Production of High Soluble Solids Fruits Without Reducing Dry Matter Production in Tomato Plants Grown in Salinized Nutrient Solution Controlled by Electrical Conductivity

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We investigated dry matter production and fruit characteristics of high-Brix tomatoes when plants were pinched above the third truss and electrical conductivity of the nutrient solution was gradually increased by changing the amounts of nutrients and NaCl. In the salinized treatment, fruit fresh weight was significantly decreased, and fruit Brix was significantly increased, relative to the non-salinized treatment. There were no significant differences in leaf area index, light use efficiency, light intercepted by leaves, total dry matter production, fruit dry weight, or dry matter distribution to fruit between treatments, but dry matter content of fruits was significantly increased in the salinized treatment. Therefore, dry matter production by plants was not reduced by the salinized treatment. The increase in fruit Brix was associated mainly with the increase in the dry matter content of fruits. Without reducing dry matter production, high-brix tomatoes can be produced by controlling the nutrient solution.

Key Words: fresh and dry weight, high-Brix tomato, intercepted light by plants, light use efficiency, yield.

Introduction

In Japan, tomato fruits with a soluble solids content, measured as degrees Brix or percentage Brix, higher than ca. 6–7 Brix% are produced commercially because Japanese consumers favor sweetness in tomato fruits. Although salinization improves fruit quality, such as Brix and dry matter (DM) content, it often reduces individual fruit weight and yield in both soil and soilless culture (Dorais et al., 2001; Ehret and Ho, 1986; Schwarz and Kuchenbuch, 1997). Salinization may also induce physiological disorders, such as blossom end rot, that decrease yield (Dorais et al., 2001). In the production of high-Brix tomatoes in Japan, salinization techniques are often applied by manipulating the electrical conductivity (EC) of the nutrient solution (Johkan et al., 2014). The salinity of the nutrient solution is gradually increased by adding nutrients or sodium chloride (NaCl) or both.

In high-Brix tomato production, growers must have the skill and techniques to control the nutrient solution, Brix, and yield. Maintaining high Brix and avoiding physiological disorders are very important; however, growers also aim for yield improvement. Although investigating DM production is important to improve high Brix tomato cultivation, in salinized tomatoes it has only been reported by De Pascale et al. (2015). They reported that salinity reduced the leaf area index (LAI), intercepted light and light use efficiency (LUE). These components determine DM production (Higashide, 2018; Higashide and Heuvelink, 2009). In their report, tomatoes were planted in soil in an open field, and ECs were maintained throughout the experiments. Daily EC values were not reported. To date, LUE or light interception in greenhouse and soilless culture tomatoes have not been reported. In addition, in high-Brix tomato production in Japan, the EC of the nutrient solution is controlled and gradually increased (Johkan et al., 2014). To improve the productivity of high-Brix tomatoes, we must clarify how daily changes in EC affect DM production in greenhouse soilless culture.
In this study, to improve yield while maintaining high Brix, we compared DM production between salinized and non-salinized conditions in soilless culture. EC in the nutrient solution was gradually increased by changing the amounts of nutrients and NaCl, which were monitored daily. Yield components and growth characteristics were investigated according to the hierarchy of yield components reported by Higashide and Heuvelink (2009).

Materials and Methods

Plants, environmental conditions, and salinized treatments

We investigated the influence of a salinized nutrient solution on DM production and fruit Brix. Experiments were conducted three times in a commercial greenhouse in Miyagi Prefecture, Japan (Table 1). Seeds of the tomato (*Solanum lycopersicum* L.) cultivar ‘Momotaro York’ (Takii & Co., Ltd., Kyoto, Japan) were sown in seed trays filled with nursery soil and germinated in the dark at 30°C. Two days later, the trays were placed in a seedling growth chamber (Nae Terrace; Mitsubishi Chemical Agri Dream Co., Ltd., Tokyo Japan), where they were illuminated with fluorescent lamps using a 16-h day length and exposed to air temperatures of 23°C (daytime) and 17°C (nighttime) and 1000 μmol·mol⁻¹ CO₂. Seedlings were fertilized every day using commercial nutrient solution (HighTempo; Sumitomo Chemical Co., Ltd., Tokyo, Japan) consisting of 10.7 mM NO₃⁻, 6.3 mM K⁺, 5.4 mM Ca²⁺, 1.9 mM Mg²⁺, 2.4 mM H₂PO₄⁻, 3.8 mg·L⁻¹ Fe, 0.38 mg·L⁻¹ Mn, 0.26 mg·L⁻¹ B, 0.15 mg·L⁻¹ Zn, 0.05 mg·L⁻¹ Cu, and 0.07 mg·L⁻¹ Mo, and adjusted to an EC of 1.8 dS·m⁻¹. After three weeks, the seedlings were transplanted into 9-cm-diameter plastic pots (2 per pot) filled with commercial soil (Ikubyou Baido; Takii). The pots were then placed in the greenhouse for one to two weeks.

Seedlings were then transplanted into 10 double rows of coconut fiber slabs (Cocobag; Toyotane Co., Ltd., Toyohashi, Japan) in the greenhouse compartment (1730 m²), with a total of 30 double rows. Each row was 28 m long, with spacing of 1.6 m between rows and 25 cm between pots. A total of 224 seedlings were transplanted per double row, and plant density was 5.0 m⁻².

All plants were pinched at two leaves above the third truss before the fourth truss flower opened. Pinching was conducted on 22 October 2014 (50 days after transplanting; DAT), 25 November 2014 (41 DAT), and 27 January 2015 (57 DAT) in Experiments 1, 2, and 3, respectively. Old leaves were not pruned. Flowers were pollinated by bumble bees (*Bombus ignitus* Smith). The number of fruits per truss was not adjusted by pruning. Initiation of ventilation and heating was set at 28 and 13°C, respectively. CO₂ levels were set at 800 μmol·mol⁻¹ when the roof window was closed and 400 μmol·mol⁻¹ when it was opened. Air temperature, CO₂ concentration, and inside solar radiation were measured at 1-min intervals by an automatic monitoring device (Shisetsu-engei SaaS; Fujitsu Limited, Kawasaki, Japan). Transplanting date and environmental conditions are shown in Table 1.

Two levels of nutrient solution EC were applied: non-salinized and salinized. The plants in both treatments were supplied with a mixture of TF Noushuku Tomato S (241.9 mM NO₃⁻, 616.9 mM K⁺, 71.8 mM Mg²⁺, 140.0 mM H₂PO₄⁻, 500 mg·L⁻¹ Fe, 200 mg·L⁻¹ Mn, 200 mg·L⁻¹ B, 18 mg·L⁻¹ Zn, 6 mg·L⁻¹ Cu, and 6 mg·L⁻¹ Mo) in 20% solution; Toyotane) and TF Mix B (Toyotane, 387.1 mM NO₃⁻, 52.9 mM K⁺, 420.5 mM Ca²⁺, and 157.1 mM Mg²⁺ in 30% solution). A 20% solution of TF Noushuku Tomato S and 30% solution of TF Mix B were diluted with water from 1000 to 4000 times to adjust the nutrient solution EC. For the salinized treatment, we added Namishio (> 95% NaCl; Naruto Salt Mfg. Co., Ltd, Naruto, Japan) to the nutrient solution. In each experiment, 10 rows were used: five rows were given the non-salinized nutrient solution and the other five rows were given the salinized nutrient solution.

Target values of nutrient solution EC at transplanting, first truss flowering, second truss flowering, and third truss flowering were 0.6, 1.0, 1.5, and 2.0 dS·m⁻¹, respectively, in the non-salinized treatment and 0.6, 1.5, 2.5, and 3.5 dS·m⁻¹ in the salinized treatment. In the salinized treatment, to increase drainage EC to >10 dS·m⁻¹ when initial fruits were harvested, nutrient solution EC was continuously increased to about 7 dS·m⁻¹ (Fig. 1). EC was measured with an EC meter (D-50; Horiba Ltd., Kyoto, Japan) at 13:00 each day. The rate of nutrient solution supply was based on the

### Table 1. Transplanting date, growing days, average 24-h air temperature, cumulative photosynthetically active radiation (PAR) and average daytime CO₂ concentration.

| Experiment | Transplanting | Growing days | Average 24-h air temperature (°C) | Cumulative PAR* (MJ·m⁻²·d⁻¹) | Average daytime CO₂† (mol·mol⁻¹) |
|------------|---------------|--------------|-----------------------------------|------------------------------|----------------------------------|
| 1          | 2 Sep. 2014   | 134          | 19.5                              | 457.4                        | 527                              |
| 2          | 15 Oct. 2014  | 135          | 17.6                              | 349.1                        | 652                              |
| 3          | 1 Dec. 2014   | 137          | 17.5                              | 339.4                        | 692                              |

*PAR was measured inside the greenhouse.
†Daytime was 08:00–16:00.
The daily drainage percentage was maintained at 15% to 30% of the total quantity of nutrient solution supplied. The drainage solution was not reused in any experiments.

**Sampling and measurements**

In each experiment, plants in the 1st, 5th, 6th, and 10th rows and plants in three slabs placed at both ends of the rows were considered guard plants and were thus excluded from the measurements. We harvested all mature fruits from the three spots (8 to 12 plants per spot) three times a week. Fresh weight (FW) of total fruit was measured together in each spot. In each spot, the FWs of marketable fruits, unmarketable fruits (including those with blossom end rot), and immature fruits were measured separately. We also measured fruit Brix by a refractometer (PAL-1; Atago Co., Ltd., Tokyo, Japan) in 77, 76, and 55 fruits in experiments 1, 2, and 3, respectively, in the non-salinized treatment and 84, 74, and 57 fruits in the salinized treatment.

We measured leaf (leaf blade + petiole) area with an LI-3100C leaf-area meter (Li-Cor Inc, Lincoln, NE, USA) and the FW and dry weight (DW) of leaves, stems, and fruits of five to 12 plants destructively sampled at transplanting, pinching, and the end of the experiment. At the end, the destructively sampled fruits included both mature and immature fruits. Changes in fruit DM content (g·g⁻¹) from pinching to the end of the experiment were calculated by linear interpolation based on the destructively samples; days after transplanting was used on the horizontal axis. DW of harvested fruits except for the threes sampling was calculated by multiplying the FW of total fruits by the DM content on each harvest day. Total fruit DW was calculated from the three spots. Total aboveground DM production (TDM) of each plant was obtained as the sum of leaf, stem, and fruit DWs. At the end of the experiment, TDM was obtained as the sum of the DWs of each plant at destructive measurement plus total fruit DW in each experiment.

The light extinction coefficient was obtained on 20 May 2015 as described by Higashide et al. (2012). Cumulative interception of photosynthetically active radiation (PAR) by each plant was obtained as described by Higashide et al. (2012, 2015) on the three dates of destructive sampling. The PAR fraction was assumed to be 50% of global radiation (Ohtani, 1997). Light use efficiency (LUE) was calculated as the slope of the linear regression of TDM as a function of cumulative intercepted PAR.

We used R v. 3.5.0 software for statistical analysis (R Core Team, 2018). Data were tested for normal distribution by the Kolmogorov–Smirnov test and for heterogeneity of variance by the Bartlett test. The confidence interval was set to at least 95%. When the tests were significant, data were analyzed with two-way ANOVA followed by the Tukey–Kramer test; when they were not significant, data were analyzed with the Kruskal–Wallis test followed by the Steel–Dwass test. For LUE, the significance of differences between treatments was assessed by 95% confidence intervals.

**Results**

Figure 1 illustrates the daily EC values in the supply and drainage solutions. In general, both the supply and drainage ECs gradually increased in both treatments, and they were higher in the salinized treatment in all experiments. In the salinized treatment, the average EC values of the supply and drainage solutions were 4.09 and 5.66 dS·m⁻¹ in Experiment 1, 5.01 and 6.99 dS·m⁻¹ in Experiment 2, and 4.84 and 7.75 dS·m⁻¹ in Experiment 3. In the non-salinized treatment, the respective average EC values were 1.49 and 1.18 dS·m⁻¹, 2.05 and 1.74 dS·m⁻¹, and 1.89 and 1.28 dS·m⁻¹.

Fruit Brix was significantly higher in the salinized treatment than in the non-salinized treatment in all trusses in all experiments (Table 2). Except in one case, fruit Brix was significantly higher in the third truss than in the first truss. The average fruit Brix values in Experiments 1, 2, and 3 were 4.8, 5.1, and 4.8 Brix% in the

![Figure 1](https://example.com/figure1.png)
Table 2. Effect of salinized treatment on fruit Brix and fruit fresh weight (FW).

| Treatment | Truss | Fruit Brix (Brix%) | Fruit fresh weight (g/fruit) |
|-----------|-------|--------------------|-----------------------------|
|           | 1     | 2                  | 3                           | 1         | 2         | 3         |
|           |       | Experiment        | Experiment                  |           |           |           |
|           |       | In the salinized treatment. There was no significant difference in the marketable yield ratio between treatments (data not shown).

TDM was significantly correlated with cumulative intercepted PAR in both treatments in all experiments (Fig. 2). LUE values (represented as slopes in Fig. 2) in Experiments 1, 2, and 3 were 2.07, 3.17, and 3.27 in the non-salinized treatment and 2.13, 3.27, and 3.51 in the salinized treatment. There was no significant difference in LUE between treatments at a 95% confidence interval.

Table 4 presents the correlation among yield components, growth characteristics, fruit Brix and average supply of EC. Average supply of EC was significantly correlated with fruit Brix, fruit FW and fruit DM content. Fruit Brix and fruit FW were significantly correlated with fruit DM content. However, the EC, fruit Brix and fresh weight were not correlated significantly with the yield components or growth characteristics such as TDM, DM distribution to fruits, LAI, intercepted PAR, and LUE. Figure 3 illustrates the effects of the salinized treatment on yield components and fruit characteristics.

non-salinized treatment and 5.7, 6.4, and 7.5 Brix% in the salinized treatment.

Except for the first truss, FWs of fruits in the same truss were significantly lower in the salinized treatment in all experiments. Total fruit number did not differ significantly between treatments (data not shown).

In all experiments, at pinching there were no significant differences in FWs or the DWs of the leaves, stems, or fruits, TDM, DM contents of leaves, stems, or fruits, DM distribution to fruits, or LAI between the salinized and non-salinized treatments (data not shown). At the end of the experiments, FWs of stems and fruits were significantly lower in the salinized treatment and DM contents of stems and fruits were significantly higher in the salinized treatment, but there were no significant differences between treatments in leaf FW, DWs of leaves, stems, or fruits, TDM, DM distribution to fruit, or LAI (Table 3). Although some fruit in the salinized treatment suffered from blossom-end rot, there was no significant difference in the marketable FW, DWs of leaves, stems, or fruits, TDM, DM contents of leaves, stems, or fruits, TDM, DM distribution to fruits, or LAI between the salinized and non-salinized treatments (data not shown).

In LUE between treatments at a 95% confidence interval.

Table 4 presents the correlation among yield components, growth characteristics, fruit Brix and average supply of EC. Average supply of EC was significantly correlated with fruit Brix, fruit FW and fruit DM content. Fruit Brix and fruit FW were significantly correlated with fruit DM content. However, the EC, fruit Brix and fresh weight were not correlated significantly with the yield components or growth characteristics such as TDM, DM distribution to fruits, LAI, intercepted PAR, and LUE. Figure 3 illustrates the effects of the salinized treatment on yield components and fruit characteristics.

non-salinized and non-salinized treatments (data not shown).
**Table 4.** Correlation coefficient ($r$) between yield components, growth characteristics, fruit Brix and average supply of EC to tomatoes grown in the salinized or non-salinized treatment in three experiments.

| Component                  | Fruit Brix | Fruit fresh weight | Fruit dry matter content | Fruit dry weight | Total dry matter | Distribution to fruit | Leaf area index | Intercepted $\text{PAR}$ | Light use efficiency |
|----------------------------|------------|--------------------|--------------------------|------------------|------------------|-----------------------|-----------------|--------------------------|----------------------|
| Electrical conductivity$^x$ | 0.89       | -0.84              | 0.96                     | 0.43             | 0.29             | 0.54                  | -0.25            | -0.29                    | 0.03                 |
| Significance$^y$            | *          | *                  | **                       | NS               | NS               | NS                    | NS              | NS                       | NS                   |
| Fruit Brix                 | -0.80      | 0.841              | 0.32                     | 0.39             | 0.3              | -0.39                 | -0.45            | 0.45                     | NS                   |
| Significance$^y$            | NS         | *                  | **                       | NS               | NS               | NS                    | NS              | NS                       | NS                   |
| Fruit fresh weight         | -0.92      | 0.12               | 0.03                     | -0.17            | -0.19            | -0.07                 | 0.08             | NS                       | NS                   |
| Significance$^y$            | **         | NS                 | NS                       | NS               | NS               | NS                    | NS              | NS                       | NS                   |

$^x$ Average supply EC.  
$^y$ NS, not significant; *, ** and *** significant correlation at $P < 0.05$, 0.01, and 0.001 levels by Pearson’s product-moment correlation ($n = 6$).

Fig. 2. Total aboveground dry matter production as a function of cumulative $\text{PAR}$ intercepted by tomato plants grown in the salinized or non-salinized treatment. Light use efficiency values (95% confidence intervals) were 2.07 (1.99–2.15) non-salinized and 2.13 (2.02–2.26) salinized in Experiment 1 (A); 3.17 (3.02–3.32) non-salinized and 3.27 (3.09–3.44) salinized in Experiment 2 (B); and 3.27 (3.02–3.53) non-salinized and 3.51 (3.30–3.72) salinized in Experiment 3 (C). Regression lines with the same letter are not significantly different according to 95% confidence intervals ($n = 16–22$). ***Significant correlation at $P < 0.001$.

Fig. 3. Effect of salinity treatment on the hierarchy of yield components, and growth and fruit characteristics. NS, not significant; *** significant difference at $P < 0.001$ between non-salinized nutrient solution and salinized nutrient solution by two-way ANOVA (roman type), $n = 3–8$; Kruskal–Wallis test (italics), $n = 55–84$; or 95% confidence intervals (boldface), $n = 16–22$. Black arrow; affected, white arrow; not affected.

**Discussion**

We analyzed the effects of salinization based on the hierarchy of yield components, and growth and fruit characteristics (Fig. 3; Higashide, 2018; Higashide and Heuvelink, 2009).

Fruit Brix and fruit DM content were both significantly increased in the salinized treatment (Tables 2 and 3). Additionally, fruit Brix was significantly correlated with fruit DM content (Table 4). Accordingly, the increase in fruit Brix was mainly determined by the increase in fruit DM content. Fruit FW was significantly decreased in the salinized treatment (Tables 2 and 3). Fruit FW is determined by fruit DW and fruit DM content; there was no significant difference in fruit DW between treatments, whereas fruit DM content was significantly increased in the salinized treatment (Table 3). Additionally, fruit FW was significantly correlated with DM content, but not with fruit DW (Table 4). Therefore, the decreases in fruit FW resulted mainly from the increased fruit DM content.

We found no significant differences in fruit DW, TDM, DM distribution to fruit, LUE, light intercepted by plants, or LAI between treatments (Table 3; Fig. 2). Average EC was not correlated significantly with these components either (Table 4). LUE is determined by the photosynthetic rate in each leaf and by the light extinction coefficient. We did not measure the photosynthetic
rate or light extinction coefficient in each experiment, but the absence of significant differences in LUE or intercepted light suggest that they were similar between the treatments. From these results, although the salinized treatment affected fruit DM content, it did not influence LAI, LUE, or DM distribution to fruit (Fig. 3). Therefore, our salinized treatment, which we controlled based on the ECs of the supply and drainage solutions, did not reduce DM production.

Although most studies of tomatoes under salinized conditions reported yield or FW reduction, responses in DW differed (Dorais et al., 2001). In some cases, the DWs of plant and fruit were reduced (De Pascale et al., 2015; Maggio et al., 2007; Romero-Aranda et al., 2001), but in other cases they were not (Ehret and Ho, 1986; Li and Stanghellini, 2001; Li et al., 2001; Schwarz and Kuchenbuch, 1997). In the former cases, leaf area, maximum leaf area, and LUE were also reduced (De Pascale et al., 2015; Maggio et al., 2007; Romero-Aranda et al., 2001), indicating a reduction in DM production due to salinity. In contrast, in the latter, although they did not report LAI or LUE, high EC did not reduce the leaf area significantly (Table 2 of this study; Li and Stanghellini, 2001; Schwarz and Kuchenbuch, 1997). The lack of a reduction in DW and leaf area in these latter studies suggest that DM production may not be affected by salinity.

A threshold EC for yield reduction in tomatoes has been reported (Dorais et al., 2001; Heuvelink et al., 2003; Maas and Hoffman, 1977). Our and previous results indicate that there may be at least two threshold EC levels that induce yield reduction. At the first threshold EC, the limitation of water uptake begins, and at the second (much higher) threshold, the reduction of DM production begins. Heuvelink et al. (2003) showed in a simulation that the decline per unit rise in EC was higher when salinity affected a specific leaf area (i.e., at a relatively low leaf area) than when it affected DM content or stomatal closure. Accordingly, if the EC of the nutrient solution can be maintained between the first and second thresholds, it should allow for an increase in fruit Brix with the smallest yield reduction. Li and Stanghellini (2001) reported the threshold EC at which leaf area reduction began to be 6.5 dS·m⁻¹. We increased EC gradually; drainage EC from transplanting to pinching at the third truss was 0.95–1.62 dS·m⁻¹ in the salinized treatment (Fig. 1), much lower than the threshold of 6.5 dS·m⁻¹, so nearly all leaves could be expanded before the drainage EC reached the threshold.

De Pascale et al. (2015) reported the linear reduction of LUE at ECs from about 2 to 8 dS·m⁻¹. In our study, although average drainage ECs from pinching to the end of the experiment were higher in the salinized treatment (8.25–12.22 dS·m⁻¹) than in the non-salinized treatment (1.57–2.13 dS·m⁻¹), there was no significant difference in LUE between the treatments. The reason for this difference is unclear, but the gradual increase in EC and/or pinching above the third truss may mitigate LUE reduction due to salinity.

Based on our findings, we conclude that high-Brix tomatoes can be produced under salinized conditions by controlling the EC of the supply and drainage solutions. In the salinized condition, although fresh fruit yield decreased, the DM production and dry fruit yield did not decrease.

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