Yield and Quality of Tomato (Solanum lycopersicum L.) Cultured in Bittern-Supplemented Hydroponic Solution

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Increasing the electric conductivity (EC) of the nutrient solution for growing hydroponic tomatoes (Solanum lycopersicum L.) is an effective way to increase fruit sugar content. The potential of bittern and coarse salt (NaCl) to cause high-EC stress, thereby improving fruit yield and quality in tomato plants under single- or double-truss cultivation were compared. Bittern is a by-product of the salt manufacturing process; it is easy to use and inexpensive. In particular, bittern is more convenient than common salt for high-EC treatment, because it is distributed as a solution, whereas common salt must be dissolved to very high concentration. The experiments reported herein were conducted during two growing seasons: spring and autumn. High-EC stress treatments (bittern or coarse salt) started when the largest fruit on the first truss was 4 cm in diameter. Fruit yield and Brix sugar content in the bittern treatment were similar or higher than in the salt treatment under both cultivation schemes. The EC of the bittern-added nutrient solution increased faster than that of the solution with added coarse salt. This trend was probably caused by the different ion compositions of bittern and coarse salt. There were no differences in tomato growth among treatments. Thus, bittern is a practical and effective additive for hydroponic single-truss tomato cultivation.

キーワード: electric conductivity (EC), hydroponics, osmotic stress, salinity, seawater

1. Introduction

Increasing sugar content in tomato (Solanum lycopersicum L.) fruit meets consumer demand; thus, currently marketed tomatoes generally have high sugar content. Usually, the osmotic stress caused by increasing electrolyte concentration in the nutrient solution is effective for attaining the desired sugar content. Techniques developed to increase sugar content in hydroponic tomatoes include using highly concentrated nutrient solutions (Hohjo et al., 1996; Masuda et al., 1989), adding salt (NaCl) to the nutrient solution (Ohta et al., 1991; Oka et al., 2004; Tsunoda and Hayashi, 1988), or adding seawater to
the nutrient solution (Hosokawa et al., 2005; Mizrahi et al., 1988). Methods for increasing osmotic stress have been developed to gain maximum benefits from this approach without increasing labor and/or cost. The simplest approach is to increase the concentration of the nutrient solution by changing the set value of the hydroponic controller, if the fertilizer cost is acceptable. Although salt addition is less costly than using a dense nutrient solution, the amount of salt required might exceed the operational range of the hydroponic controller. Seawater addition is available only in coastal areas where producers can obtain and transport the water themselves, as seawater is not distributed in the market, except for some special products such as deep-sea water (Kawai et al., 2002; Kitano et al., 2008).

Bittern is an untapped by-product of saltworks that can be directly added to nutrient solutions. This dense liquid contains abundant magnesium, potassium, and calcium, along uncollected sodium. Therefore, bittern treatment might be a more practical alternative to induce osmotic stress in tomato than salt addition. However, the effect of each ion within this dense nutrient solution on plant growth and fruit quality has not been reported so far.

Recently, some producers started using low-truss cultivation to induce high sugar content in tomatoes. In this type of cultivation, only 1–3 trusses per plant are allowed. Additionally, high planting density and cultivation of multiple crops per year allow high yields without extra labor (Oishi et al., 1996; Okano et al., 2002; Sakamoto et al., 1997). Osmotic stress has been proved effective in tomato varieties such as Momotaro and First Power, which are highly sensitive to changes in electrolyte concentration under this type of cultivation. These changes are evaluated by measuring electrical conductivity (EC) (Sato et al., 2004). Low-truss cultivation is expected to have great benefits, such as simple management, because it can solve the conflict between increasing sugar content in expanding fruits in lower trusses and suppressing the growth of young fruits or the occurrence of blossom end rot in upper trusses. Therefore, we examined the effects of adding bittern to the nutrient solution of hydroponically grown low-truss tomatoes. Specifically, we focused on changes in the EC of the nutrient solution, crop yield, and fruit quality of plants grown on a nutrient solution with or without coarse salt and bittern addition.

2. Materials and Methods

Tomato growth is temperature-dependent. Under high temperature conditions, the second truss initiates flowering within one week after the first truss. Absorption of the nutrient solution also occurs rapidly. Conversely, under low temperature conditions, flowering of the second truss often takes more than two weeks after flowering of the first truss. Therefore, it is unlikely that changing the concentration of the nutrient solution will allow attaining the same yield and fruit quality in the second truss as in the first one. On the other hand, similar yield and quality might be obtained for the second truss and first truss under high temperature conditions. Therefore, we compared the effect of bittern treatment on the yield and quality of tomato fruits in experiments carried out during two cropping cycles with contrasting temperature regimes, namely, spring and autumn.

Experiment 1: Spring cultivation

Experiment 1 was carried out in 2010, using the tomato variety Momotaro (TAKII Seed Co., Japan), in a greenhouse at the Field Science Center, Ibaraki University, Ami, Inashiki, Ibaraki, Japan (latitude 36°03'N, longitude 140°21'E). Seeds were sown in 72-cell plastic trays containing the commercial seeding substrate Sakata super-mix (Sakata Seed Co., Japan), on March 31. Seedlings grown to the three-leaf stage in these trays were transplanted to 54 L Deep Flow Technique (DFT) hydroponic tanks (inner dimension: w502 × d350 × h284 mm), which were transferred to the greenhouse on April 20. Stringing was used for plant tutoring.

This experiment included three treatments, each applied to groups of four seedlings: control treatment (NT, no addition), coarse salt (CS, NaCl dissolved in water), and bittern (BI). Bittern and coarse salt were provided by Nihonkaisui Co. Ltd. (Japan), and their compositions are shown in Table 1. The high-
EC stress treatments, which consisted of adding BI or CS (5 dS•m⁻¹ EC) to the normal nutrient solution, started when the first fruit on the first truss reached 4 cm in diameter. NT was used as a negative control. High-EC stress treatments based on the addition of either BI or CS to the nutrient solution started on June 18, and harvest was carried out from July 5 to July 26.

In all treatments, 1 unit (U) of commercial nutrient solution (Otsuka A formula, Otsuka Agri Techno, Japan, current name: OAT-A formula, OAT Agrio, Japan) was used as the base solution. This concentration was doubled to 0.5 U on May 21 (Fig. 1A) based on observations of plant growth. Each hydroponic tank containing four plants was considered as an experimental unit.

When the water level of the nutrient solution had decreased to 25 L, the whole volume was replaced with fresh solution. Coarse salt was dissolved in water to obtain a 20% salt stock solution. All tanks were aerated at 0.8 L•min⁻¹ with an air pump. Fruiting promoter 4-Chlorophenoxyacetic acid (4-CPA) was sprayed once, when a few flowers opened in a truss. All lateral buds were removed once a week and the main stem was pinched above the second truss (i.e., plants were double-trussed); three leaves remained above the second truss. The number of fruits was restricted to five by thinning. Fruits were harvested when 80% of the fruit surface area had turned red. Fruit number and fruit weight were recorded. Small fruits (less than 30 g), blossom end rot, puffy fruit, and cat-facing fruits were classified as unmarketable. Typically, three marketable fruits per plot were used for quality analysis. Fruits were squeezed with a garlic press before analysis. Brix sugar content was measured

### Table 1 Composition of tested bittern and coarse salt

| Composition     | Content (%) |
|-----------------|-------------|
| MgSO₄           | 0.1         |
| CaCl₂           | 4.2         |
| MgCl₂           | 11.2        |
| KCl             | 5.4         |
| NaCl            | 8.4         |

![](image.png)

**Fig. 1** Changes in EC of nutrient solution under high-EC treatments (Experiment 1: spring cultivation, 2010)

A: Concentration of nutrient solution changed to 0.5 U
B: Start of high-EC treatment
C–F: Change of nutrient solution
NT, no treatment (control); CS, coarse salt; BI, bittern

Vertical bars indicate standard error (n = 3)
with a refractometer (IN-1E, Iuchi, Japan). Glutamic acid content was measured with a reflectance photometer (RQflex 2, Merck KGaA, Germany) using a test kit (Agrocheck glutamic acid test, Kanto Kagaku, Japan), according to the manufacturer’s instructions. Daily changes in the EC of nutrient solutions were determined using a conductance meter (CM–14P, TOA, Japan).

Pesticides and fungicides were sprayed as needed to prevent late blight (Phytophthora infestans) in July and whiteflies (Trialeurodes vaporariorum) toward the end of the harvest season.

The experiment was laid in a randomized block design with three replications. Tukey’s multiple range test was conducted after Analysis of variance (ANOVA) using Ekuseru-Toukei 2015 (Social Survey Research Information, Japan).

Experiment 2: Autumn cultivation

Experiment 2 was carried out in the same facility as Experiment 1. Seeds were sown on July 31 and transplanted on August 11, 2009. The starting concentration of the basic nutrient solution was set at 0.5 U of Otsuka A formula. This concentration was doubled to 1 U on September 19 (Fig. 2A), and later halved to 0.5 U on October 12 (Fig. 2B), based on observations of plant growth. The main stem of each plant was pinched just above the first truss (i.e., plants were single-trussed). Minimum ambient air temperature in the greenhouse was kept at 8°C using an oil heater. Pesticides and fungicides were sprayed several times from November until the end of cultivation to prevent late blight and white flies. Experimental design and conditions were as in Experiment 1. The high-EC stress treatment started on October 19, and harvest was carried out from December 17, 2009 to January 7, 2010.

3. Results

Experiment 1: Spring cultivation

EC of nutrient solutions

Changes in nutrient solutions and on their ECs are shown in Fig. 1. There was no difference in the ECs of nutrient solutions before treatment initiation. After treatments began (Fig. 1B), the EC of NT remained constant at about 1.3 dS•m⁻¹. In contrast,
Experiment 2. Autumn cultivation

EC of nutrient solution

Changes in nutrient solutions and on their ECs are shown in Fig. 2. There was no difference in EC among plants before starting the treatment. After treatment began, the EC of NT remained constant at 1.5–2.0 dS•m⁻¹, approximately. In contrast, the EC of CS and BI ranged from 6 to 8 dS•m⁻¹ and from 6 to 11 dS•m⁻¹, respectively. The increase of EC in BI tended to be more rapid than in CS (Fig. 2C–F), as in the spring growing season. However, EC increased more slowly and the nutrient solution was changed less frequently than during spring cultivation, presumably due to lower water absorption rates at the prevailing lower temperatures than at high temperatures.

Yield and quality

Fruit yield and quality resulting from each treatment are shown in Table 2. The number of marketable fruits obtained in BI or CS tended to decrease compared to that in NT due to flower or fruit abscission on the second truss caused by the occurrence of blossom end rot or other growth suppression. These factors explain the reduced yield upon initiation of high-EC stress by BI or CS at an earlier fruit growth stage than that of fruits on the first truss. Control fruits were significantly heavier than BI or CS fruits (ANOVA, *p* < 0.05). Most unmarketable fruits were small. Average fruit weight was significantly higher in NT than in BI, while CS was intermediate. In contrast, Brix was highest in BI, followed by CS and by NT; differences in Brix were all significant among treatments. Glutamic acid content was highest in CS and lowest in NT; again, differences among treatments were significant.

| Treatment | No. of fruits obtained (/plant) | Yield (g/plant) | Fruit weight (g) | Brix (%) |
|-----------|-------------------------------|----------------|-----------------|---------|
|           | marketable | unmarketable | marketable | unmarketable | marketable | unmarketable | marketable | unmarketable |
| NT | 3.6 a | 1 | 888 a | 220 | 246.7 a | 6.0 b |
| BI | 3.8 a | 0.4 | 877 a | 70 | 230.8 a | 7.5 a |
| CS | 3.8 a | 0 | 726 a | 0 | 191.1 a | 7.3 a |

NT, no treatment (control); CS, coarse salt; BI, bittern. Different lower-case letters within a column indicate significant differences (*p* < 0.05) between treatments according to Tukey’s multiple range test.

The EC of CS and BI ranged from 5 to 10 and from 6 to 14 dS•m⁻¹, respectively. The increase of EC in BI tended to be more rapid than in CS (Fig. 1B–F).

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| Treatment | No. of fruits obtained (/plant) | Yield (g/plant) | Fruit weight (g) | Brix (%) |
|-----------|-------------------------------|----------------|-----------------|---------|
|           | marketable | unmarketable | marketable | unmarketable | marketable | unmarketable | marketable | unmarketable |
| NT | 8.0 a | 0.3 | 1300 a | 36 | 162.5 a | 6.0 c |
| BI | 6.6 ab | 0.3 | 809 b | 10 | 122.6 b | 7.2 a |
| CS | 6.3 b | 0.3 | 840 b | 57 | 133.3 ab | 6.3 b |

NT, no treatment (control); CS, coarse salt; BI, bittern. Different lower-case letters within a column indicate significant differences (*p* < 0.05) between treatments according to Tukey’s multiple range test.
large differences among replications. The harvest period lasted three weeks for the single-truss plants in this growing season; thus, the effects of high-EC treatments may vary among late fruits. This might result in a wide range of fruit-size. Brix sugar content was significantly higher in BI and CS than in NT.

4. Discussion

The ratios of bittern and coarse salt to basic nutrient solution (OAT No. 1, 15% w/v) were approximately 2:3 and 1:2, respectively. It is difficult to prepare concentrated solutions of coarse salt due to the low solubility of salt. On the other hand, bittern is commonly provided as a liquid. This is an advantage over coarse salt, if problems associated with its transporting are solved, because bittern can be used for treatment by simple dilution on the commercial product. The balance of calcium, magnesium, sodium, and potassium in a nutrient solution influences the growth of tomato plants (Carvajala et al., 1999). Furthermore, Kitano et al. (2008) added deep-sea water to hydroponics tomatoes and the sodium content of the fruits increased rapidly. However, increases in potassium and magnesium contents were relatively slow and calcium content was lower than in the nutrient solution without deep-sea water addition. This result suggested that sodium ions are selectively absorbed from the cations present in deep-sea water. Therefore, other slightly absorbable cations might be more effective in increasing osmotic stress than sodium. Bittern involves divalent ions, such as calcium (Ca$^{2+}$) and magnesium (Mg$^{2+}$), and the osmotic pressure of a solution is determined by molar concentration of the solutes present in it. When the nutrient solution EC was set at 5 dS•m$^{-1}$, regardless of coarse salt or bittern addition, the molar concentration of bittern should be lower than that of coarse salt. This means that the degree of osmotic stress associated with bittern would be lower than that of coarse salt, at the same final EC of the nutrient solution. If Brix larger than 8% is required for marketed tomatoes, a high EC or some other method will be needed to attain the desired fruit quality. Initially, lower stress is likely to result in higher water uptake. In this experiment, the volume of each hydroponic tank was limited to 54 L, and additional solution was not supplied until the water volume was reduced to 25 L. Therefore, the solution might have become concentrated rapidly at the beginning of cultivation, and its enrichment with divalent ions may suppress further water uptake. However, the rate of water decrease was not different among the three treatments. Thus, bittern’s mode of action must be clarified through further studies.

Double-truss cultivation might be inconvenient to use for production of high-sugar tomatoes, because high-EC stress treatment has to start at the flowering of the first truss, and a 7-day difference in growth between the first and second truss seems to cause not only flower or fruit abscission due to blossom end rot on the second truss but also uneven fruit quality between first and second truss tomatoes (Watanabe, 2006). Growth rate was higher in spring than in autumn cultivation, while the time lag of flowering between first and second truss was shorter in spring than in autumn cultivation. However, EC increases rapidly after initiation of high-EC treatment because of larger water absorbance under higher temperature than autumn cultivation (Fig. 1). Therefore, the osmotic stress affects flowers and fruits on the second truss from earlier stage of fruits development. As the result of differed osmotic stress condition, flower or fruit abscission and blossom end rot occur on the second truss in spring cultivation, additionally to uneven fruit quality. Thus, double-truss cultivation loose the advantage in comparing with single-truss cultivation. In conclusion, bittern addition is practical, having similar effects to coarse salt addition in single-truss tomato cultivation, although both additives seem to have different modes of action.

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要旨
トマト養液栽培において養液の電気伝導度（EC）を上昇させることにより、果実糖度の上昇を効率的に行うことができる。海水由来の苦汁と粗塩（NaCl）がEC上昇や果実収量ならびにトマトの品質改善に及ぼす効果を一段と増幅に二段栽培で比較した。苦汁は製塩過程で生じる副産物であり利用が簡単で安価に入手することができる。特に苦汁は液体で流通されるため、溶解作業が必要な塩による高EC処理より便利である。春まき夏どり栽培と夏まき秋どり栽培が1回ずつ行われた。第1花房の最も大きい果実が直径4cmに肥大したときに高EC処理（苦汁または粗塩）を開始した。2回の実験とも、苦汁処理の収量ならびに品質は粗塩処理と同等であった。養液の苦汁の添加後、養液のECは粗塩処理よりも速やかに上昇した。この原因は不明であるが、両者のイオン組成の違いに起因する可能性が考えられた。トマトの生育に対して特に差異は見受けられなかった。以上のことからトマト低段栽培における高糖度化を目的とした苦汁の添加は、実用的、効果的に利用しうると考えられた。

キーワード
塩濃度、海水、浸透圧ストレス、水耕、電気伝導度