

Possibility of High Soluble Solid Content Tomato Production under Water Stress Conditions Controlled by Matric Potential

Shahnaz Sarkar¹, Yoshikazu Kiriwa², Masanobu Endo², Shinichiro Uchino²
and Akira Nukaya^{2*}

¹The United Graduate School of Agricultural Science, Gifu University, Yanagido, Gifu 501-1193, Japan

²Faculty of Agriculture, Shizuoka University, Ohya, Suruga-ku, Shizuoka 422-8529, Japan

The present study was conducted to clarify the possibility of high soluble solid content tomato production in soilless culture with a small volume of substrate under water stress conditions, which was separate from salinity stress and controlled by matric potential for fertigation using a tensiometer. Treatments consisted of 2 set point levels of matric potential (–2 and –4 kPa) for fertigation in Experiment 1-1, 3 application rates (20, 80, and 180 mL/time/plant) in Experiment 1-2, and a combination of 2 set points of matric potential (–2 and –6 kPa) and 2 application rates (40 and 70 mL/time/plant) in Experiment 2. In Experiment 1, tomato plants and fruit production seemed to be affected by higher water stress treatment, but salinity stress was also applied simultaneously, in spite of leaching of salts into medium. In Experiment 2, it assumed that water stress treatment was mostly achieved by keeping the EC of medium solution below 5 dS·m⁻¹. The matric potential in the medium fluctuated –0.5 to 2 kPa at –2 kPa and –1 to –6 kPa at –6 kPa during the day. The proline content of leaves is considered an index of stress degree. It tended to increase with time during the experiment and to be higher at –6 kPa than –2 kPa treatment, although there seemed to be no distinct difference in the EC of medium solution among treatments. Therefore, according to the above proline content, it is suggested that water stress itself can stress the plant to some extent in soilless culture, but it may be difficult to induce sufficient stress intensity, which is comparable to the salinity stress producing high soluble solid content tomatoes, by water stress itself.

Key Words: fertigation rate, matric potential, proline, salinity stress, water stress.

Introduction

In our previous study (Sarkar et al., 2008), an experiment was conducted to clarify the effects of different fertigation systems (drip or sub fertigation) in combination with 2 nutrient solution formulae (Modified Enshi formula or Shizudai tomato formula) at 4 dS·m⁻¹ of electrical conductivity (EC) for the response of high soluble solid content tomato grown in soilless culture. As a result, it was estimated that growth and yield suppression were mainly caused by salinity stress in the sub fertigation system, and mainly caused by water stress in the drip fertigation system. The difference in culture systems, including the fertigation system, affects plant responses in various ways through the application of

water and nutrients. It is important to know the individual characteristics of water stress and salinity stress, as fundamental information, to establish a culture system, for stable and high quality tomato production. In the present study, water stress was chosen to clarify the effect on the possibility of high soluble solid content tomato production.

One of the major problems is separating the stresses. When the fertigation rate is restricted to induce water stress, salinity stress simultaneously occurs, because salts which are not absorbed by plants accumulate in media. Therefore, in order to avoid salt accumulation, leaching was assessed by EC measurement of medium solution in the present experiment.

On the other hand, previous studies on water stress applied different application rates for fertigation (Ray and Sinclair, 1998), changing the watering time (Mitchell and Shennan, 1991; Nuruddin et al., 2003) or PEG treatment (Alian et al., 2000). The biggest problem with the above mentioned experiment was that the water status

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* Corresponding author (E-mail: abanuka@agr.shizuoka.ac.jp).

in the root environment was not expressed as matric potential and was not compared. Few reports have regulated the water status by matric potential in soilless culture (Takei et al., 1999). In the present experiment, the water status of medium was expressed as matric potential and was controlled by a tensiometer with a frequent fertigation strategy. In soilless culture, the matric potential of medium commonly varies between -1 and -10 kPa regardless of the medium (Raviv et al., 2004). However, in most practical cases the matric potential is generally kept around -1 to -2 kPa, if fertigation management is performed properly (Dorais et al., 2005; Endo et al., 2006; Sarkar et al., 2008) and by decreasing the matric potential, plants are exposed to some degree of water shortage, inducing water stress. Therefore, in the present experiment, water stress is defined as the matric potential of medium, which reaches somewhat lower values than the -2 kPa mentioned above.

In addition, salinity stress is expressed as the EC in $\text{dS}\cdot\text{m}^{-1}$ of medium solution in the present experiment. Therefore, it is difficult to compare the intensity of salinity and water stresses, because the unit of stress is different. In order to compare stress intensity, EC in $\text{dS}\cdot\text{m}^{-1}$ should be converted to osmotic potential in kPa. According to the data shown by Nukaya et al. (1977) and Meiri et al. (1971), the equation to convert from EC to osmotic potential (ϕ_{π}) is $\phi_{\pi}=0.04\text{EC}+0.014$ for NaCl. For example, EC at 5 and 10 $\text{dS}\cdot\text{m}^{-1}$ are comparable with about -0.2 and -0.4 kPa of osmotic potential, respectively. The equation slightly varies with the salt included in the solution; however, the difference of osmotic potential obtained from a different equation is relatively small compared with the water stress treatment (-6 kPa) described later in the present experiment. Therefore, increased EC of medium solution may not influence the matric potential of medium.

The use of salinity stress might be more efficient to produce high sugar content tomato fruit rather than water

stress, as stated by Zushi et al. (2005). There should be a different function between salinity stress and water stress. Recently, the increase of proline has been shown in various plant parts when exposed to various stresses (Hare et al., 1999). The proline content should be a parameter to compare the intensity of stress, as reported by Claussen et al. (2006). Therefore, the stress degree was compared with the proline content of leaves in the present experiment.

The present study was conducted to clarify the influence of water stress separate from salinity stress on tomatoes in soilless culture. Therefore, tomatoes were grown under different water stress by controlling the set point of the matric potential for fertigation and the fertigation rate in a lower volume (800 mL/plant) of substrate culture. Moreover, the possibility of high soluble solid content tomato production under water stressed conditions was discussed.

Materials and Methods

Experiment 1

Tomato seedlings (*Solanum lycopersicum* L. 'House Momotaro') were raised in non-woven fabric pots (12 cm diameter) filled with approximately 800 mL of fine coir dust. On September 21, 2006, seedlings at the 4 true leaf stage were placed in troughs (20 cm wide, 4 m long with 3 cm side walls) with a free drainage fertigation system. The trough was covered by gray plastic film, with a spacing of 50 cm between pots and 80 cm between troughs. The treatments shown in Table 1 were initiated on October 11, at the flowering stage of the 1st cluster with 10 true leaves. The experiment was conducted in a heated glasshouse in which minimum (heating) and ventilation air temperatures were 18°C and 23°C , respectively. Plants were grown vertically with a single stem and detopped at the 2nd upper leaf above the 4th truss on October 31, 20 days after treatment (DAT). Flowers during anthesis were vibrated manually every day to ensure pollination. The number of fruits was

Table 1. Effect of set point of matric potential for fertigation and the fertigation rate on the stem length and diameter, fruit fresh weight, total yield and soluble solid content of fruit in Experiment 1.

Experiment	Treatment		Stem length ^x (cm)	Stem diameter ^w (mm)	Fruit weight (g/fruit)		Total yield (g/plant)	Soluble solid content (%)
	MP ^z (kPa)	FR ^y (mL·time ⁻¹)			1st cluster	2nd cluster		
Exp. 1-1	-2	20	138	14	109	91	748	5.8
	-4	20	139	12	92	74	618	6.6
	t-test		NS ^v	**	***	**	**	***
Exp. 1-2	-4	20	139	12	92	74	651	6.6
	-4	80	139	14	123	165	808	5.6
	-4	180	144	14	252	118	1007	5.1
	r		0.09 ^{NS}	0.43*	0.59***	0.46***	0.80***	0.78***

^z Matric potential at which fertigation initiated.

^y Fertigation rate at each time.

^x measured at 20 DAT (October 31) before pinching.

^w measured just below the 4th cluster on 20 DAT (October 31).

^v *, **, and *** mean significantly different at 5, 1, and 0.1% levels, by t-test or correlation analysis respectively and NS means not significant.

adjusted to have 4 fruits per cluster at the appropriate time. Harvesting of the 1st cluster of fruits commenced on November 27 (47 DAT), and cultivation was terminated halfway to the 2nd cluster on December 5 (55 DAT), due to *Fusarium* wilting disease.

Treatments consisted of 2 set point levels of matric potential (-2 and -4 kPa) for fertigation with 20 mL fertigation per time in Experiment 1-1, and 3 application rates (20, 80 and 180 mL/time/plant) at -4 kPa of the set point of the matric potential for fertigation in Experiment 1-2. The matric potential of the coir substrate in pots was measured by tensiometer (Model AG-T-200, Ishiguro Nozai Co. Ltd., Japan) at intervals of 5 seconds, and the average value during 5 minutes was recorded by a data logger (Model 21x, Campbell Co. Ltd., USA) throughout the experiment. In both Experiments 1-1 and 1-2, fertigation was initiated when the matric potential dropped to the designated initial set point for fertigation from 6:00 to 24:00. The nutrient solution was distributed by a drip fertigation system through one emitter per pot at the designated flow rate, from a single reservoir tank for each treatment. One to 1/2 strength of Enshi nutrient solution was applied during the experiment according to the EC value of the medium solution. The drained solution at 180 mL fertigation rate was collected at the bottom end of each trough to measure the volume. A complete randomized block experimental design was adopted with 2 blocks in each treatment, which consisted of 16 plants (8 plants per trough); thus, 64 plants were used in Experiments 1-1 and 1-2.

Stem length and stem diameter were measured at pinching on October 31 (20 DAT). The weight and number of fruits harvested during the ripening stage were recorded. Soluble solid content of fruit juice, squeezed by hand with cheese cloth, was determined with a hand refractometer (Model FR-100, Atago Co. Ltd., Japan). In order to measure the stress level of plants, proline content of the leaf lamina around the 2nd and 3rd truss was measured every 2 weeks from October 12 (1 DAT) to November 24 (44 DAT), as described by Bates et al. (1973). Medium solutions were extracted using a porous cup buried in the pot and sucked up with a syringe almost every week during the experiment. The salt accumulated in medium was leached by a large quantity of nutrient solution during the nights of November 13 (33 DAT) and November 25 (45 DAT).

All data were subjected to ANOVA and Scheffe's Multiple Range Test, as and when necessary.

Experiment 2

Tomato seedlings raised in granule rockwool in 250 mL plastic pots were transplanted into the same non-woven fabric pots as Experiment 1 at the flowering stage with 8 true leaves on November 29, 2006. The tomato plants were placed in the same growing trough as Experiment 1 on December 12, after the 1st truss and leaves below the 2nd truss, leaving 5 leaves, were

removed. Thus, the original 2nd truss was called the 1st truss in the present experiment. Treatments were initiated on December 16. Plant growth was stopped by pinching at the 2nd upper leaf above the 3rd truss on December 23 (7 DAT). Harvesting of the 1st cluster of fruits commenced on February 1, 2007 (47 DAT) and terminated at the 3rd cluster on February 26 (72 DAT).

Treatments consisted of a combination of 2 set points of matric potential (-2 and -6 kPa) for fertigation and 2 application rates (40 and 70 mL/time/plant), as shown in Table 2. The treatments were abbreviated as -2 kPa/40 mL, -2 kPa/70 mL, -6 kPa/40 mL, and -6 kPa/70 mL. In each treatment, fertigation was initiated when the matric potential dropped to the initial set point for fertigation, giving nutrient solution at a designated application rate, 40 or 70 mL/time/plant. The 2/3 strength of Enshi nutrient solution was applied from December 16 (0 DAT) to January 18 (33 DAT), and half strength of nutrient solution was then applied. In order to leach the accumulated salt in the coir medium, a large quantity of nutrient solution was applied on fine days at 34, 49, and 63 DAT.

Stem diameter during the experiment, and stem length and the fresh weight of leaves and stems at the end of the experiment were measured. In addition to the weight and number of fruits harvested during the ripening stage, the incidence of non-marketable fruit was also recorded. Proline concentration of the leaf lamina around the 2nd and 3rd truss was measured almost every week from December 17 (1 DAT) to February 26 (72 DAT). The medium solutions at -2 kPa/40 mL, -2 kPa/70 mL, and -6 kPa/40 mL were also extracted every week from December 25 (9 DAT) to February 26 (72 DAT). Sufficient sample could not be taken at -6 kPa/70 mL due to less available water in the medium.

The other methods, which are not described, followed Experiment 1.

Results

Experiment 1-1

Daily changes of the matric potential of medium on a fine day at 5 DAT are shown in Figure 1 (A). The matric potential fluctuated from approximately -2 kPa to -1 kPa at -2 kPa treatment and -4 kPa to -3 kPa at -4 kPa treatment during the day. Average values during the fertigation period (6:00 to 24:00) were -1.6 kPa and -3.1 kPa at -2 kPa and -4 kPa treatments, respectively. There was no drainage from pots after fertigation in both treatments. A similar tendency of the matric potential was observed during the experiment even on cloudy and rainy days (data not shown). There was a difference in fertigation time per day due to weather. For example, the times were 45, 25, and 8 times per day on fine, cloudy and rainy days, respectively; however, there was no difference in fertigation times per day due to the set points.

Stem diameter was greater at -2 kPa than -4 kPa

treatment, although stem length was not significantly different (Table 1). Total yield and fresh weight per fruit were higher, but soluble solid content of fruit was lower at -2 kPa than -4 kPa treatment (Table 1).

The leaf proline content was higher at -4 kPa than

-2 kPa treatments during the experiment, especially after 29 DAT, as shown in Figure 2A. The EC of medium solution at -4 kPa treatment also became higher than that at -2 kPa treatment until 29 DAT; however, it decreased after 36 DAT by leaching at 33 DAT, as shown in Figure 2B.

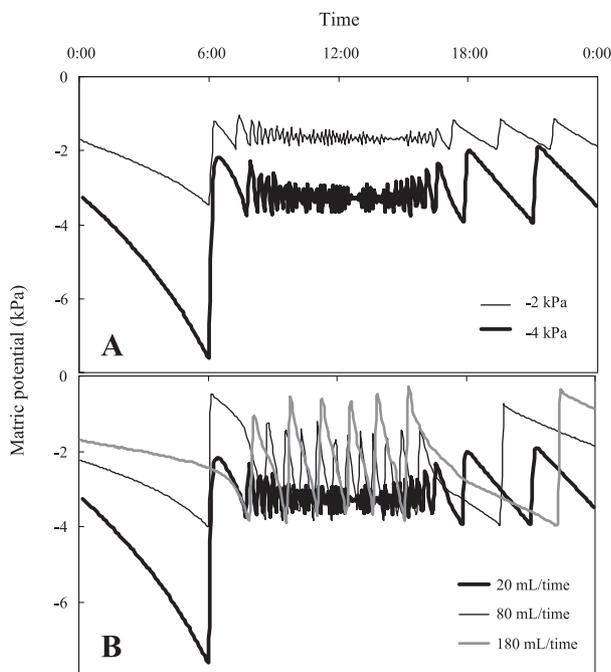


Fig. 1. Daily changes of the matric potential of medium as affected by (A) set point of matric potential for fertigation and (B) the fertigation rate on a fine day (5 DAT, October 16) in Experiment 1.

Experiment 1-2

Daily changes of the matric potential of medium on a fine day at 5 DAT are shown in Figure 1B. The matric potential fluctuated approximately from -4 kPa to -3 kPa, -4 kPa to -1.5 kPa, and -4 kPa and -0.5 kPa during the day at 20, 80, and 180 mL fertigation treatments, respectively. Average values during the fertigation period (6:00 to 24:00) were -3.1 , -2.4 , and -2.4 kPa at 20, 80, and 180 mL fertigation treatments, respectively. The duration of the matric potential of the medium above -1.0 kPa was 165 minutes a day at 180 mL treatment, although 0 and 110 minutes a day at 20 and 80 mL treatments, respectively, on a fine day at 5 DAT. Drainage from the pot after fertigation was observed only at 180 mL treatment and the mean leaching fraction was about 20% during the experiment. A similar tendency of the matric potential was observed during the experiment even on cloudy and rainy days (data not shown). There was a difference in fertigation times per day due to fertigation amount. For example, they were 45, 13, and 7 times at 20, 80, and 180 mL treatment, respectively, at 5 DAT. The mean fertigation times were 49, 11, and 8 times during the experiment at 20, 80, and 180 mL treatment, respectively, although the times were influenced by the weather.

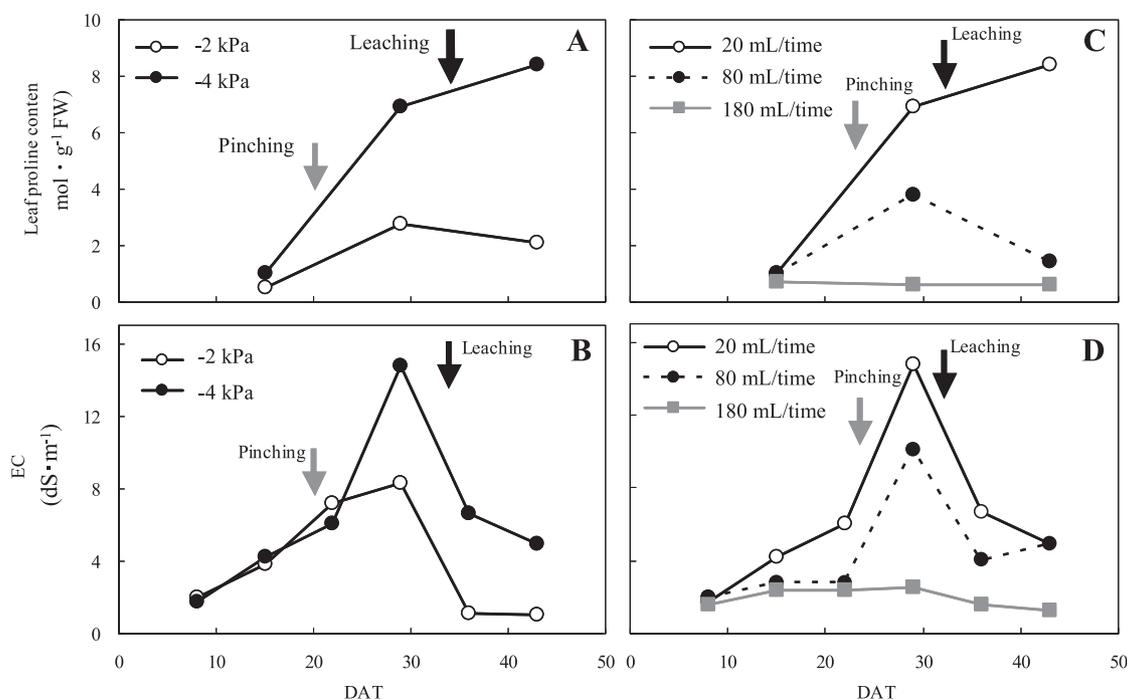


Fig. 2. Changes of (A and C) the leaf proline content and (B and D) EC of the medium solution in Experiment 1. Gray and black arrows indicate date of pinching and leaching, respectively.

Stem length was not significantly different among treatments. Stem diameter, total yield and fresh weight per fruit were increased, and the soluble solid content of fruit became lower with increasing fertigation amount per time (Table 1).

Leaf proline contents at 20 and 80 mL treatments became higher at 29 DAT, compared with 180 mL treatment (Fig. 2C). The EC of medium solution at 20 and 80 mL treatments also increased until 29 DAT, compared with 180 mL treatment, as shown in Figure 2D. Leaf proline content at 80 mL treatment and the EC at 20 and 80 mL treatments at 36 DAT decreased by leaching at 33 DAT. The proline content and the EC at 180 mL treatment remained stable at low values during the experiment, as shown in Figure 2C, D.

Experiment 2

Daily changes in the matric potential of medium on a fine day at 28 DAT and on a rainy day at 10 DAT are shown in Figure 3. The matric potential fluctuated from approximately -2 kPa to -1 kPa at -2 kPa/40 mL, -2 kPa to -0.5 kPa at -2 kPa/70 mL, -6 kPa to -3 kPa at -6 kPa/40 mL, and -6 kPa to -1 kPa at -6 kPa/70 mL during the day. These fluctuations showed almost the same tendency regardless of the weather. The average values during the fertigation period (6:00 to 24:00) were -1.5, -1.3, -4.5, and -3.3 kPa on a fine day (28 DAT) and -1.4, -1.3, -4.1, and -3.0 kPa on a rainy day (10 DAT), at -2 kPa/40 mL, -2 kPa/70 mL, -6 kPa/40 mL, and -6 kPa/70 mL, respectively. The number of fertigation times was markedly affected by weather conditions. For example, it was about 20 to 25 times a day with -40 mL treatment on a fine day (28 DAT), and 6 times at -40 mL treatment on a cloudy day (10 DAT). The frequency of fertigation was about 4 times more on fine days than rainy days.

There was no significant interaction of shoot and fruit fresh weight, total yield and soluble solid content of the fruit among treatments (Table 2). Shoot and fruit fresh weight and total yield were significantly lower at -6 kPa than -2 kPa treatments. The occurrence of blossom end

rot of fruits was somewhat higher at -6 kPa treatment, although it was only 5.4% even at -6 kPa/40 mL (data not shown). On the other hand, soluble solid content was higher at -6 kPa fertigation treatment (6.0%) than -2 kPa fertigation treatment (5.5%). There was no significant effect of the fertigation rate on shoot and fruit fresh weights, and total yield.

Leaf proline contents markedly increased at 30 DAT in the order of -6 kPa/70 mL ≥ -6 kPa/40 mL ≥ -2 kPa/40 mL ≥ -2 kPa/70 mL, as shown in Figure 4A. However, they decreased to the lowest level after leaching at 34 DAT and then increased at 44 DAT. The contents tended to be higher at -6 kPa than -2 kPa treatments during the experiment. The proline content at -2 kPa/70 mL remained relatively lower during the

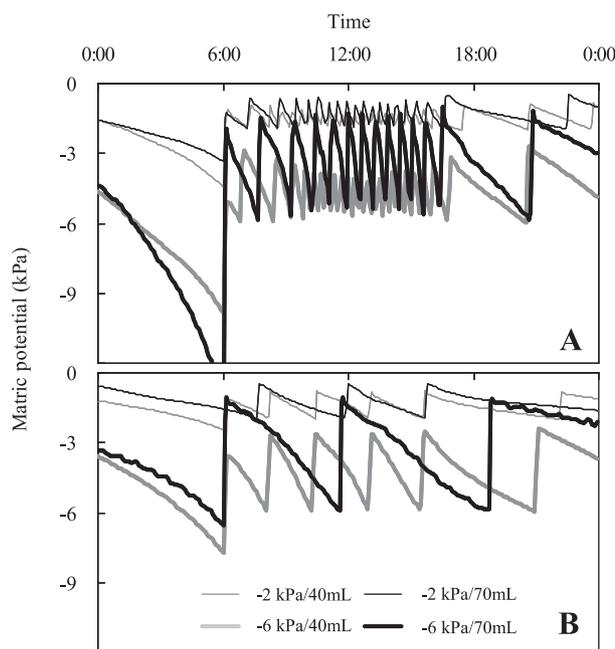


Fig. 3. Daily changes of the matric potential of media as affected by a combination of set point of matric potential for fertigation and the fertigation rate on a fine day (28 DAT, January 13, A) and a rainy day (10 DAT, December 26, B) in Experiment 2.

Table 2. Effect of a combination of set point of matric potential for fertigation and the fertigation rate on the shoot fresh weight, fruit fresh weight, total yield, soluble solid content of fruit in Experiment 2.

Treatment		Shoot fresh weight (g/plant)	Fruit fresh weight (g/fruit)	Total yield (g/plant)	Soluble solid content (%)
MP ^z (kPa)	FR ^y (ml·time ⁻¹)				
-2	40	728	155	1839	5.6
-2	70	765	155	1880	5.5
-6	40	627	136	1561	6.1
-6	70	617	153	1719	5.9
MP		***x	*	**	***
AF		NS	NS	NS	*
Interaction		NS	NS	NS	NS

^z Matric potential at which fertigation initiated.

^y Fertigation rate at each time.

^x NS means not significant and *, **, and *** mean significant by t-test at 5, 1, and 0.1% levels, respectively.

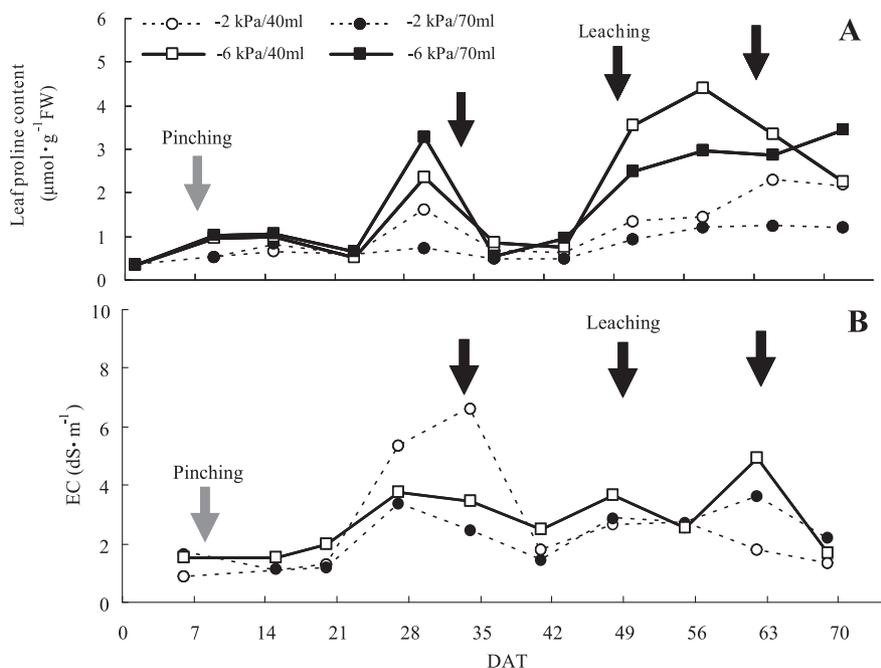


Fig. 4. Effect of a combination of set point of matric potential for fertigation and the fertigation rate on changes of (A) the leaf proline content and (B) EC of medium solution in Experiment 2. Gray and black arrows indicate date of pinching and leaching, respectively. Medium solution was not extracted due to low water content at -6 kPa/70 ml treatment.

overall experiment period. There might be little effect of the fertigation rate on the proline content.

The EC of medium solution was relatively low (0.8 to 1.5 $\text{dS}\cdot\text{m}^{-1}$) until 20 DAT. It then fluctuated between 1.5 and 3.5 $\text{dS}\cdot\text{m}^{-1}$ at -2 kPa/40 mL, -2 kPa/70 mL and -6 kPa/40 mL, except for -2 kPa/40 mL at 27 and 34 DAT and -6 kPa/40 mL at 62 DAT. There was no distinct difference in the EC among treatments, as shown in Figure 4B.

Discussion

In the present study, tomatoes were grown under different water stress, without less or no salinity stress by controlling the set point of the matric potential for fertigation and the fertigation rate, in order to clarify the possibility of producing high soluble solid content tomatoes by water stress.

However, it was relatively difficult to give only water stress separate from salinity stress in a substrate culture, because excess salts accumulated easily in media, as shown in Figure 2, when grown without any drainage from medium. In Experiment 1, tomato plants and fruit production seemed to be affected by higher water stress at -4 kPa compared with -2 kPa of fertigation treatment, and at 20 and 80 mL compared with 180 mL fertigation rate treatment, as shown in Table 1; however, salinity stress was also given, as shown in Figure 2.

Therefore, the treatments of Experiment 2 were a combination of 2 set points of matric potential (-2 and -6 kPa) for fertigation and 2 application rates (40 and 70 mL/time/plant). The set point of -6 kPa was decided to investigate the effect of a much lower set point of

matric potential on growth and productivity, compared with -4 kPa in Experiment 1. The set point of -6 kPa should be the minimum matric potential, when controlled by a tensiometer, in a growing system using less (800 mL) substrate volume with drip fertigation, because uniform water distribution in a pot was not achieved in our preliminary experiment when applied with a lower fertigation rate, such as 40 or 70 mL/time/plant (unpublished data). With regard to the application rate, 20 and 70 $\text{mL}\cdot\text{time}^{-1}$ were applied to induce water stress, because 80 $\text{mL}\cdot\text{time}^{-1}$ treatment showed the possibility of inducing water stress in Experiment 1-2. Salt accumulation (salinity stress) in medium was avoided in Experiment 2 because fertigation was administered at a lower concentration compared with Experiment 1, and leaching was performed at 34, 49, and 63 DAT on the basis of periodical EC measurement of medium solution. As a result, during Experiment 2, the EC value was mostly kept below 5 $\text{dS}\cdot\text{m}^{-1}$. Enough medium solution to measure the EC was not extracted at -6 kPa/70 mL, but the degree of salt accumulation was estimated to be almost the same level as in the other 3 treatments, judging from analysis of a small quantity of medium solution for nitrate nitrogen and other mineral concentrations (data not shown).

In the present experiment, fruit yield decreased and the soluble solid content of fruit increased at -6 kPa than -2 kPa fertigation treatments; however, it might be very difficult to conclude which stress, salinity or water, affected the above results. Dorais et al. (2001) reported that yield thresholds for undesirable yield reduction of tomatoes ranged between 2.1 to 5.1 $\text{dS}\cdot\text{m}^{-1}$ according to

various reports and conditions in relation to tomato fruit quality and productivity. If the tomatoes used in this experiment have relatively higher thresholds around $5 \text{ dS}\cdot\text{m}^{-1}$ for production, the results might be caused by water stress, not by salinity stress; however, if the thresholds are relatively low, the result might be caused by salinity stress.

Recently, an increase of proline has been shown in various plant parts when exposed to various stresses (Hare et al., 1999). For instance, the proline concentration was 10-fold and 18-fold in shoots and roots, respectively, when plants were subjected to a nutrient solution containing 100 mM NaCl (Storey and Wyn Jones, 1975). Therefore, proline should be a reliable indicator of the environmental stress imposed on plants, as reported by Claussen et al. (2006). In Experiment 1, the EC of medium solution and leaf proline content showed almost the same changing pattern during the experiment; therefore, the effect of different stresses could not be clarified. However, in Experiment 2, the leaf proline content at -6 kPa treatment (higher water stress) tended to become higher than -2 kPa (lower water stress) after 44 DAT, although there seemed to be no distinct difference in the EC of medium solution among treatments. Therefore, judging from the changing pattern of the proline content and the EC, it might be concluded that the reduction of yield and increased soluble solid content of fruit at -6 kPa treatment were induced by water stress, not salinity stress. With regards to solar radiation, it was $9.3 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and $65.4 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{week}^{-1}$ from 0 to 41 DAT, although it increased to $12.8 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and $89.3 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{week}^{-1}$. Therefore, the main reason for the increasing proline content at -6 kPa after 44 DAT might be the lower matric potential of medium and plants during the day, which was induced by higher transpiration, as a result of higher solar radiation, as stated above. It was often observed that the matric potential of medium did not reach a high level under strong solar conditions, especially on a fine day in February compared with a cloudy or rainy day.

In our previous report (Sarkar et al., 2008), when tomatoes were grown in a drip fertigation system between -2 and -1 kPa of matric potential of medium, 67 g of fruit with 10.0% soluble solid content was produced and the leaf proline content was about $10 \mu\text{mol}\cdot\text{g}^{-1}$ FW. On the other hand, in the present Experiment 2, when tomatoes were grown at higher water stress (-6 kPa set point for the fertigation) than previously, larger (155 g per fruit) fruit with lower soluble solid content (5.5%) were produced and the leaf proline content was lower by 1 to $2 \mu\text{mol}\cdot\text{g}^{-1}$ FW. The major difference was higher EC (about 16 to $21 \text{ dS}\cdot\text{m}^{-1}$) of medium solution in the previous experiment compared with the present experiment. Therefore, it is concluded that water stress itself can stress a plant to some extent, but it is difficult to induce equal stress intensity as salinity stress to produce high

soluble solid content tomatoes by water stress itself.

Similar results, in which yield and fruit size were reduced and soluble solid content of fruit was increased by water stress or water application restriction, have been reported by other researchers (Alian et al., 2000; Mitchell and Shennan, 1991; Nuruddin et al., 2003). However, there is no report in which water stress was separated from salinity stress, and water stress is expressed clearly as the matric potential. Zushi et al. (2005) concluded that the use of salinity stress was more efficient to produce high quality tomato fruit than water stress, based on the proline and other amino acid contents of tomato fruit; however, they did not discuss the intensity of the stress and they determined the proline content of fruit only.

The fertigation strategy in the present experiment could evaluate the response of tomato plants to water stress of medium and presents useful knowledge on the behavior of water stress in soilless culture. In order to clarify more clearly the relationship among yield reduction, strength of salinity and water stresses, further investigation is necessary to observe a wider range of physiological response, such as the content of ABA in plants, stomata conductance, transpiration rate, and so on without applying any salinity stress in medium.

Literature Cited

- Alian, A., A. Altman and B. Heuer. 2000. Genotypic difference in salinity and water stress tolerance of fresh market tomato cultivars. *Plant Sci.* 152: 59–68.
- Bates, L. S., R. P. Waldren and I. D. Teare. 1973. Rapid determination of free proline for water-stress studies. *Plant Soil* 39: 205–207.
- Claussen, W., B. Bruckner, A. Krumbein and F. Lenz. 2006. Long-term response of tomato plants to changing nutrient concentration in the root environment—the role of proline as an indicator of sensory fruit quality. *Plant Sci.* 171: 323–331.
- Dorais, M., A. P. Papadopoulos and A. Gosselin. 2001. Influence of electric conductivity management on greenhouse tomato yield and fruit quality. *Agronomie* 21: 367–383.
- Dorais, M., J. Caron, G. Begin, A. Gosselin, L. Gaudreau and C. Menard. 2005. Equipment performance for determining water needs of tomato plants grown in sawdust based substrates and rockwool. *Acta Hort.* 691: 293–304.
- Endo, M., Y. S. Kim, Y. Kiriiwa and A. Nukaya. 2006. Effects of different fertigation management controlled by matric potential in the morning and afternoon on growth and yield of strawberry ‘Akihime’ in soilless culture. *J. Japan. Soc. Hort. Sci.* 75 (Suppl. 2): 239 (In Japanese).
- Hare, P. K., W. Cress and J. van Staden. 1999. Proline synthesis and degradation: a model system for elucidating stress-related signal transduction. *J. Exp. Bot.* 50: 413–434.
- Meiri, A., J. Kamburoff and A. Poljakoff-Mayber. 1971. Response of bean plants to sodium chloride and sodium sulphate salinization. *Ann. Bot.* 35: 834–847.
- Mitchell, J. P. and C. Shennan. 1991. Tomato fruit yields and quality under water deficit and salinity. *J. Amer. Soc. Hort. Sci.* 116: 215–221.
- Nukaya, A., M. Masui and A. Ishida. 1977. Salt tolerance of green soybeans. *J. Japan. Soc. Hort. Sci.* 46: 18–25.
- Nuruddin, M. M., C. A. Madramootoo and G. T. Dodds. 2003.

- Effects of water stress at different growth stages on greenhouse tomato yield and quality. *HortScience* 38: 1389–1393.
- Raviv, M., R. Wallach and T. J. Blom. 2004. The effect of physical properties of soilless media on plant performance—a review. *Acta Hort.* 644: 251–259.
- Ray, J. D. and T. R. Sinclair. 1998. The effect of pot size on growth and transportation of maize and soybean during water deficit stress. *J. Exp. Bot.* 49: 1381–1386.
- Sarkar, S., Y. Kiriwa, M. Endo, T. Kobayashi and A. Nukaya. 2008. Effect of fertigation management and the composition of nutrient solution on the yield and quality of high soluble solid content tomatoes. *J. Japan. Soc. Hort. Sci.* 77: 143–149.
- Storey, R. and R. G. Wyn Jones. 1975. Betaine and chlorine levels in plants and their relationships to NaCl stress. *Plant Sci.* 7: 161–168.
- Takei, A., A. Nukaya and N. Ui. 1999. Growth and quality of tomatoes grown in coir media using water potential as indicator of moisture level. *J. Japan. Soc. Hort. Sci.* 68 (Suppl. 2): 318 (In Japanese).
- Zushi, K., N. Matsuzoe, S. Yoshida and J. Chikushi. 2005. Comparison of chemical composition contents of tomato fruit grown under water and salinity stresses. *J. SHITA* 17: 128–136 (In Japanese with English abstract).