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ORIGINAL PAPER

Effect of stage-specific saline irrigation on greenhouse tomato production

Hexigeduleng Bao · Yinxin Li

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Abstract In many water scarce areas, saline water has been included as an important substitutable resource in agricultural irrigation. It would be of practical use to investigate the effect of stage-specific saline irrigation on yield, fruit quality, and other growth responses of greenhouse tomato, to establish a proper irrigation management strategy for tomato production in these regions. Here, saline irrigations (3.33, 8.33, and 16.67 dS m^{-1} NaCl solution) were applied during four growth stages of greenhouse tomato (*L. esculentum* Mill. cv. Zhongza No. 9) grown in the North China Plain, respectively. These include flowering and fruit-bearing stage (stage 1), first cluster fruit expanding stage (stage 2), second cluster fruit expanding stage (stage 3), and harvesting stage (stage 4). Compared with the following three stages, yield loss was most remarkable in stage 1 under all three salinity levels. Under irrigation practices using 3.33 dS m^{-1} saline water in all four stages, 8.33 dS m^{-1} saline water in latter three stages, and 16.67 dS m^{-1} saline water in stage 4, yield reduction was not significant while fruit quality was improved. In conclusion, it is feasible to use stage-specific saline irrigation for tomato production in water scarce areas like North China Plain.

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H. Bao · Y. Li (✉)
Key Laboratory of Photosynthesis and Environmental Molecular Physiology, Institute of Botany, Chinese Academy of Sciences, 100093 Beijing, Pepole's Republic of China
e-mail: yxli@ibcas.ac.cn

Introduction

The problem of water shortage is a global issue (Bennett 2000). Owing to the continuous increase of world population, as much as 60% of the global population may suffer water scarcity by the year 2025 (Qadir et al. 2007). In China, per capita annual water resource in 1999 is 2,230 m^3, which is less than one-third of the global average (He et al. 2007). The unbalanced regional distribution of water resource makes the water shortage even worse in some parts of the country (Xia et al. 2008). North China Plain, with an area of 3,50,000 km^2, is one of the most important centers of agricultural production in China (Zhang et al. 2004). Water is becoming one of the scarcest natural resources, which limits the agricultural and economic development in the region (Mao et al. 2003).

Efforts have been made to reduce irrigation volume of fresh water in water-saving agriculture, such as the development of deficit irrigation (DI) (Kirda et al. 2004; Pulupol et al. 1996; Shahnazari et al. 2008). In deficit irrigation, the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. Studies have been concentrated on deficit irrigation practices in the North China Plain in the past few years (Mao et al. 2003; Zhang et al. 2004). However, the improvement of fresh water-saving techniques is not enough to cope with the production demand. Therefore, many countries take the use of non-conventional water resources as an alternative method of deficit irrigation in water-saving agriculture (Assouline et al. 2006; Qadir et al. 2007). Utilization of non-conventional water resources refers to the desalination of seawater and highly brackish groundwater, the harvesting of rainwater, and usage of marginal-quality water for irrigation (Malash et al. 2008; Qadir et al. 2007). The marginal-quality water is used widely in the agricultural production of arid and semiarid places in the world (Heuer et al. 2005). Driven by the need to produce more under water scarce conditions, larger amounts of saline groundwater are pumped for irrigation in several countries in the Middle East as well as in numerous areas elsewhere (Qadir et al. 2007). For example, India's annual net groundwater draft is 135 km^3, of which 32 km^3 is estimated to consist of saline and/or sodic water, which is about one-fourth of the total volume of groundwater used in the country (Sharma and Minhas 2005). In China, especially North China Plain, as less and less fresh water is available for agriculture with increasing population and rapid economic growth, saline water has been included as an important substitutable resource of fresh water in agricultural irrigation (Wan et al. 2007). They were often divided further into subgroups as brackish water (with salinity of 1.67–5.0 dS m^{-1}), semi-saline water (5.0–8.33 dS m^{-1}), and saline water (8.33–16.67 dS m^{-1}) according to salt concentrations (Zhang et al. 2009). In this region, annual exploitable volume (average from 1991 to 2003) of fresh water, brackish water, and semi-saline water (including saline water) is 11.644, 6.495, and 2.223 km^3, comprising 57.2, 31.9, and 10.9% of total exploitable volume of water resources, respectively (Zhang et al. 2009). However, most of these saline water resources remain unexplored.

Tomato is one of the important and widespread crops in the world. In recent years, the greenhouse tomato industry has grown rapidly and now plays a major role in the fresh tomato industry. For example, between the early 1990s and 2003, North American greenhouse tomato area is estimated to have grown by almost 600% to 1,726 hectares (Cook and Calvin 2005), and the total greenhouse tomato production for 2003 is estimated at 528,078 metric tons, from negligible amounts in the early 1990s. Studies on saline irrigation of tomato have been executed by many researchers in different countries. Ayers (1977) reported that the use of irrigation water with ECs of 1.7, 2.3, 3.4, and 5.0 dS m^{-1} reduce the tomato yield by 0, 10, 25, and 50%, respectively. Cuartero and Fernandez-Munoz (1999) summarized that the yields of tomato reduced when the plants were irrigated with nutrient solution of 2.5 dS m^{-1} electrical conductivity or higher. Unitary increase of salinity above 3.0 dS m^{-1} reduced the yield by about 9–10% (Cuartero and Fernandez-Munoz 1999; Maas 1986). Del Amor et al. (2001) conducted a greenhouse study where tomatoes (cv. Daniela) were drip irrigated with nutrient solutions of four salinity levels (2, 4, 6, and 8 dS m^{-1}) initiated at three different plant growth stages. The results indicated that salt tolerance of tomato plants increased when the application of salinity was delayed, while yield was not significantly reduced when 4 dS m^{-1} saline water was applied 16 days after transplanting. Campos et al. (2006) compared effects of five levels of salinity (1, 2, 3, 4, and 5 dS m^{-1}) of the irrigation water on industrial tomato and concluded that total yield reduced by 11.0% upon each unit increase in the salinity of the irrigation water while fruit quality increased with the increasing salinity. Wan et al. (2007) conducted field experiments in North China Plain and concluded that when applying saline water about 30 days after transplanting, irrigation water salinity ranging 1.1–4.9 dS m^{-1} had little effect on tomato yield. Malash et al. (2005) pointed out that when judging the suitability of brackish water for irrigation, the varying sensitivity of the plants at different growth stages to salinity should be considered. Although the growth stage at which salinization is initiated had been discussed in tomato, to our knowledge, the sensitivity of tomato in specific growth stages to salt stress has not well been characterized. Moreover, few studies have been concentrated on the utilization of highly brackish saline water with electrical conductivity above 5 dS m^{-1} without significant yield reduction. While in water scarce area such as North China Plain, response of greenhouse tomato plant to stage-specific saline water irrigation and the effect of stage-specific multilevel salt stress are still of practical significance in water saving and substitutable use of saline water on tomato production.

Therefore, the objectives of this study are (1) to investigate the effect of stage-specific saline irrigation on yield, fruit quality, and other growth responses of greenhouse tomato; (2) to develop a saline water irrigation strategy for greenhouse tomato in water scarce regions such as North China Plain.

Materials and methods

Plant material and growth conditions

A local tomato cultivar (*L. esculentum* Mill cv. Zhongza No. 9) was used for all experiments. The experiment was conducted at greenhouse (photoperiod of 16 h, relative humidity at 50 ± 10%, thermo period of 30/22°C (day/night) in spring and 33/25°C in summer) of the Institute of Botany, Chinese Academy of Sciences, Beijing (latitude: 39°99′N; longitude: 116°20′E).

Seed germination, transplanting (in nursing media), and topping were conducted on 1 February, 16 March, and 10 May for experiment 1 (or spring experiment), and on 1 April, 10 May, and 31 July for experiment 2 (or summer experiment), respectively. Seeds were surface-sterilized in 55°C distilled water for 15 min and placed on water-soaked filter paper in Petri dish for 2 days in the dark at 25°C. Germinated seeds were then transferred to plastic plugs (5 × 10 holes) in the greenhouse to grow on vermiculite for more than 40 days, to ensure uniform seedling establishment.

Then, the uniformed seedlings were transplanted individually in drainable plastic plant pots (20 cm in diameter and 20 cm in depth). The row spacing was 80 cm with pots spaced at 40 cm apart. The nursing media consists of humus and vermiculite with the same proportion (bulk density of about 1.40 g cm^{-3} and field capacity of about 50%). A 0.5 kg commercial fertilizer (containing 14% N, 12% P_2O_5, and 14% of K_2O) together with 5 kg chicken manure was added to every 1 m^3 nursing media before transplanting. A dosage of 1 g urea was added at each pot before the first cluster fruit expanding stage of the plants. A week after the application of urea, potassium dihydrogen phosphate (KH_2PO_4) of a concentration of 0.2% was sprayed on the leaf of all plants. Plants were vertically supported by nylon cord guides, and regular pruning was conducted during growth such that all auxiliary shoots were removed and only the main stem was left. In order to guarantee fruit yield and quality, plants were topped at the end of the first cluster fruit expanding stage (Table 1), at 96 and 115 days after germination in two experimental batches, respectively.

Treatments

The growth period of tomato for our tests was divided into four continuous growth stages as flowering and fruit-bearing stage (stage 1), the first cluster fruit expanding stage (stage 2), the second cluster fruit expanding stage (stage 3), and harvesting stage (stage 4), as in Table 1. Stage 1 covers from flowering to the fruit on the first truss reached ping-pong ball size. Stage 2, from the end of stage 1 to the first fruit on the second truss reached ping-pong ball size. Stage 3, from the end of stage 2 to the ripening of first fruit (of first truss). Stage 4, from the end of stage 3 till the end of watering (Table 1). NaCl solutions with electrical conductivity (EC) of 3.33, 8.33, and 16.67 dS m^{-1}, respectively, were applied for the salt treatments. In each treatment, saline water was applied at one of 1–4 growth stages of tomato. Thus, the two factors (growth stage and salinity level) constituted 12 saline treatments in total. Irrigation with tap water throughout the whole growing season was used as control treatment (CK). The EC of the tap water used was about 0.54 dS m^{-1}. The soil volumetric moisture content was detected daily by the moisture meter (type HH2; Delta-T Devices Ltd., Cambridge, UK) connected with a soil moisture sensor (ThetaProbe, type ML2x; Delta-T Devices Ltd.). When the soil moisture (m^3 m^{-3}) was under 25%, the irrigation was applied. A preliminary experiment was performed to determine the irrigation volume adequate for all the treatments, and 2 L applied water at a time was found to be the least irrigation volume to hit that target in this study. Therefore, the irrigation volume for each pot was 2 L at a time. The leaching fraction was about 25–50%, which enabled the maintenance of very similar EC in both the root zone and drainage solutions for a given treatment (Li et al. 2001; Magan et al. 2008).

The treatments were organized following a completely randomized distribution and each irrigation regime including four replicates in experiment 1 and six replicates in experiment 2. Irrigation intervals were approximately 6–7 days in all experiments.

Measurements of plant growth parameters

Growth parameters including plant height, stem diameter, and leaf number of each seedling were recorded at the end of stage 1 and stage 2, respectively. Plants were topped at the end of stage 2, so we stopped recording these parameters since stage 3. Total yield and fruit number were recorded when harvest. Average fruit weight was determined simply by dividing the total yield by fruit number. Yield reduction

Table 1 Phenological development of greenhouse tomato in the two batches of experiments

Growth stage	Growth stage[a]	Description	Duration (day–day)[b]	Duration (day–day)
			Experiment 1	Experiment 2
Flowering and fruit-bearing stage	Stage 1	Flowering—first fruit of first truss reached ping-pong ball size	28 March–24 April	18 June–17 July
The first cluster fruit expanding stage	Stage 2	End of stage 1—first fruit of second truss reached ping-pong ball size	24 April–10 May	17 July–31 July
The second cluster fruit expanding stage	Stage 3	End of stage 2—first fruit ripening	10 May–24 May	31 July–13 August
Harvesting stage[c]	Stage 4	End of stage 3—end of watering (or treatment)	24 May–10 June	13 August–28 August

[a] Saline irrigations were applied at four different growth stages of tomato. Treatment symbols are indicated as "Sm-n", in which letter "*S*" represents for **s**aline treatments, while "*m*" and "*n*" represent the growth stage and NaCl concentration, respectively, e.g., S1-2 indicates irrigation at stage 1 with NaCl solution of 3.33 dS m^{-1} (equal to 2 g/L), S2-5 indicates irrigation at stage 2 with NaCl solution of 8.33 dS m^{-1} (equal to 5 g/L), and S3-10 indicates irrigation at stage 3 with NaCl solution of 16.67 dS m^{-1} (equal to 10 g/L). The same hereinafter

[b] Both experiments were conducted in 2007

[c] Harvesting stage includes only the treatment period, but not including the period from the end of watering until ripening of all fruits

was calculated for saline irrigations and expressed in percentage of reduction compared with control. Fruits were picked by hand at 2–4 days interval. Shoot and root of plants were then collected and oven-dried at 70°C for 2 days to constant weight to determine the dry weights. Measurements of all these parameters included four replicates in experiment 1 and six replicates in experiment 2.

Measurements of photosynthesis parameters

Photosynthetic ratio, stomatal conductance, and transpiration rate of plants in experiment 1 were measured with a portable photosynthesis system (LI-6400; LI-COR Inc., Lincoln, NE, USA) on day 6 during stages 2 and 3 (measured during 9:00 a.m. to 11:00 a.m.). The fifth leaves from the top down were used for measurements. Four seedlings were used for measurement in each treatment, and on each seedling, the measurements were repeated for three times ($n = 12$).

Measurements of soluble sugar and titratable acid contents

Soluble sugar of the fruit was determined by anthrone sulfuric acid method (Fales 1951), and titratable acid contents were determined by titration with 0.1 M NaOH (Campos et al. 2006). The measurements were repeated twice.

Statistical analysis

Microsoft Excel and the SPSS 11.0 statistical package were used for the statistical analysis. Differences among treatments were assessed by one-way ANOVA followed by Duncan's multiple range tests ($P = 0.05$). For yield, we analyzed effects of two factors (phenological stage and salinity level) separately when using Duncan test for mean separations according to the method used by Yurtseven et al. (2005). Before doing this, interaction of the two factors on yield was assessed by univariate analysis and they showed no significant interaction on yield. For convenience and clarity, all the other parameters except yield were analyzed for regular Duncan test according to treatments without considering the interaction.

Results

The impact of stage-specific saline irrigations on earlier growth stages of greenhouse tomato

Plant height, stem diameter, and number of leaves

Plant height, stem diameter, and number of leaves were determined at the end of stages 1 and 2 to evaluate the effect of stage-specific saline irrigations on growth parameters of greenhouse tomato (Fig. 1). Plants were topped at the end of stage 2, so we stopped recording these parameters since stage 3. As shown in Fig. 1, these growth parameters were not significantly changed between most of the saline-irrigated groups and the control in experiment 1, while they showed quite remarkable changes in experiment 2. It was probably because the plants grow much more quickly in summer than in spring due to the higher temperature and higher solar radiations, thus amplified the negative effects of salinity on growth. In experiment 2, high salinity (16.67 dS m^{-1}) caused larger decrement on plant height, stem diameter, and leaf number compared with lower NaCl concentrations (3.33 or 8.33 dS m^{-1}), while slight changes were observed between the two lower concentrations (3.33 or 8.33 dS m^{-1}; Fig. 1).

Photosynthesis

As presented in Fig. 2, saline irrigation significantly decreased photosynthetic ratio in most of the treatments. In general, the higher the salinity level, the larger the decrease of photosynthetic ratio of the plant. Salt concentration of 16.67 dS m^{-1} applied, respectively, in the first two stages decreased the photosynthetic ratio with significance, while same concentration of saline irrigation in stage 3 did not significantly reduce photosynthetic ratio. Stomatal conductance and transpiration rate showed similar trends with photosynthetic ratio under most of the saline irrigations (Fig. 2).

These results indicated that stage-specific saline irrigations influenced both growth and photosynthetic parameters of greenhouse tomato during growth. Whether these irrigation regimes also influence harvest parameters of tomato remained unknown. Since the final goal of crop production always concerns yield, the effects of stage-specific saline irrigations on harvest parameters were also determined at harvest.

The impact of stage-specific saline irrigations on harvest quality of greenhouse tomato

Fruit yield

Tomato fruit is the most sensitive organ to the salinity, and it shows significant yield reduction under salinity (25–75 mM NaCl, equal to 2.50–7.33 dS m^{-1}) (Reina-Sanchez et al. 2005). The effect of stage-specific saline irrigations on tomato yield was shown in Table 2. In order to distinguish the mixed effects of phenological stages and salinity levels on yield, we analyzed effects of these factors separately when using Duncan test for mean separations (Table 3). Before doing this, interaction of the two factors on yield was assessed by univariate analysis and they showed no significant interaction on yield. In experiment 1, compared

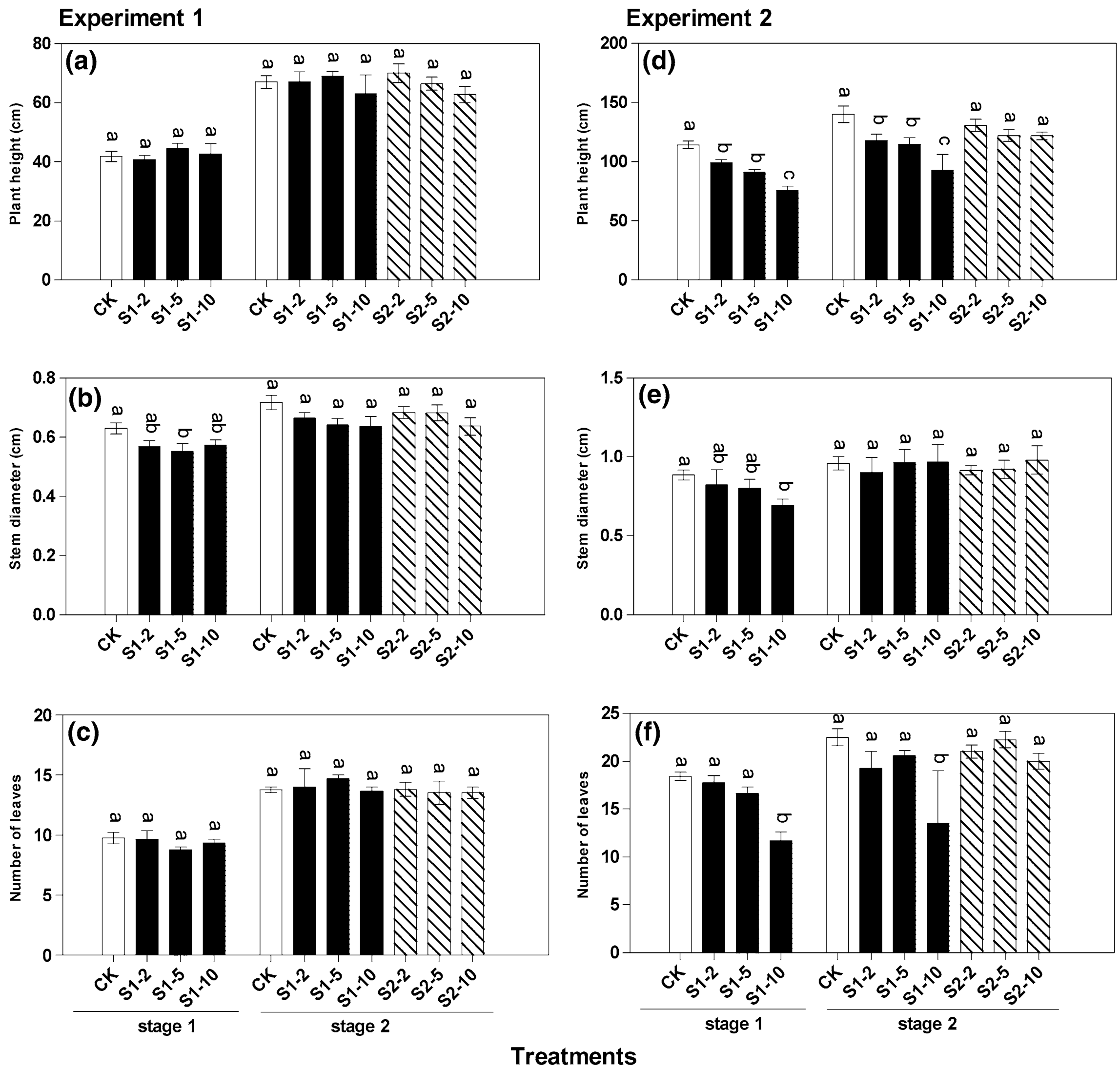

Fig. 1 Plant height (**a**, **d**), stem diameter (**b**, **e**), and number of leaves (**c**, **f**) of greenhouse tomato under stage-specific saline irrigations in experiment 1 and experiment 2. Values were recorded at the end of stage 1 and stage 2. Bars represent means ± SD, and $n = 4$ (experiment 1) or $n = 6$ (experiment 2). *Different letters* indicate significant differences evaluated by Duncan's multiple range test at $P = 0.05$ level. Values in stage 1 and stage 2 were analyzed separately in each figure part

with the control, saline treatments decreased the final yield of tomato from 3 to 42%. However, yield reduction was statistically significant from control only in treatments S1-10 and S2-10, in which 16.67 dS m^{-1} saline water was applied during stage 1 and stage 2, respectively (Table 3). When applied in the same growth stage, 16.67 dS m^{-1} saline irrigation led to more remarkable yield decrement compared with those of 3.33 or 8.33 dS m^{-1}, in all four growth stages. The two lower salinity levels had similar effects on final yield while being applied in all growth stages. What should be noticed was that tomato plants seemed to be more sensitive to salt stress in stage 1 than the other three stages. The greatest yield reduction was obtained in stage 1, which was similar for all three concentrations of saline irrigation. Moreover, yield reduction was more sharp when the salt concentration of irrigation water increased (from 3.33 to 16.67 dS m^{-1}) in stages 1 and 2 than in the latter two stages. These results indicated that compared with the latter three stages under same level of stress, stage 1 not only was more sensitive to salinity but also was susceptive to increment of salinity levels than other stages.

Results of experiment 2 that conducted in summer of 2007 were similar to those of experiment 1, with small differences. Compared with experiment 1, yield reduction was severe under higher salinity (8.33 and 16.67 dS m^{-1}) and less under 3.33 dS m^{-1} salinity in experiment 2 (Tables 2, 3). Vanieperen (1996) reported that higher temperatures, illumination, and the lower relative humidities led to lower water potential in the plant by inducing faster

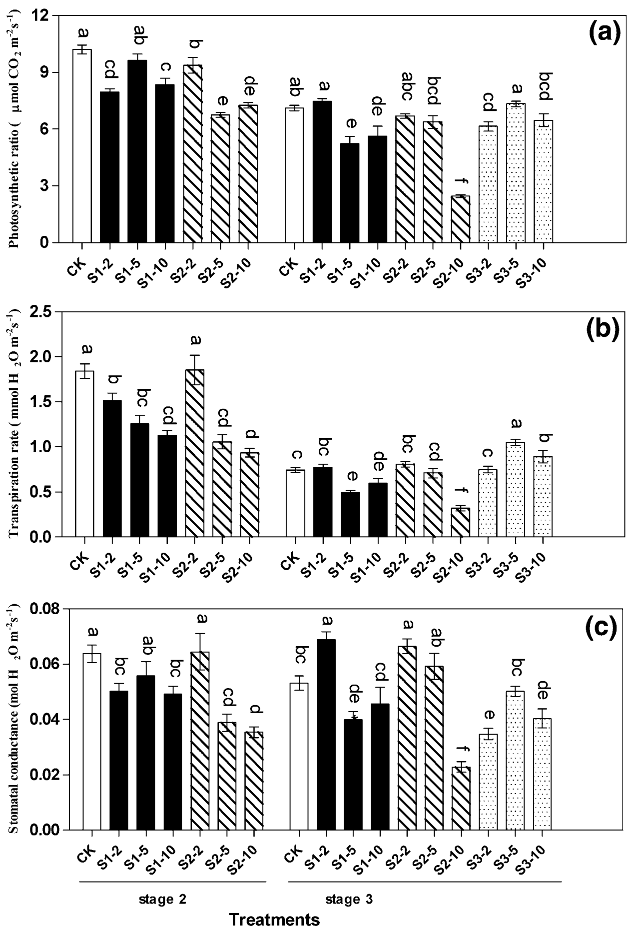

Fig. 2 Effects of stage-specific saline irrigations on photosynthesis of greenhouse tomato in experiment 1. Treatments were applied during stages 1, 2, and 3 of tomato, and photosynthetic ratio, stomatal conductance, and transpiration rate were measured on day 6 during stage 2 and 3. *Bars* represent means ± SD, and $n = 12$. *Different letters* indicate significant differences evaluated by Duncan's multiple range test at $P = 0.05$ level. Values in stage 2 and stage 3 were analyzed separately in each figure part

transpiration under salinity and cause higher yield reductions. Data in Table 2 showed that saline treatments reduced the final yield of tomato into different levels, from 25% increment to 97% reduction, compared with the control. Similar to experiment 1, when irrigated with saline water of the same concentration, the greatest yield loss was obtained in stage 1, which was similar for all three salinity levels (Table 2). When applied in the same growth stage, 16.67 dS m^{-1} saline irrigation led to more remarkable yield decrement compared with those of 3.33 or 8.33 dS m^{-1}, in all four growth stages. Moreover, stage 1 is most sensitive to the increment of salinity level since most significant yield decrement was observed under the application of 8.33 or 16.67 dS m^{-1} saline water in stage 1. Less fruit (4.3 g per plant) was harvested under treatment S1-10. It was not advisable to use saline water with a concentration as high as 16.67 dS m^{-1} in agricultural production even in a manner of short-term application in the earlier three growth stages, though it did not markedly decrease tomato yield in stage 2 and stage 4. Saline irrigation of 3.33 dS m^{-1} applied in the last two growth stages led to increased yield by 25 and 1%, respectively, though it was not statistically significant. These results suggested that when carefully managed, saline irrigation in specific growth stages was able to increase tomato yield. In conclusion, low yield loss or even yield increase can be obtained in stage-specific saline irrigation in the appropriate growth stage of tomato. Consequently, it could provide a method of using marginal water for agricultural production in areas with water shortages.

Average fruit weight and number

Tomato yield can be reduced by the decrease of average fruit weight and/or the number of fruits produced per plant (Cuartero and Fernandez-Munoz 1999). Differences in average fruit number and average fruit weight among treatments were not significant in experiment 1 (Table 2). However, in experiment 2, average fruit weight in stage 1 was significantly decreased under higher salinity treatments (8.33 and 16.67 dS m^{-1}) compared with non-saline control treatment. Moreover, Average fruit weights decreased more when the treatment time was earlier in the higher salinity treatments (8.33 and 16.67 dS m^{-1}), which was similar to the results of experiment 1 under 16.67 dS m^{-1} salinity. Although in experiment 2, compared with control, decreases in average fruit number were more markedly in stage 1 than the other three stages, average fruit number decreased significantly only under 16.67 dS m^{-1} salinity.

Fruit quality

Sugar, acids and their interactions are important to sweetness, sourness, and flavor in tomato fruits (Stevens et al. 1977), as were the quality indexes of tomato. Fruit quality increased under most of the given treatments (Table 2). Titratable acid content of fruits was increased under saline irrigations apart from that of stage 2. It was reported previously that tomato irrigated with saline water of various concentrations throughout the growing season led to higher acid content in fruits, compared with the control that was irrigated with fresh water (Campos et al. 2006; Reina-Sanchez et al. 2005). As can be seen in Table 2, changes of soluble sugar content showed a similar trend with that of titratable acid, although the increase was more markedly in stages 3 and 4 for 8.33 dS m^{-1} saline water. That salinization initiated at different growth stages increases fruit quality by increasing total soluble solids, and sugar content has been recorded by del Amor et al. (2001). These results indicated that fruit quality was improved under most of

Table 2 Effects of stage-specific saline irrigations on harvest quality of greenhouse tomato

Treatment[a]	Yield				Fruit quality	
	Yield (g/plant)	Yield reduction (%)	Average fruit weight (g/plant)	Average fruit number (/plant)	Titratable acid (g/100 g FW)	Soluble sugar (g/100 g FW)
(A) Experiment 1						
CK	221.2	0	28.4	8.8	0.504 de	5.730 efgh
S1-2	159.8	28	21.6	7.8	0.735 abcd	3.370 h
S2-2	188.7	15	20.8	9.0	0.504 de	9.666 cd
S3-2	203.0	8	20.9	10.0	0.812 abc	7.239 def
S4-2	178.9	19	21.1	8.5	0.910 a	7.638 de
S1-5	152.5	31	16.4	9.5	0.588 cde	3.254 h
S2-5	201.9	9	24.0	8.5	0.420 e	4.489 fgh
S3-5	215.0	3	33.1	7.0	0.784 abc	15.09 b
S4-5	158.0	29	20.5	7.8	0.718 abcd	7.963 cde
S1-10	127.7	42	15.8	7.7	0.518 de	18.14 a
S2-10	132.5	40	18.2	7.3	0.413 e	4.039 gh
S3-10	155.5	30	24.6	6.8	0.637 bcde	10.93 c
S4-10	180.2	19	25.7 NS[b]	7.0 NS	0.875 ab	6.618 defg
(B) Experiment 2						
CK	132.4	0	42.7 ab	3.9 abc		
S1-2	119.2	10	38.7 abc	3.3 abc		
S2-2	123.6	7	24.6 bc	5.3 a		
S3-2	165.4	−25	39.3 abc	4.2 ab		
S4-2	133.8	−1	41.4 ab	3.8 abc		
S1-5	39.1	70	16.3 cd	1.8 cd		
S2-5	113.7	14	24.6 bc	4.3 ab		
S3-5	88.6	33	34.4 abc	2.7 bc		
S4-5	120.8	9	50.5 a	2.5 bcd		
S1-10	4.3	97	4.3 d	1.0 d		
S2-10	78.3	41	21.0 bcd	3.7 abc		
S3-10	42.3	68	26.7 bc	1.8 cd		
S4-10	94.6	29	34.0 abc	2.7 bc		

Different letters within the same column indicate significant differences evaluated by Duncan's multiple range test at $P = 0.05$ level

[a] Treatment symbols are indicated as "Sm-n", in which letter "*S*" represents for **s**aline treatments, while "*m*" and "*n*" represent the growth stage and NaCl concentration, respectively, e.g., S1-2 indicates irrigation at stage 1 with NaCl solution of 3.33 dS m^{-1} (equal to 2 g/L), S2-5 indicates irrigation at stage 2 with NaCl solution of 8.33 dS m^{-1} (equal to 5 g/L), and S3-10 indicates irrigation at stage 3 with NaCl solution of 16.67 dS m^{-1} (equal to 10 g/L)

[b] *NS* no statistically significant difference

stage-specific saline irrigation regimes mainly due to higher concentrations of soluble sugar and titratable acid.

Results in Table 2 demonstrated that saline irrigation not only had an advantage of saving fresh water, but also improved fruit quality of tomato plants. However, even given the same treatment, distinct effects were brought to different growth parameters. Thus, it is required to consider not only yield but also fruit quality as well as the objective of production, to determine the appropriate irrigation regime.

Discussion

In many water scarce places in China, including North China Plain, there are plenty of underground saline water resources. Although the usage of these waters would help alleviate the water shortage problems in agriculture in the area, most of them remain unexplored, mainly due to the lack of proper management strategies in using these valuable resources, especially those with high salinity. Here, we investigated the feasibility of three different concentrations

Table 3 Effects of growth stage and salinity level on yield (g/plant) of greenhouse tomato

NaCl (dS m^{-1})	Growth stage												Average	↓
	Stage 1	↓	→	Stage 2	↓	→	Stage 3	↓	→	Stage 4	↓	→		
(A) Experiment 1														
0.54 (CK)	221.2	A		221.2	A		221.2	A		221.2	A		221.2	A
3.33	159.8	AB	a	188.7	AB	a	203.0	A	a	178.9	A	a	184.1	AB
8.33	152.5	AB	a	201.9	AB	a	215.0	A	a	158.0	A	a	181.8	AB
16.67	127.7	B	a	132.5	B	a	155.5	A	a	180.2	A	a	150.7	B
Average	171.1		a	181.3		a	197.8		a	186.7		a		
(B) Experiment 2														
0.54 (CK)	132.4	A		132.4	A		132.4	AB		132.4	A		132.4	A
3.33	119.2	AB	a	123.6	A	a	165.4	A	a	133.8	A	a	137.0	A
8.33	39.1	BC	b	113.7	A	a	88.6	BC	ab	120.8	A	a	90.5	B
16.67	4.3	C	b	78.3	A	ab	42.3	C	ab	94.6	A	a	65.0	B
Average	91.0		a	114.3		a	110.0		a	121.7		a		

↓ shows the vertically Duncan test results, the salinity level effects on the fresh yield; → shows the horizontally Duncan test results, the growth stage effects on the fresh yield. Different letters (within the same column or same row) indicate significant differences evaluated by Duncan's multiple range test at $P = 0.05$ level

of saline water (ranged between 3.33 and 16.67 dS m^{-1}) on tomato production in greenhouse condition in the North China Plain, with saline irrigating the plants in specific growth stages.

Many studies were conducted on saline irrigation of tomato in different countries. It is widely accepted that salinity affects yield, quality, and plant physiology of various plant species including tomato. Satti et al. (1994) found that in tomato, plant height and number of leaves were significantly reduced when irrigated with saline regimes of 50 mM (equal to 4.83 dS m^{-1}) NaCl in contrast with control tomato plants that received only the Hoagland solution. Salinity reduces photosynthesis resulting in reduced plant height and dry weight when irrigated with water containing 35 and 70 mM NaCl (equal to 3.33 and 6.66 dS m^{-1}; Psarras et al. 2008). In our experiment, plant height, stem diameter, and leaf number of plants were also affected by salinity but changes were significant only in experiment 2 under high salinity (16.67 dS m^{-1}; Fig. 1). The same is for photosynthesis parameters, and the higher the salinity level, the larger the decrease of photosynthetic ratio of the plant (Fig. 2).

Tomato yield is quite sensitive to the salinity and unitary increase of salinity above 3.0 dS m^{-1} in the nutrient solution reduced the yield by about 9–10% (Cuartero and Fernandez-Munoz 1999; Maas 1986). This ratio was even higher in other experiments (Ayers 1977; Campos et al. 2006). This means that at least 30% reduction was not avoidable when using saline water with 6.0 dS m^{-1} or higher ECs for irrigation. In most cases in our experiment, when yield reduction was higher than 30% under saline irrigation, it was significant upon statistical analysis compared with control (Tables 2, 3), so we considered 30% reduction as threshold value of acceptable yield loss. Among our experimental period, greatest yield loss of tomato occurred under saline irrigation in the flowering and fruit-bearing stage (stage 1), which indicated that tomato yield was most sensitive to salt stress at this stage. Moreover, yield reduction was most significant in stage 1 compared with the latter growth stages upon the increase of salinity levels. On the contrary, saline irrigation in the latter three growth stages brought relative narrow range of yield loss or even yield increase (e.g., in treatments S3-2 and S4-2). High salinity water (16.67 dS m^{-1}), however, was not a good alternative for fresh water in the earlier three growth stages as it caused yield reduction by at least 30% under all treatments applied in stages 1–3. The only period that could use 16.67 dS m^{-1} saline water for irrigation was stage 4, in which yield reduction was under 30% in the two batches of experiments. Salinity negatively affected yield: the higher the concentration, the lower the yield. However, under irrigation practices using 3.33 dS m^{-1} saline water in all four stages, 8.33 dS m^{-1} saline water in latter three stages, and 16.67 dS m^{-1} saline water in stage 4, yield reduction could be controlled within 30%. Since 8.33 and 16.67 dS m^{-1} are the upper bounds of semi-saline water (5.0–8.33 dS m^{-1}) and saline water (8.33–16.67 dS m^{-1}), and 3.33 dS m^{-1} fall within the scope of brackish water (1.67–5.0 dS m^{-1}; Zhang et al. 2009), it is feasible to use these water resources for tomato production without causing significant yield reduction. Therefore, when carefully managed, saline waters with ECs of 3.33–16.67 dS m^{-1} were capable of irrigating tomato.

It is widely believed that fruits from tomato plants grown under saline conditions posses higher quality (Cuartero and

Fernandez-Munoz 1999). In our experiment, stage-specific saline irrigation also improved fruit quality by increasing titratable acid and soluble sugar content of the fruits. These results demonstrated that stage-specific saline irrigation had an advantage of not only saving fresh water, but also improving fruit quality of tomato plants.

While using saline water for irrigation, it is very important to avoid redundant salt accumulation in the growing medium, which may inhibit the growth and production of the crops. This can be avoided by irrigation with a large leaching fraction and it could be a basic principle for farmers trying to use the saline groundwater. In this study, irrigation volume of 2 L at a time was shown to be adequate to all the treatments in a preliminary experiment. With 2 L applied water, the leaching volume is mainly between 0.5 and 1 L, so the leaching fraction should be 25–50%. In practical application, therefore, leaching fraction of about 25–50% is required to avoid the salt overaccumulation in the growing medium, and this could be rectified by measuring the electroconductivity of the leaching water. From data of our present study, we can roughly estimate 2 L irrigation water at a time as the least irrigation volume adequate for individual plant grown in $20 \times 20\ cm^2$ pot for all the treatments to avoid redundant salt accumulation. To further answer the question how and when the irrigation should be applied as a function of quality, according to the result of He et al. (2006) that the best soil water content (soil moisture) was 35–45% ($m^3\ m^{-3}$) and 25% could be margin of irrigation, we defined in this study the soil moisture 25% ($m^3\ m^{-3}$) as margin of irrigation, i.e., when the irrigation should be applied. And the soil moisture ($m^3\ m^{-3}$) was detected by the moisture sensor. In addition, while considering the developmental stage of tomato, as yield loss was most remarkable in stage 1 under saline irrigation compared with stages 2–4 and fruit quality was increased under saline irrigations apart from stage 2, the irrigation would be better applied in stages 3 and 4.

It was described above that the greenhouse tomato industry now plays a major role in the fresh tomato industry. As in open-field or other kinds of protected land, should local environment affect the growth conditions like temperature within greenhouse, and then our experimental results need to be considered. The greenhouse where our experiments were conducted is the most popular type that represented the greenhouse conditions in the North China Plain, which has a heating equipment (traditional hot water heating systems) and a cooling system (based on wet pads and shade cloth) to control the temperature, so the temperature within the greenhouse will not affected by the local environment. In order to uniformize the growth conditions of each tested plant, pot culture was used in our study. However, it is not necessarily for the local farmers to take pot cultivation as cropping pattern in practical use, they can directly grow the plants in soil. In addition, as topping is a regular step in greenhouse tomato cultivation in the North China Plain to eliminate the apical dominance, then accelerate fruit expanding, and control the overly vegetative growth of the plant, in our experiments, plants were topped at the end of the first cluster fruit expanding stage.

Furthermore, it needs to be mentioned why NaCl, instead of a balance between NaCl and $CaCl_2$, was used for saline treatments in this study. Firstly, as we know, NaCl is the main component of the salts in saline waters including seawater, underground saline water in the North China Plain and many other areas; therefore, the stress that plant suffered from the saline water is mainly from NaCl. Secondly, the salt stress from the mechanism side can usually be recognized as toxic effect of ions and osmotic stress. Compared with the composition effect of a balance like between NaCl and other salts such as $CaCl_2$, toxic effect of NaCl as a monosalt generally leads to much severe damage in crops. Hence, when the research target was due from the harmful effect of saline water irrigation, NaCl can appropriately represent the salt stress treatment. Yet, further work using underground saline water for irrigation may needed in future to provide more detailed practical guidance for farming application.

It can be concluded that stage-specific saline irrigation regimes are important for agricultural production since they make good use of multiple levels of saline water and do not cause significant yield loss. Furthermore, stage-specific saline irrigation regime has another advantage of improving fruit quality of tomato plants. Under these irrigation regimes, saline water could be used as a substitutable resource for fresh water in irrigation of tomato in water scarce areas like North China Plain.

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