruit development growth stage), the stems were hanged with plastic sting, and the flowers were manually treated using *p*-chlorophenoxy acetic acid solution.

In the 2008 season, there were 7 trusses per plant and each truss had 4–5 tomato loadings. Harvesting started on May 11 and ended on July 19 2008. In the 2008–2009 season, there were 12 trusses per plant and each truss also had 4–5 tomato loadings. The harvesting started on January 24 and ended on July 14, 2009. During the whole growth season, all treatments had similar fertilization, flower treatment, pruning branch stem, and pest and weed control, etc.

2.4. Measurements

2.4.1. Soil moisture content and crop water consumption

To monitor the soil water content, two PVC access tubes (with a diameter of 50 mm and a wall thickness of 2 mm) of 1 m in length were installed in each plot, and one was positioned on the center of bed, and the other tube was positioned in the middle furrow (Fig. 1). Soil water content was measured at 5 days interval or before and after irrigation using a portable soil moisture monitoring system (Diviner 2000, Sentek Pty Ltd., Australia). The vertical profile of soil water content in each tube was determined from measurements of soil water content at 0.1 m intervals. Readings were taken through the wall of the PVC access tube. Data was collected from a network of access tubes installed at selected sites. Soil water contents measured by Diviner 2000 were calibrated by the oven drying method.

Crop water consumption or evapotranspiration was estimated using water balance equation (Wang et al., 2009).

$$ET_c = I + \Delta W - R - D \quad (2)$$

where ET_c is crop water consumption (mm), I is irrigation water amount (mm), ΔW is the change in soil water storage (mm), R is the run-off (mm) and D is the drainage (mm). Because the greenhouse is flat, surface runoff is negligible, so $R = 0$. According to the actual measurement from medium-lysimeter in the greenhouse, there was no drainage below 60 cm, so $D = 0$.

2.4.2. Yield and water use efficiency

Individual fruit weight (w) and fresh yield (Y) of tomato were measured at each harvesting. In order to avoid border effects, only the 30 plants in the middle part of each plot were used for the yield and subsequent quality measurements. According to local large-fruited grade standard, single fruit size was divided into four categories according to individual fruit weight, i.e. $w < 60$ g, 60 g $\leq w <$ 125 g, 125 g $\leq w <$ 250 g and $w \geq 250$ g. Then tomato yields of four categories were, respectively, weighted, i.e. Y_1 ($w < 60$ g), Y_2 (60 g $\leq w <$ 125 g), Y_3 (125 g $\leq w <$ 250 g) and Y_4 ($w \geq 250$ g).

Water use efficiency was determined using the following equation (Wang et al., 2009):

$$WUE = \frac{Y}{ET_c} \times 100 \quad (3)$$

where WUE is water use efficiency (kg m^{-3}), Y is total fruit yield (t hm^{-2}).

2.4.3. Single quality attributes

From the beginning of harvest, tomato quality was measured every 7 days and 14 days in the 2008 and 2008–2009 seasons, respectively. At each measurement, 20 fruits per plot with similar size, maturity and no external defects were chosen at harvesting date. The fruits were firstly used to measure the size, shape and colour, and then divided into two halves. One half was used to measure fruit firmness and water content, the other half was washed with distilled water and homogenized in a blender for measuring the contents of total soluble solids (TSS), soluble sugar, organic acid, lycopene and vitamin C.

2.4.3.1. Preferential fruit yield percentage and fruit size uniformity. According to the survey of 744 local consumers for preferential individual fruit weight (w) of large-fruited tomato, the consumers who preferred $60\,g \le w < 125\,g$ and $125\,g \le w < 250\,g$ fruit occupies 38.5% and 53.4%, respectively, but those who preferred $w < 60\,g$ and $w \ge 250\,g$ fruit only occupied 8.1%. Thus the $60\,g \le w < 250\,g$ fruit was regarded as the preferential fruit, and then its yield percentage can be calculated as follows:

$$Y' = \frac{Y_2 + Y_3}{Y} \times 100\% \quad (4)$$

where Y' is preferential fruit yield percentage (%), Y is total yield ($t\,hm^{-2}$), Y_2 and Y_3 ($t\,hm^{-2}$) are fruit yields for $60\,g \le w < 125\,g$ and $125\,g \le w < 250\,g$, respectively.

The preferential fruit size uniformity was expressed by the coefficient of variation (CV) of preferential individual fruit weight and was calculated as follows:

$$CV = \frac{\sigma}{\bar{w}} \times 100\% \quad (5)$$

where CV is coefficient of variation (%), σ is standard deviation of preferential individual fruit weight (g), and $\bar{w}$ is average preferential individual fruit weight (g).

2.4.3.2. Fruit shape index, colour index and firmness. Fruit diameters in the horizontal and vertical direction were measured using a Vernier caliper, and shape index was calculated using the ratio of vertical to horizontal diameters.

Fruit colour was measured with a spectrophotometer (SP60, X-rite, Incorporated, MI, USA). Three readings of CIE (Commission International d'Eclairage) colour space coordinates L, a, b values were obtained from four fruit equatorial orientation, and then average values were converted to colour index using Eq. (6) (Hobson et al., 1983; Intelmann et al., 2005)

$$\text{Colour index} = 2000 \frac{a}{L(a^2 + b^2)^{0.5}} \quad (6)$$

where L is the lightness and ranges from 0 (black) to 100 (white), a is a scale ranging from green (−100) to red (+100), and b is a scale ranging from blue (−100) to yellow (+100).

Fruit firmness ($kg\,cm^{-2}$) was detected using a fruit firmness tester (FHR-5, Takemura electric works, Ltd., Japan) at harvesting. Measurements were done on the fruit shoulder 1.5 cm from blossom scar using a cylindrical probe (5 mm diameter).

2.4.3.3. Chemical components. Total soluble solids (TSS) of tomato juice were determined using a handheld refractometer (PR-32, Co., Ltd., Tokyo, Japan) with automatic temperature compensation. Organic acid was titrated with 0.1 mol L^{-1} NaOH and calculated as equivalents of citric acid expressed as percentage of fresh mass (AOAC, 1990). Total soluble sugar content was measured using anthrone method (Spiro, 1966). Vitamin C (ascorbic acid) was measured with the 2,6-dichloroindophenol titrimetric method (AOAC, 1984). Lycopene content was measured at 474 nm on a spectrophotometer using the modified method developed by Davies (1976) and Sharma and Le Maguer (1996). Fruit water content was measured using oven-drying method. There are totally 10 and 12 measurements in the 2008 and 2008–2009 seasons, respectively, and the average values were for single quality attributes.

2.5. Data analysis

Statistical analysis was done using SAS8.2 version software (SAS Institute, Cary, NC, USA). Analysis of variance (ANOVA) was performed using the GLM procedure and multiple comparisons of mean values were performed using least significant difference (LSD) test at $P_{0.05}$ level. The matrix calculation was done with Matlab 7.0.4 (The Mathworks Inc.)

3. Determination of comprehensive quality index for tomato

3.1. Determination of weight for single quality attributes using AHP

(1) The evaluation hierarchy for comprehensive quality, including objective, criteria and attribute levels, was built as Fig. 2. The objective level on the top is the determination of comprehensive quality, and the second level is the quality criteria, including external, taste, nutritional and storage qualities, and the bottom level is the single quality attributes measured in this study except for the fruit shape index. Fruit shape index was excluded due to no significant difference among treatments (see Section 4.1.1).

(2) Once the evaluation hierarchy was constructed, prioritization procedure started to determine the relative importance of the elements within each level in respect to the related criteria in the adjacent higher level. The pair-wise judgment started from the second level and finished at the bottom level. In each level, the elements were compared pair-wisely according to the importance based on the specified criteria in the higher level (Albayrak and Erensal, 2004). In this study, there were totally 1000 customers and 25 horticultural experts who participated in the comparisons for the criteria and attribute levels, respectively. In the criteria level, 744 effective questionnaires were returned with return rate of 74.4%, and in the attribute level, all questionnaires were returned with return rate of 100%. The pair-wise comparison in both levels was indicated by the known standardized comparison scale of nine levels (Table 2). The geometric means of every evaluator's pair-wise comparison were calculated to obtain the final pair-wise comparison matrix $A = (a_{i,j})_{m \times n}$ for a consensus. The element $a_{i,j}$ in matrix A was the i element to j factor importance quotient in response to the criteria of higher level. At the last step, the mathematical process commenced to normalize and find the relative local weights for each matrix. The relative local weights were given

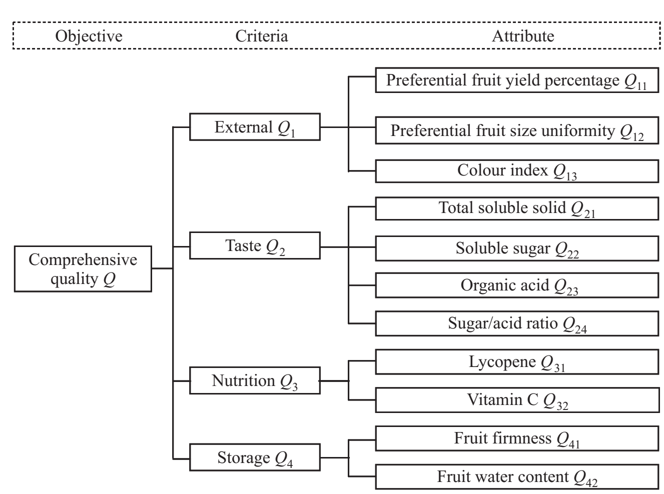

Fig. 2. Evaluation hierarchy of tomato comprehensive quality.

Table 2
Nine intensity scales of importance and its definition.

Intensity scale of importance	Definition
1	Equal importance
2	Weak or slightly
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance

by the right eigenvector (W) corresponding to the largest eigenvalue λ_{max}, as the follows (Amiri, 2010):

$$AW = \lambda_{max} W \quad (7)$$

where λ_{max} was the largest eigenvalue of A, W is the normalized eigenvector belonging to λ_{max}.

(3) When the local weights of the elements in each level were obtained, the overall weight of the quality attributes at the bottom level with respect to the objective of the top level can be acquired by multiplying the local weights of related elements in each level.

(4) If the pair-wise comparison matrix is completely consistent ($a_{ij} \times a_{jk} = a_{ik}$), the matrix A has the max eigenvalue ($\lambda_{max} = n$). In this case, the local weights can be obtained by normalizing any of the rows or columns of A. It should be noted that the actual comparison matrix is not always completely consistent, and then the maximal eigenvalue may be slightly greater than n. Thus the consistency index (CI) is proposed for the evaluation of the coherence between the comparisons and calculated as Eq. (8)

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (8)$$

The consistency ratio (CR) that lets someone to conclude whether the evaluation is sufficiently consistent can be calculated as follows:

$$CR = \frac{CI}{RI} \quad (9)$$

where RI is the average random consistency index, which is from Saaty (1980). When $CR < 0.1$, the pair-wise comparison matrix is sufficiently consistent.

3.2. Calculation of comprehensive quality index using TOPSIS

According to the calculation steps of modified TOPSIS method (Deng et al., 2000) and the specific quality evaluation in this study, the comprehensive quality of tomato is established and calculated as the following.

(1) Normalization of quality attributes. Normalization seeks to obtain comparable scales, which allows attribute comparison. The vector normalization approach divides the rating of each attribute by its sum to calculate the normalized value of r_{ij} as defined in Eq. (10)

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (10)$$

where $r_{ij} = x_{ij}/\sum_{i=1}^{m} x_{ij}, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n, x_{ij}$ is the measured value of attribute j in alternatives A_i (i.e. irrigation treatment in this study).

(2) Determination of positive (A^+) and negative (A^-) ideal solutions. The A^+ and A^- are defined in terms of the normalized values, as shown in Eqs. (11) and (12), respectively:

$$A^+ = \left\{ r_1^+, \ r_2^+, \ldots, r_j^+, \ldots, r_n^+ \right\} = \left\{ (\max_i \ r_{ij} \left| j \in J_1 \right.), (\min_i \ r_{ij} \left| j \in J_2 \right.) \left| i = 1, \ 2, \ldots, m \right. \right\} \quad (11)$$

$$A^- = \left\{ r_1^-, \ r_2^-, \ldots, r_j^-, \ldots, r_n^- \right\} = \left\{ (\min_i \ r_{ij} \left| j \in J_1 \right.), (\max_i \ r_{ij} \left| j \in J_2 \right.) \left| i = 1, 2, \ldots, m \right. \right\} \quad (12)$$

where J_1 is a set of the-greater-the-better quality attributes and J_2 is a set of the-smaller-the-better quality attributes.

(3) Calculation of weighted Euclidean distances. The weighted Euclidean distance (d_i^+) between A_i and positive ideal solution (A^+) is given by Eq. (13)

$$d_i^+ = \sqrt{\sum_{j=1}^{n} w_j (r_{ij} - r_j^+)^2}, \quad i = 1, \ 2, \ldots, m \quad (13)$$

Similarly, the weighted Euclidean distance (d_i^-) between A_i and negative ideal solution (A^-) is given by Eq. (14)

$$d_i^- = \sqrt{\sum_{j=1}^{n} w_j (r_{ij} - r_j^-)^2}, \quad i = 1, 2, \ldots, m \quad (14)$$

where w_j is the overall weight of jth attribute in respective to the comprehensive quality.

(4) Calculation of comprehensive quality index for different irrigation treatments. The relative closeness of quality vector of each treatment to the positive ideal solution is defined as the comprehensive quality index (Q_i), and Q_i is calculated by Eq. (15)

$$Q_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad i = 1, 2, \ldots, m \quad (15)$$

Note that $0 \le Q_i \le 1$, $A_i = A^-$ when $Q_i = 0$ and $Q_i = 1$ when $A_i = A^+$. When Q_i is close to 1, tomato had better comprehensive quality.

4. Results

4.1. Response of single quality attributes of tomato to different irrigation treatments

4.1.1. External and storage qualities

Fruit appearance is the first quality trait to consumers and determined by fruit size, shape and colour (Labate et al., 2007; Salunkhe et al., 1974). In the 2008 season, Fig. 3 shows that the preferential fruit yield percentage was not significantly affected by deficit irrigation treatments compared to CK ($P > 0.05$), but in the 2008–2009 season, the preferential fruit yield percentage of T2, T3 and T4 were significantly higher than that of CK ($P < 0.05$), while other treatments were not significantly higher. However, the preferential fruit yield percentage of T3 was significantly higher than that of T5 and T6 in both seasons ($P < 0.05$) (Fig. 3a). In the 2008 season, the preferential fruit size uniformity of T5 and T6 was significantly higher than that of CK ($P < 0.05$), indicating poor fruit size uniformity. In the 2008–2009 season, only the T4 treatment had significantly higher preferential fruit size uniformity ($P < 0.05$) as compared to CK (Fig. 3b). For both seasons, there was no significant difference ($P > 0.05$) in the fruit shape index of tomatoes harvested from different irrigation treatments (Fig. 3c), which implied that

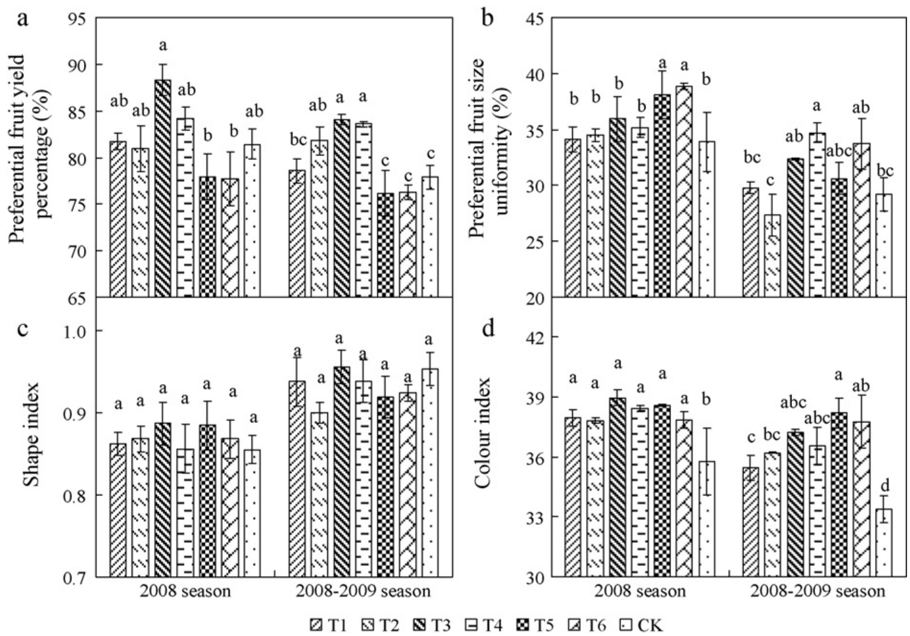

Fig. 3. Effects of different irrigation treatments on external quality attribute of tomato fruit in the 2008 and 2008–2009 seasons. Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the LSD test. Each value is the mean ± SD (n = 3). The treatment symbols of T1, T2, . . . , CK is the same as in Table 1.

the fruit shape was mainly determined by the genetic cultivar. All the deficit irrigation treatments tended to have redder fruit colour. When compared to CK, the deficit irrigation treatments significantly increased ($P < 0.05$) the fruit colour index by 5.7–8.9% and 6.2–14.4% in the 2008 season and 2008–2009 season, respectively (Fig. 3d).

Fruit firmness and water content are the main attributes which determine storage quality of tomato (Batu, 2004; Dorais et al., 2001; Viskelis et al., 2008). A higher fruit firmness can stand more tough mechanical damage and thus prolong storage duration, and most consumers prefer buying firmer tomato (Kader, 1986). In the 2008 season, the fruit firmness of T5 and T6 was significantly higher than that of CK ($P < 0.05$), while other treatments were not significantly higher. In the 2008–2009 season, no significant difference for the fruit firmness was observed among the irrigation treatments ($P > 0.05$) (Fig. 4a). In terms of the fruit water content, T5 significantly decreased the fruit water content in both seasons ($P < 0.05$) when comapred to CK (Fig. 4b).

4.1.2. Taste and nutritional qualities

Tomato taste quality is largely determined by the contents of soluble sugar and organic acid and their ratio (Dorais et al., 2001). In the 2008 season, compared to CK, T5 and T6 significantly increased ($P < 0.05$) TSS by 33.9% and 27.0% and SSC by 39.0% and 29.4%, respectively. In the 2008–2009 season, T5 and T6 also significantly increased ($P < 0.05$) TSS by 17.7% and 10.0% and SSC by 29.5% and 23.0%, respectively. Compared to CK, T5 significantly increased ($P < 0.05$) the organic acid content of fruit by 24.4% and 20.9%, and the sugar/acid ratio by 18.8% and 13.0% in two seasons, respectively (Fig. 5).

Lycopene and vitamin C are two important antioxidants representing the main fruit nutritional quality. In both seasons, the lycopene and vitamin C content was significantly higher ($P < 0.05$) in T3, T5 and T6 compared to CK (Fig. 6). The mean lycopene content in T3, T5 and T6 was 18.1%, 20.7% and 16.5% higher than that in CK in the 2008 season, and 13.9%, 14.5% and 12.5% in the 2008–2009 season, and they increased the vitamin C content by 9.8%, 27.0% and 14.1% in the 2008 season, 11.1%, 29.6% and 20.3% in the 2008–2009 season, respectively.

4.2. Comprehensive quality index and its response to different irrigation treatments

According to the survey results from weight decision-making team, the local weights calculation results from AHP were shown in Table 3. The results indicate that taste was the most important quality, which had the highest criteria weight of 0.351. And the criteria weight of nutritional, external and storage quality was 0.249, 0.204 and 0.196, respectively. Among the single quality attributes, the lycopene had the highest overall weight of 0.143, while the preferential fruit yield percentage had the lowest overall weight of 0.044 (Table 3).

Using the overall weights obtained from AHP, the comprehensive quality index was calculated with the TOPSIS method, as shown in Table 4. The results show that different irrigation treatments had similar ranking for the comprehensive quality index in both seasons. In the 2008 season, T5, T6 and T3 had higher comprehensive quality index, with the values of 0.824, 0.693 and 0.442, respectively, but T1 and CK had lower comprehensive quality index, with the values of 0.238 and 0.172. In the 2008–2009 season, the comprehensive quality index of T5, T6 and T3 were 0.824, 0.591 and 0.488, while T1, T4 and CK had lower comprehensive quality index, with the values of 0.318, 0.317 and 0.228, respectively.

To identify the rationality of comprehensive quality index in evaluating the tomato overall quality performance of different irrigation treatments, the Spearman ranking correlation analysis between the comprehensive quality index and single quality attributes performance were conducted. Table 4 shows that the ranks of the preferential yield percentage and fruit size uniformity were negatively correlated with that of the comprehensive quality index, while the ranks of the other attributes were positively correlated with that of the comprehensive quality index. The numbers of negative and positive correlation coefficients occupied 18.2% and 81.8% of total, respectively, and among the positive quality attributes, the percentage of significant correlation coefficient numbers was 66.7% in both seasons. Moreover, the spearman correlation coefficient of comprehensive quality index in both seasons was 0.96.

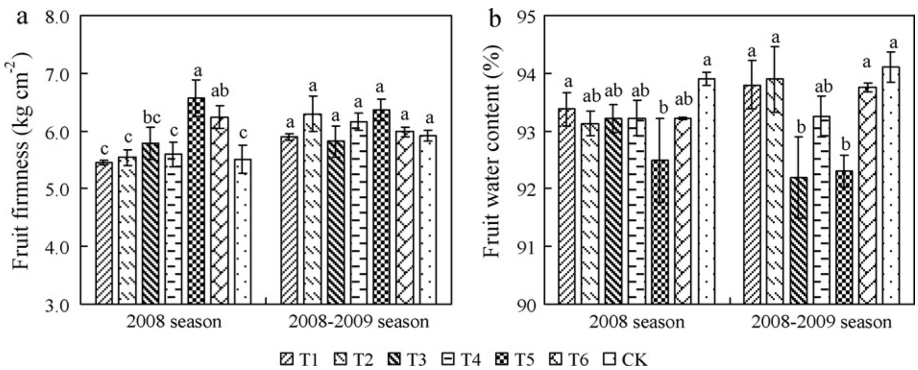

Fig. 4. Effects of different irrigation treatments on storage quality attributes of tomato fruit in the 2008 and 2008–2009 seasons. Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the LSD test. Each value is the mean ± SD ($n = 3$). The treatment symbols of T1, T2, . . ., CK are the same as in Table 1.

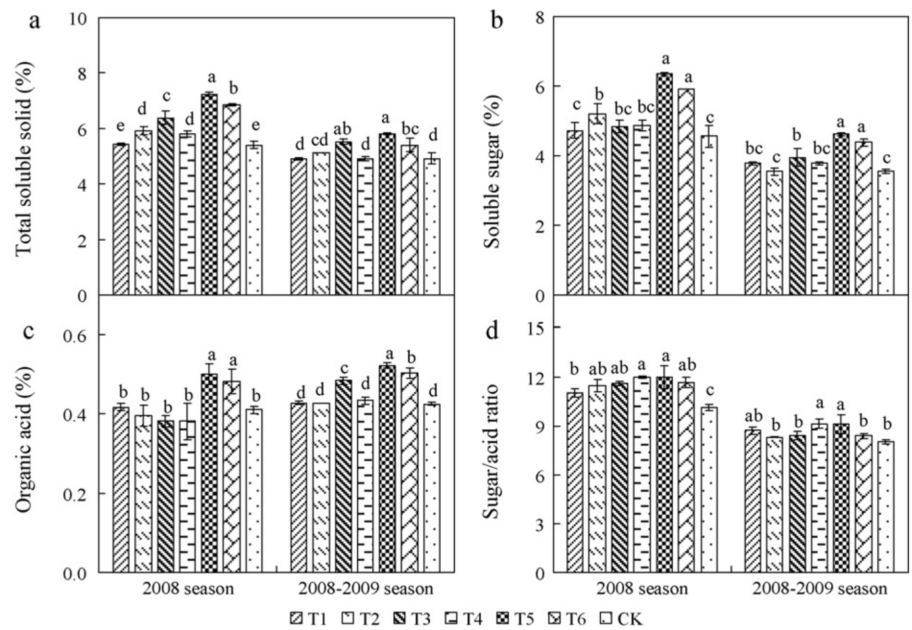

Fig. 5. Effects of different irrigation treatments on taste quality attributes of tomato fruit in the 2008 and 2008–2009 seasons. Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the LSD test. Each value is the mean ± SD ($n = 3$). The treatment symbols of T1, T2, . . ., CK are the same as in Table 1.

4.3. Irrigation scheduling with the compromise between yield and quality

The economic benefit of tomato is determined by both yield and fruit quality. But simultaneous control of them is usually a challenge due to the inverse relationship between yield and fruit quality. A scientific irrigation scheduling should be a compromise that comprehensively considers the effects of water stress on the yield and fruit quality as well as water save capacity. Fig. 7 shows that in the 2008 season, the crop water consumption of T1, T3, T4, T5

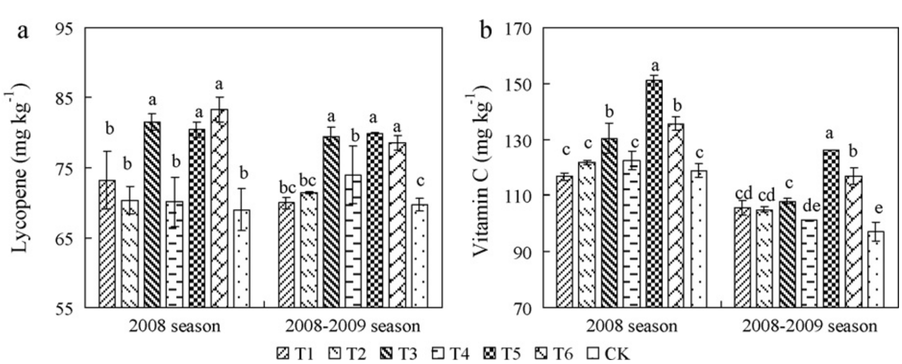

Fig. 6. Effects of different irrigation treatments on nutritional quality attributes of tomato fruit in the 2008 and 2008–2009 seasons. Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the LSD test. Each value is the mean ± SD ($n = 3$). The treatment symbols of T1, T2, . . ., CK are the same as in Table 1.

Table 3
Pair-wise comparison matrix and weights from AHP for the evaluation hierarchy criteria and attribute level. λ_{max} is the largest eigenvalue, *CI* is the consistency index, *RI* is average random consistency index, *CR* is the final consistency ratio and the accepted upper limit is 0.1. When the dimension of pair-wise comparison matrix equals to 2, the *CR* needs not to be calculated. The other symbols are the same as in Fig. 2.

Level or sub-level of evaluation hierarchy		Pair-wise comparison matrix				Local weight	Overall weight
		Q_1	Q_2	Q_3	Q_4		
Criteria level	Q_1	1.00	0.56	0.82	1.07	0.204	
	Q_2	1.77	1.00	1.40	1.76	0.351	
	Q_3	1.22	0.71	1.00	1.27	0.249	
	Q_4	0.94	0.57	0.79	1.00	0.196	
		λ_{max} = 4.000, *CI* = 0.000, *RI* = 0.900, *CR* = 0.000					

Level or sub-level of evaluation hierarchy		Pair-wise comparison matrix			Local weight	Overall weight
		Q_{11}	Q_{12}	Q_{13}		
Sub-level of external quality attributes	Q_{11}	1.00	0.62	0.49	0.215	0.044
	Q_{12}	1.61	1.00	0.79	0.346	0.070
	Q_{13}	2.05	1.27	1.00	0.439	0.089
		λ_{max} = 3.002, *CI* = 0.001, *RI* = 1.120, *CR* = 0.000				

Level or sub-level of evaluation hierarchy		Pair-wise comparison matrix				Local weight	Overall weight
		Q_{21}	Q_{22}	Q_{23}	Q_{24}		
Sub-level of taste quality attributes	Q_{21}	1.00	0.89	1.69	0.89	0.263	0.092
	Q_{22}	1.12	1.00	1.30	0.67	0.243	0.085
	Q_{23}	0.59	0.77	1.00	0.53	0.170	0.060
	Q_{24}	1.12	1.49	1.90	1.00	0.324	0.114
		λ_{max} = 4.018, *CI* = 0.006, *RI* = 0.900, *CR* = 0.007					

Level or sub-level of evaluation hierarchy		Pair-wise comparison matrix		Local weight	Overall weight
		Q_{31}	Q_{32}		
Sub-level of nutritional quality attributes	Q_{31}	1.00	1.36	0.576	0.143
	Q_{32}	0.74	1.00	0.424	0.106

Level or sub-level of evaluation hierarchy		Pair-wise comparison matrix		Local weight	Overall weight
		Q_{41}	Q_{42}		
Sub-level of storage quality attributes	Q_{41}	1.00	1.62	0.618	0.121
	Q_{42}	0.62	1.00	0.382	0.075

and T6 were significant lower than that of CK ($P < 0.05$). The yield of T1, T2, T3 and T4 were not significantly affected ($P > 0.05$), but T5 and T6 significantly ($P < 0.05$) decreased the yield by 40.9% and 32.2%, respectively, when compared to CK. And there was no significant difference for the water use efficiency among treatments ($P > 0.05$). In the 2008–2009 season, T3, T4, T5 and T6 significantly decreased the crop water consumption ($P < 0.05$). The yield of T1, T2 and T4 were not significantly different from CK ($P > 0.05$), but

Table 4
TOPSIS analysis in both seasons. Q_{12} and Q_{42} are the-smaller-the-better quality attributes, while others were the-greater-the-better ones. A^+ and A^- are the positive and negative ideal solution, respectively. d_i^+ and d_i^- are the weighted Euclidean distances between each alternative and the positive or negative ideal solutions, respectively. Q_i is the comprehensive quality index. *R* means the Spearman correlation coefficient between comprehensive quality rank and single quality index rank, the asterisk (*) means the *R* was significant at the 0.05 probability level. 2008 season, 2008–2009 season, T1, T2, . . ., CK are the same as in Table 1. The other symbols are the same as in Fig. 2.

Cropping season	Treatment	Q_{11}	Q_{12}	Q_{13}	Q_{21}	Q_{22}	Q_{23}	Q_{24}	Q_{31}	Q_{32}	Q_{41}	Q_{42}	d_i^+	d_i^-	Q_i	Rank
2008 season	T1	0.143	0.136	0.143	0.126	0.130	0.141	0.138	0.139	0.130	0.134	0.143	0.026	0.008	0.238	6
	T2	0.141	0.138	0.142	0.138	0.143	0.133	0.144	0.133	0.136	0.136	0.143	0.023	0.010	0.307	4
	T3	0.154	0.143	0.147	0.148	0.133	0.129	0.145	0.154	0.145	0.142	0.143	0.020	0.016	0.442	3
	T4	0.147	0.140	0.145	0.135	0.133	0.128	0.150	0.133	0.137	0.137	0.143	0.025	0.011	0.301	5
	T5	0.136	0.152	0.145	0.168	0.174	0.169	0.150	0.152	0.168	0.161	0.142	0.006	0.029	0.824	1
	T6	0.136	0.155	0.143	0.159	0.162	0.163	0.146	0.158	0.151	0.153	0.143	0.010	0.023	0.693	2
	CK	0.142	0.135	0.135	0.126	0.125	0.138	0.127	0.131	0.133	0.135	0.144	0.029	0.006	0.172	7
	A^+	0.154	0.135	0.147	0.168	0.174	0.169	0.150	0.158	0.168	0.161	0.142				
	A^-	0.136	0.155	0.135	0.126	0.125	0.128	0.127	0.131	0.130	0.134	0.144				
	R	−0.46	−0.93*	0.54	1.00*	0.89*	0.43	0.64	0.79*	0.93*	0.93*	0.87*				
2008–2009 season	T1	0.141	0.137	0.139	0.134	0.137	0.133	0.145	0.134	0.139	0.139	0.144	0.019	0.009	0.318	5
	T2	0.147	0.125	0.142	0.140	0.128	0.132	0.138	0.136	0.138	0.148	0.144	0.019	0.011	0.376	4
	T3	0.151	0.149	0.146	0.151	0.143	0.150	0.140	0.152	0.142	0.137	0.141	0.014	0.013	0.488	3
	T4	0.150	0.159	0.143	0.135	0.137	0.135	0.152	0.141	0.133	0.145	0.143	0.020	0.009	0.317	6
	T5	0.136	0.141	0.150	0.158	0.167	0.162	0.152	0.153	0.166	0.150	0.141	0.005	0.024	0.824	1
	T6	0.137	0.155	0.148	0.148	0.159	0.156	0.140	0.150	0.154	0.141	0.144	0.011	0.017	0.591	2
	CK	0.140	0.134	0.131	0.134	0.129	0.132	0.134	0.133	0.128	0.140	0.144	0.023	0.007	0.228	7
	A^+	0.151	0.125	0.150	0.158	0.167	0.162	0.152	0.153	0.166	0.150	0.141				
	A^-	0.136	0.159	0.131	0.134	0.128	0.132	0.134	0.133	0.128	0.137	0.144				
	R	−0.36	−0.21	0.89*	0.86*	0.79*	0.86*	0.21	0. 85*	0.96*	0.32	0.60				

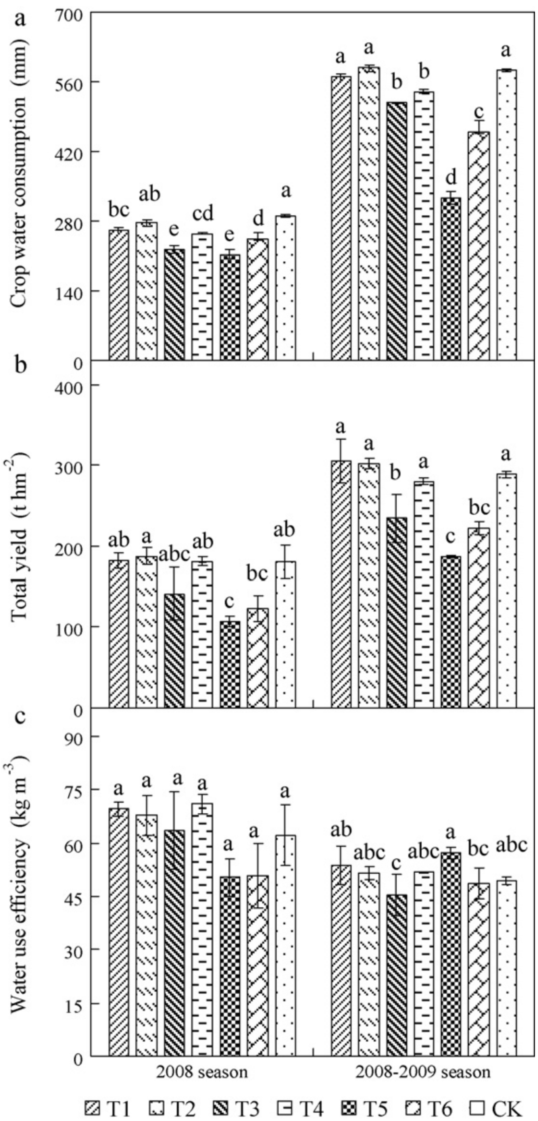

Fig. 7. Effects of different irrigation treatments on total yield and water use of tomato in the 2008 and 2008–2009 seasons. The treatment symbols of T1, T2, . . . , CK are the same as in Table 1.

T3, T5 and T6 significantly decreased the yield by 18.8%, 35.2% and 23.0%, respectively, when compared to CK.

Therefore, compared to full irrigation, applying 1/3 or 2/3 of full irrigation amount at the seedling stage had slight improvement of comprehensive quality and limit water saving (except T1 in the 2008 season), so even though there was no significantly negative effects on the yield, deficit irrigation was not a good choice at this stage. Applying 1/3 or 2/3 of full irrigation amount at the fruit maturation and harvesting stage had the best comprehensive quality, but significantly decreased the yield by 23.0–40.9%, so deficit irrigation is not suitable at this stage, either. However, in the 2008 season, applying 1/3 of full irrigation amount significantly reduced crop water consumption ($P < 0.05$) and had obvious improvement of comprehensive quality, but did not decrease the yield and water use efficiency (WUE) significantly ($P > 0.05$). And in the 2008–2009 season, applying 2/3 of full irrigation amount did not decrease the yield significantly ($P > 0.05$), but significantly decreased crop water consumption ($P < 0.05$) and slightly improved comprehensive quality. Considering the water-saving effect, yield and comprehensive quality, applying 1/3 or 2/3 of full irrigation amount at the flowering and fruit development stage and no water stress in other growth stages appears to be the suitable irrigation scheduling with a compromise between higher yield and better quality. This was similar to the conclusion on processing tomato (Favati et al., 2009).

5. Discussion and conclusion

Fresh fruit weight is an important external quality attribute of tomato and is mainly determined by the cultivar. However, within the same cultivar, the fresh weight is also affected by the irrigation treatment to some extent. In this study, applying 1/3 or 2/3 of full irrigation amount at fruit maturation and harvesting stage decreased the preferential fruit yield percentage. This is mainly the result of increased small fruit numbers. During this stage, all fruit trusses for the 2008 season or most of them for the 2008–2009 season have been set. The requirement of tomato fruit for photosynthesis assimilates and water is drastically increased, which increases the total crop water consumption greatly. If the irrigation is reduced, the rate of water absorption by roots will be lower than that of crop transpiration, which induces an internal water deficit affecting photosynthesis and results in reduced leaf area, cell size and intercellular volume, thus fruit water accumulation and consequently fruit weight are decreased (Madrid et al., 2009). Our result was also in agreement with the previous observation (Gianquinto et al., 1989).

Water deficit promotes the ripeness of tomato and increases fruit reddish (Matsuzoe et al., 1998). In this study, all the deficit irrigation significantly increased the colour index and thus made the pericarp colour redder. This is because water stress increased the ethylene content of tomato fruit (Basiouny et al., 1994) which in turn increased carotenoid concentration of tomato fruit (Paz et al., 1982), and peak lycopene content coincided with peak ethylene content (Ishida et al., 1993), thus the deficit irrigation fruits had redder colour, which may be the result of higher ethylene production (Pulupol et al., 1996).

In general, a small fruit tends to have a harder firmness. In this study, applying 1/3 of full irrigation amount at the fruit maturation and harvesting stage increased fruit firmness of tomato. This may be explained by the increased total soluble solid content and cellular density due to the reduction in fruit size. However, other observations show that there is no significant difference of fruit firmness between small and large fruits if fruit volume is considered (Ebel et al., 1993).

Generally, higher contents of soluble sugar and organic acid can be considered better tomato taste quality (Bucheli et al., 1999). In this study, applying 1/3 or 2/3 of full irrigation amount at the fruit maturation and harvesting stage significantly improved the fruit taste quality of tomato. This is because the fruit maturation and harvesting stage is critical for fruit quality and yield, water stress at this stage increases the activities of sucrose synthase and sucrose phosphate synthase (Qi et al., 2003), thus enlarges the gradient of sucrose concentration between leaves and fruits (Walker et al., 1978), which transports more assimilates into the fruits and increases the rate and amount of fructose and glucose transformation from sucrose, and thus improves fruit TSS and SSC content (Kan, 2008).

A higher fruit light exposure is found to be favorable for the accumulation of vitamin C and lycopene (Dumas et al., 2003). In this study, applying 1/3 of full irrigation amount at the flowering and development stage or 1/3 or 2/3 of full irrigation amount at the fruit maturation and harvesting stage improved tomato nutritional quality. This is mainly due to the reduced leaf area index. Because lower leaf area index increases light intensity and duration for fruit, and then promotes the formation of vitamin C and lycopene. However, full irrigation increases shading effect on fruit, which decreases vitamin C and lycopene (Toor et al., 2006).

Fruit quality is an important factor for the determination of irrigation scheduling. But in many cases, the quality is difficult to be defined because it concerns consumer's preference. In this study, the AHP and TOPSIS methods are used to determine the single quality attributes importance weight and comprehensive quality index. The results show that the taste and nutritional qualities have a higher criteria weight than external and storage quality. It is easy to understand that the taste and nutritional qualities is important evaluation criteria for the consumers. Although the external quality gives consumers the first impression and the other three qualities can be felt and evaluated only after purchase, it has not the highest criteria weight as expected. This is because the survey was based on the assumption that every evaluation team member was fully aware of each quality performance, which may decrease the weight of external quality evaluation criteria. Since the main purpose of large-fruited tomato is cooking and freshly eating, the storage quality is the less important criteria. The overall weight of a single quality attributes is determined by both the criteria weight and the numbers of single quality attributes included. For example, although the taste quality had the greatest criteria weight, the overall weight of TSS, SSC and organic acid attributes was decreased due to the four single quality attributes included.

As for the comprehensive quality index, the results show that applying 1/3 of full irrigation amount at the flowering and fruit development stage, applying 1/3 or 2/3 of full irrigation amount at the fruit maturation and harvesting stage had higher comprehensive quality performance than other treatments. This is because the comprehensive quality index was determined by both the measured value and the overall weight of single quality attributes. These three treatments had higher contents of total soluble solids (TSS), lycopene, vitamin C, sugar/acid and fruit firmness, and had overall weight of 0.577 for these five quality attributes. However, other treatments had lower comprehensive quality index because they had lower contents of the five quality attributes even though the overall weights of single quality attribute were same for all the irrigation treatments.

The comprehensive quality index ranks should be consisted with single quality performance ranks as close as possible. In this study, the analysis of spearman correlation coefficient shows that 81.8% of single quality attributes was consisted with that of comprehensive quality, and 66.7% of positive correlation coefficient was significant, indicating that the rank of comprehensive quality index has good fitting to that of most single quality attributes. Moreover, the significant positive correlation coefficient between two seasons shows that the ranks of comprehensive quality index were stable when applying similar irrigation regimes. Therefore, the comprehensive quality index was reliable. As for the negative correlations between the preferential fruit yield percentage, fruit size uniformity and the comprehensive quality index, the possible reason is that water stress reduced these two attributes but increased other single quality attributes.

In summary, comprehensive quality index determined by AHP and TOPSIS is reliable. Applying 1/3 or 2/3 of full irrigation amount at the flowering and fruit development stage and no water stress in the other growth stages can acquire a better compromise between the tomato yield and quality, which can be recommended as the suitable irrigation scheduling for the spring–summer and winter to summer greenhouse-grown tomato, respectively, i.e. 196 mm and 484.5 mm irrigation water applied during whole growth season.

Acknowledgements

We are grateful for Grants from the National Natural Science Foundation of China (50939005, 51079147) and the Ministry of Water Resources of China (201001061).

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