Effects of Different Application Methods of Controlled-release Fertilizers on Capillary Wick Culture of Tomato

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Abstract. Application of controlled-release fertilizer (CRF) to root-proof capillary-wick irrigation systems (a type of subirrigation method) has both economic and environmental benefits because it does not require any equipment for fertigation and minimizes water leaching. In this study, we compared three CRF fertilization methods: 1) mixed with the substrate completely (“mixed-fertilization” (MF)); 2) packed in bags and placed on the wick (“packed bag-fertilization” (PF)); and 3) supplied in the water reserve tank (“tank-fertilization” (TF)) in tomato cultivation using the root-proof capillary-wick irrigation system. We also refined the TF method to simplify and reduce labor requirements for fertigation of CRF and reuse of substrate. Fruit yield was lower in PF and TF than in MF because of high incidence of blossom-end rot (BER) in PF and TF during both cultivation periods, spring—summer and fall—winter. However, promotion of nitrification in TF by supplying nitrogen through the addition of bark compost and aeration of the water reserve tank increased fruit yield to the same level as that observed in MF as a result of a decrease in BER incidence. Nutrient residue in the substrate was lower in TF than in MF. On the basis of the analysis of nitrogen concentration in xylem exudates, the uptake ratio of NH$_4$-N/NO$_3$-N was thought to be lower in MF than in PF and TF. The high NH$_4$-N uptake in PF and TF could be the cause of calcium (Ca) deficiency and increased incidence of BER. Thus, the use of “tank fertilization” of CRF in the root-proof capillary-wick irrigation system for tomato production is possible by promoting nitrification in the water reserve tank.

The efficiency of nutrient and water use is generally higher with subirrigation than with drip irrigation because subirrigation greatly reduces water leaching (Goodwin et al., 2003; Incrocci et al., 2006; Santamaria et al., 2003). For uniform water distribution in potted ornamental plants, capillary wick irrigation, a subirrigation method, has become popular in Japan since the 1980s. Capillary-wick irrigation eliminates the need for irrigation equipment (e.g., pumps, timers, sensors) because it uses capillary forces to supply the water, and this method is also labor-efficient and economical. However, in the case of long-term cultivation, the use of capillary-wick irrigation results in weaker growth because the roots penetrate the wick and decrease capillary action. To solve this problem, Masuda (2008) developed a root-proof capillary-wick irrigation system for long-term vegetable production by making the wick impenetrable to the roots. In this irrigation system, water is stably supplied by capillary action from the side of the substrate without root invasion into the wick. Many studies have attempted to determine a suitable nutrient concentration to improve tomato cultivation by using this system (Masuda and Fukumoto, 2008; Morishige et al., 2009).

Compared with liquid fertilizer (LF), CRF is economical, because it does not require equipment to adjust the nutrient concentration and deliver the fertilizer. In our previous study, we demonstrated that CRF application was able to maintain the same fruit production with high nutrient use efficiency by suppressing luxury nutrient uptake compared with LF application (Kinoshita and Masuda, 2011a). In our study, CRF was supplied by mixing fertilizer with substrate in the usual way. However, this method of fertilization is labor-intensive, and uniform fertilization is difficult for large-scale cultivation. Moreover, reuse of substrates is difficult because residual fertilizer can remain in the substrates after the first cultivation, and this must be considered when deciding the fertilizer application rate for the subsequent cultivation. Imano et al. (2011) investigated the “packed bag-fertilization” method of CRF for tomato cultivation. In this method, fertilizers required for each plant are packed in polyester bags and put in the substrates. Imano et al. reported that this method facilitated the removal of residual fertilizer before the substrates were reused and prevented nutrient enrichment of the substrates. Therefore, substrates fertilized using this method may have high reusability. However, this method is likely to require high costs and labor to prepare fertilizer bags for each plant, making it very difficult to introduce this method for large-scale tomato cultivation.

We developed a method for applying all fertilizers required for the whole cultivation period to a water reserve tank (“tank-fertilization” method). This method also facilitates the removal of residual fertilizer before reuse of the substrates and simplifies fertilizer application. Furthermore, it is expected that there is no nutrient enrichment in the substrates at the end of the cultivation period when using this method. However, high incidence of BER was observed in tomato plants when the “tank-fertilization” method was used in our preliminary investigations (unpublished data). In general, the ratio of NH$_4$-N to total nitrogen in CRF is higher than that in commercial LF, which is usually used in soilless culture. Application of NH$_4$-N fertilizers, or higher NH$_4$-N(NO$_3$-N) ratios in the nutrient solution, is often associated with increased incidence and severity of BER (Aki et al., 2003; DeKock et al., 1979, 1982; Pill and Lambeth, 1980; Pill et al., 1978). Therefore, high incidence of BER in our preliminary investigations might have been caused by high NH$_4$-N ratios in the CRF. However, very low incidence of BER was observed when the CRF was supplied by mixing the fertilizer with substrates (Kinoshita and Masuda, 2011a). Thus, the effect of high NH$_4$-N content in CRF on the incidence of BER is likely attributable to the different between the different methods of CRF application.

In the present study, we compared a number of CRF fertilization methods for tomato cultivation by using the root-proof capillary-wick irrigation system and continued to develop the “tank-fertilization” method to decrease BER occurrence.

Materials and Methods

Three experiments were conducted at the Western Regional Agricultural Research Center, Zentsuji, Kagawa, Japan (lat. 34°13′ N, long. 133°46′ E). Expt. 1: Development of a nitrification method in a water reserve tank. This experiment
was conducted to develop a method for nitri
of treatments in a plastic greenhouse (area, 108 m²). Seeds of large-fruit tomato plants

tative to the seasonal difference
of nitrogen (N) fertilizer in a water
reserve tank to decrease the incidence of BER
when using the "tank-fertilization" method.
We dissolved (NH₄)₂SO₄ in plastic buckets (4 L) filled with well water (3 L). N concentra-
tion in the water was adjusted to 400 mg
N/L. The surface of the buckets was cov-
ered with silver mulch to prevent evapora-
tion. Four treatments were set up: 1) addition
of bark compost (15 g) to the buckets to
provide the source and nest for nitri
fying bacteria and aeration of the water by using an air pump (24 h) to supply oxygen; 2) ad-
dition of bark compost (15 g) without aeration; 3) no addition of bark to the buckets and
aeration of the water; and 4) no addition of
to the buckets and no aeration of the
water. Three replicate buckets were set up
for each of the four treatments, and the
experiment followed a completely random-
dized design. We collected 1 mL of water
from each bucket every several days to con-
trol the rate of nitri
fication. The samples
were diluted 10 times with distilled water
and filtered with a membrane filter (0.45 μm, pore size). Concentration of NO₂-N and
NO₃-N was determined using ion chroma-
tography (DX-AQ; Nippon Dionex K.K.,
Osaka, Japan) The operating parameters
were as follows: analytical column AS12A
(4 mm) with guard column AG12A (4 mm); as
eluent, a solution with 2.7 mM Na₂CO₃ and 0.3
mM NaHCO₃; 1.2 mL·min⁻¹ eluent flow rate;
and injection volume, 0.1 mL. The quantifica-
tion was obtained by conductivity measure-
ments. The experiment was conducted at a
fixed temperature (25 °C) to minimize the
effects of temperature.

Expt. 2: Development of a "tank-fertilization"
method. This experiment was conducted to
compare three CRF fertilization methods, in-
cluding the "tank-fertilization" method, for
tomato cultivation by using the root-proof
capillary-wick irrigation system and to inves-
tigate the effects of nitri
fication in the water
reserve tank of the "tank-fertilization" method.
The experiment was conducted twice, dur-
ing spring–summer and fall–winter, sea-
sons to investigate the seasonal difference
in the water reserve tank (TF); and 4) supplied
in the water reserve tank and nitri
fied by adding bark compost and aeration, as a result of Expt. 1 ["tank-fertilization + nitri
fication" (TFN)]. The nutrient components of CRF are
shown in Table 1. The ratio of NO₃-N: NH₄-N
was 2:1. Ash of chicken droppings was
mixed with the substrate in all treatments to
adjust pH and to supply macro- and micro-
minerals, except N. All fertilizers were sup-
plied before planting. In PF, all CRFs except
ash of chicken droppings were packed in poly-
ester bags with water permeability (9.5 cm
long × 7.0 cm wide, spring–summer; 10.5 cm
long × 11.0 cm wide, fall–winter) and placed
on each wick. In TF and TFN, all CRFs supplied for all plants, except ash of
chicken droppings, were packed with poly-
ester sheet that divided each fertilizer type
applied in the water reserve tank (20 L). In TF
and TFN, one water reserve tank was used for
irrigating plants of all replicates. In addition,
a treatment supplying LF was set. For LF,
a half-strength commercial nutrient solution
with an electrical conductivity of 1.4 dS·m⁻¹
(Otsuka Chemical Co. Ltd., Osaka, Japan)
and containing N (NO₃-N:NH₄-N = 9:1), phos-
phorus (P), potassium (K), Ca, and
magnesium (Mg) at concentrations of 130,
26, 168, 82, and 18 mg·L⁻¹, respectively, was
applied to the plants. The experimental de-
sign was a randomized complete block with
three replicate plots of each treatment. Each
plot was comprised of six plants, all of which
were in a single container.

NH₄-N and NO₃-N concentrations in the
nutrient solution in the water reserve tanks
were determined using a reflectometer (RQ
flex; Merck KGaA, Darmstadt, Germany)
three times a week. Individual mature fruits
from six plants per plot were harvested from
each plot once or twice a week, and the fresh
weight of each fruit was measured. Market-
able fruit was defined as fruit weighing over
80 g with no physiological damage. Fruit
Brix was measured using a digital refrac-
tometer (PAL-1; ATAGO Co., Ltd., Tokyo,
Japan).

The petiole of the leaflet just under each
fruit truss was collected 2 weeks after

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![Diagram](Image)
anthesis as described by Tanaka (2003). Samples were immediately homogenized by adding distilled water at a 1:9 ratio of sample (g) to water (mL). The mixture was centrifuged for 5 min at 6000 rpm and the supernatant was diluted 10 times with distilled water and filtered with a membrane filter (0.45 μm, pore size). Concentration of NH₄-N and Ca in the filtrate (petiole juice) was determined using ion chromatography (detailed in Expt. 1). The operating parameters were as follows: analytical column CS12A (4 mm) with guard column CG12A (4 mm); as eluent, 20 mM methanesulfonic acid; with guard column CG12A (4 mm); as eluent, follows: analytical column CS12A (4 mm). Determination using ion chromatography, as described in Kinoshita and Masuda (2011a). The samples were stored at –20 °C until analysis. Concentrations of NH₄-N and NO₃-N in the exudates were determined using ion chromatography, as described in Expts. 1 and 2. Total N concentration in the exudates was measured using the NC analyzer, as described in Expt. 2. Organic N concentration was calculated by deducting NH₄-N and NO₃-N concentrations from the total N concentration. Furthermore, anion and cation fractions in the exudates were extracted using cation and anion exchange resins (cation, Amberlite IR120-B-NA; anion, Amberlite IRA400J-CL; Organo Corp., Tokyo, Japan) by the batch method as follows: ∼500 mg of each resin and 1.5 mL of the exudates per plot were put in a plastic tube (2.0 mL) and shaken 24 h. The supernatant was concentrated by a vacuum evaporator and atom percentage of ¹⁵N for the concentrate was determined using stable isotope mass spectrometers (ANCA-GSL+ GE20-20; Europa Scientific Ltd., Crewe, U.K.). Nitrogen formed in the supernatant exchanged with cation resins was regarded as an anion form, and that exchanged with anion resins was regarded as a cation form, because almost all N in the exudates probably carried an electrical charge.

**Data analysis.** One-way analysis of variance and Tukey’s multiple comparison tests were performed using the statistical software Excel Tokei 2010 (SSRI, Tokyo, Japan).

### Results and Discussion

**Expt. 1: Development of a nitrification method in a water reserve tank.** NO₃-N and NO₂-N concentrations in the water buckets are shown in Figure 2. The rate of nitrification to NO₃-N was highest in Treatment 1 (addition of bark compost and aeration). In Treatment 3 (only aeration), the rate of nitrification to NO₃-N was comparatively high, but there was little NO₂-N production; there was very little NO₂-N and NO₃-N production in Treatment 2 (only bark compost addition). Therefore, the rate of nitrification to NO₃-N remained low with only the addition of bark compost or aeration of the water. However, efficient nitrification to NO₃-N was achieved by combining the addition of bark compost (for the nest of nitrifying bacteria) and aeration of the water, as reported by Shinohara (2006) and Shinohara et al. (2011).

**Expt. 2: Development of the tank-nitrification method.** Changes in the ratio of NH₄-N/NO₃-N and nitrogen conversion of supplied fertilizer. This experiment was conducted to investigate the difference in the uptake ratio of NH₄-N/NO₃-N and N conversion of the supplied fertilizer and to explain the reason of the difference in BER rate among the different CRF application methods. The experiment was conducted in a plastic greenhouse (area, 252 m²). Seeds of ‘House Momotaro’ were sown in 128-well plug trays filled with the same growth medium as Expt. 2 on 12 Sept. 2010. Seeds were transferred to 9-cm polyethylene pots filled with the same substrate as Expt. 2 on 29 Sept. 2010. On 28 Oct. 2010, the seedlings were transplanted to the root-proof wick-irrigation system for home use (Tomato-Meijin; Growwell, Fukuoka, Japan). In this system, plastic boxes (35 cm long × 24 cm wide × 27 cm high) containing the same substrate (3 L per plant) were used for planting two plants per box, and the substrates were separated for each plant. The plastic boxes were placed on 4-L water reserve tanks (43 cm long × 41 cm wide × 4 cm high). Each plant was allocated one wick (45 cm long × 4 cm wide). The substrate surface was covered with rice husks to prevent evaporation. CRF (6N–6P₂O₅–6K₂O; 4NO₃-N:6NH₄-N, 40 d type; JCAM AGRI. Co., Ltd., Tokyo, Japan) was supplied (2.0 g N/plant) using the following three methods: 1) MF; 2) PF; and 3) TF. In PF and TF, the CRF was packed in polyester bags (9.5 cm long × 7.0 cm wide) for each plant and placed on the wick (PF) or supplied in the water reserve tank (TF). NH₄-N in the fertilizer was labeled with ¹⁵N (6.6 atom%¹⁵NH₄-N). Ash of chicken droppings was mixed with the substrate in all treatments (10 g/plant). The experimental design was a completely randomized design with three replicates per treatment. Each replicate contained two plants. The greenhouse temperature was controlled as described in Expt. 2.

Xylem exudates were collected from two plants in each plot on 8 Dec. 2010, at the early stage of fruit enlargement of the first fruit truss. For this purpose, the plants were decapitated at 5 cm above the ground at 1000 HR, and xylem exudates were collected for 3 h, as described in Kinoshita and Masuda (2011a). The samples were stored at –20 °C until analysis. Concentrations of NH₄-N and NO₃-N in the exudates were determined using ion chromatography, as described in Expts. 1 and 2. Total N concentration in the exudates was measured using the NC analyzer, as described in Expt. 2. Organic N concentration was calculated by deducting NH₄-N and NO₃-N concentrations from the total N concentration. Furthermore, anion and cation fractions in the exudates were extracted using cation and anion exchange resins (cation, Amberlite IR120-B-NA; anion, Amberlite IRA400J-CL; Organo Corp., Tokyo, Japan) by the batch method as follows: ∼500 mg of each resin and 1.5 mL of the exudates per plot were put in a plastic tube (2.0 mL) and shaken 24 h. The supernatant was concentrated by a vacuum evaporator and atom percentage of ¹⁵N for the concentrate was determined using stable isotope mass spectrometers (ANCA-GSL+ GE20-20; Europa Scientific Ltd., Crewe, U.K.). Nitrogen formed in the supernatant exchanged with cation resins was regarded as an anion form, and that exchanged with anion resins was regarded as a cation form, because almost all N in the exudates probably carried an electrical charge.

### Table 1. Fertilizer component concentrations in the substrate of controlled-release fertilizer application treatments (g/plant, Expt. 2).

| Japanese standard name of fertilizer | Days | Nitrogen | Phosphorus | Potassium | Calcium | Magnesium |
|--------------------------------------|------|----------|------------|-----------|---------|-----------|
| Ash of chicken droppings              | 70   | 1.4      | 0.9        | 1.5       | 1.6     | 0.4       |
| Eco long total 313°C                  |      |          |            |           |         |           |
| Super eco long                        | s100 | 2.9      | 2.1        | 1.1       | 1.1     | 2.4       |
| Long calcium nitrate                  | 10   | 1.6      | 1.6        |           |         |           |
| Coating potassium                     | 100  | 0.2      | 2.7        |           |         |           |
| Long magnesium sulfate                | 100  | 0.3      |            |           |         |           |
| Total                                | 6.0  | 2.5      | 7.7        | 3.8       | 0.3     |           |
| Ash of chicken droppings              | 70   | 1.4      | 2.5        | 1.6       | 1.6     | 0.4       |
| Eco long total 313°C                  |      |          |            |           |         |           |
| Super eco long                        | s100 | 2.9      | 2.1        | 1.1       | 1.1     | 2.4       |
| Long calcium nitrate                  | 100  | 0.2      | 2.7        |           |         |           |
| Coating potassium                     | 100  | 0.3      |            |           |         |           |
| Long magnesium sulfate                | 100  | 0.3      |            |           |         |           |
| Total                                | 8.0  | 2.8      | 10.3       | 5.0       | 0.4     | 1.1       |

*Number of days until 80% of the amount is released at 25 °C.

This fertilizer contained nitrogen, phosphorus, potassium, and magnesium in the ratio 13:4.8:10.8:1.2 plus small amounts of micronutrients.

**Nutrients are released sigmoidally in contrast to linear nutrient release in other fertilizers.**
Nitrification treatment was definitely effective in reducing the ratio of NH$_4$-N concentration in the tank. Fluctuations in the ratio of NH$_4$-N concentration in TF and TFN were greater in fall–winter than in spring–summer. The nitrification rate was probably kept high in spring–summer because of the warmer temperatures (nitrification rate is generally high at warmer temperatures), whereas the rate is likely to have decreased on colder days in the fall–winter season. Thus, the difference in nitrification rate between cropping seasons is likely a result of difference in water temperature.

There were no significant differences among CRF treatments in the total amount of nutrient residue in the substrates and the fertilizer at the end of the experiment, except P and K in fall–winter (Table 2). Therefore, the difference in the elution rate of the fertilizer and the apparent nutrient uptake varied little among the different CRF application treatments. On the other hand, nutrient residue in the substrates in TF and TFN was lower than that in MF, except Mg in spring–summer and Ca in fall–winter. This indicates that TF and TFN prevent nutrient enrichment of the substrates and the substrates treated by these methods have high reusability.

Fruit yield and BER incidence are shown in Table 3. Marketable fruit yield was lower in PF and TF than in MF in both seasons. Marketable fruit yield in TFN was greater than that in TF in both seasons and equivalent to that in MF. In spring–summer, fruit yield in CRF-supplied plants was lower than that in LF-supplied plants. This may be caused by low nutrient elution in the second half of the growing season in plants supplied with CRF judging from the smaller stem diameter and fruit yield of the upper trusses (data not shown) in CRF-supplied plants. There was no significant difference in fruit weight, whereas the lower marketable fruit number differed significantly among CRF application treatments. Total fruit number was similar among treatments in the fall–winter season, but during the spring–summer season, the highest fruit number was observed in MF and the smallest in TF among the treatments of CRF application. BER incidence was generally higher in PF and TF than in the other treatments for the first two trusses in the spring–summer and the first truss in the fall–winter. Therefore, the difference in marketable fruit weight between the treatments was likely caused by the difference in BER incidence as well as the total fruit number in both seasons. BER incidence tended to be higher in the spring–summer season than in the fall–winter season. Our results are in agreement with those of Ikeda and Osawa (1988) who reported that the incidence of BER was higher in spring–summer than in fall–winter in tomato plants when the NH$_4$-N rate in the supplied N was high.

Therefore, it was revealed that BER incidence differs among the CRF application treatments. It has been reported that Ca uptake from 1 to 3 weeks after anthesis strongly affects the occurrence of BER (Chiu and Bould, 1976; Ehret and Ho, 1986; El-Gizawy and Adams, 1986; Gerard and Hipp, 1968; Westerhout, 1962). Ca concentration in the petiole juice at the early stage of fruit growth (≈2 weeks after anthesis) of trusses with high BER incidence differed significantly between treatments (Table 4). Moreover, there was a significant correlation between the incidence of BER and Ca concentration (Fig. 4). Thus, the difference in Ca concentration at the early stage of fruit growth is likely to have led to the difference in BER incidence between the treatments. BER incidence tended to increase drastically when Ca concentration decreased below 100 to 200 mg·L$^{-1}$. Morikuni and Shimada (2000) also reported that BER incidence increased when Ca concentration in the petiole juice decreased below 200 mg·L$^{-1}$. Furthermore, He et al. (1998) suggested that Ca deficiency could be diagnosed by checking the Ca concentration in the petiole juice.
Table 2. Amount of nutrient residue in the substrates and in the fertilizer at the end of the experiment for the different fertilization methods (g/plant, Expt. 2).

| Treatmenta | Substrate | Fertilizer | Total |
|------------|-----------|------------|-------|
|            | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| Spring–summer crop | | | | | | | | | | |
| MF | 5.29 ab | 2.48 a | 2.49 a | 4.84 b | 0.81 b | | | | | |
| PF | 4.54 bc | 1.12 c | 1.03 b | 3.23 c | 0.69 b | | | | | |
| TF | 4.10 c | 1.07 b | 1.02 b | 3.73 c | 0.75 b | | | | | |
| TFN | 4.19 c | 1.08 c | 0.76 b | 3.19 c | 0.64 b | | | | | |
| LF | 5.77 a | 1.69 b | 3.21 a | 6.24 a | 1.25 a | | | | | |
| ANOVA | *** | *** | *** | NS | *** | ** | NS | NS | NS | NS |
| Fall–winter crop | | | | | | | | | | |
| MF | 5.69 a2 | 1.97 a | 3.66 a | 7.81 a | 1.40 a | | | | | |
| PF | 4.35 b | 0.53 c | 0.57 b | 6.07 b | 1.10 b | | | | | |
| TF | 4.48 b | 0.61 b | 0.52 b | 7.37 b | 1.19 b | | | | | |
| TFN | 4.55 b | 0.58 c | 0.51 b | 7.00 b | 1.16 b | | | | | |
| LF | 5.46 a | 1.19 b | 2.32 a | 7.51 a | 1.51 a | | | | | |
| ANOVA | ** | *** | *** | NS | ** | * | NS | NS | NS | NS |

aMF = mixed-fertilization; PF = packed bag-fertilization; TF = tank-fertilization; TFN = tank-fertilization + nitrification; LF = liquid fertilizer.

Table 3. Fruit yield, soluble solids concentration, and BER incidence in the different fertilization methods (Expt. 2).

| Treatmenta | Total Fruit yield (g/plant) | Marketable Fruit number (plant) | Individual fruit wt (g/fruit) | Soluble solids (Brix %) | BER incidence (%) |
|------------|-----------------------------|---------------------------------|--------------------------------|------------------------|-------------------|
|            | Yield (g/plant) | Fruit number (plant) | Yield (g/plant) | Fruit number (plant) | Individual fruit wt (g/fruit) | Firstx | Second | Third | Fourth | Fifth |
| Spring–summer crop | | | | | | | | | | | |
| MF | 2711 b2 | 20.2 ab | 2612 b | 18.4 b | 142 b | 5.9 b | 2.5 a | 6.8 ab | 1.2 | 0.0 | 0.0 |
| PF | 2167 cd | 17.9 bc | 1995 cd | 14.5 d | 137 b | 6.4 a | 18.2 a | 12.2 ab | 5.8 | 0.0 | 2.6 |
| TF | 2054 d | 16.8 c | 1896 d | 13.9 d | 136 b | 6.1 ab | 15.0 a | 20.0 a | 9.5 | 0.0 | 1.9 |
| TFN | 2432 bc | 18.3 bc | 2349 bc | 16.2 c | 145 ab | 6.1 ab | 8.4 ab | 3.0 b | 3.7 | 0.0 | 0.0 |
| LF | 3483 a | 21.4 a | 3390 a | 20.2 a | 168 a | 6.1 ab | 1.1 b | 3.5 b | 1.2 | 0.0 | 0.0 |
| ANOVA | *** | ** | *** | NS | *** | ** | NS | NS | NS | NS | NS |

aMF = mixed-fertilization; PF = packed bag-fertilization; TF = tank-fertilization; TFN = tank-fertilization + nitrification; LF = liquid fertilizer.

Table 4. Ca and NH₄-N concentrations in the petiole juice at the early stage of fruit growth in the different fertilization methods (Expt. 2).

| Treatmenta | Spring–summer crop | Fall–winter crop | Spring–summer crop | Fall–winter crop |
|------------|-------------------|------------------|-------------------|------------------|
|            | First truss | Second truss (4 June) | Third truss (11 June) | First truss | Second truss (4 June) | Third truss (11 June) |
| Ca (mg L⁻¹) | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| MF | 290 b2 | 592 a | 582 a | 184 a | 203 c | 120 b | 144 b |
| PF | 65 c | 236 b | 230 c | 84 ab | 448 a | 117 b | 130 b |
| TF | 81 c | 267 b | 308 bc | 76 b | 396 ab | 156 a | 139 a |
| TFN | 132 bc | 464 a | 507 ab | 152 ab | 372 abc | 108 a | 132 a |
| LF | 583 a | 626 a | 718 a | 190 a | 279 bc | 112 b | 115 b |
| ANOVA | *** | ** | *** | * | ** | NS | NS |

aMF = mixed-fertilization; PF = packed bag-fertilization; TF = tank-fertilization; TFN = tank-fertilization + nitrification; LF = liquid fertilizer.

Ca = calcium; ANOVA = analysis of variance.
In contrast, high NH₄-N concentration is often associated with increased incidence and severity of BER (Akl et al., 2003; DeKock et al., 1979, 1982; Pill and Lambeth, 1980; Pill et al., 1978). In general, the ratio of NH₄-N to total N is higher in CRF than in commercial LF. The ratio was 33% to 35% in this experiment. It was reported that BER incidence increased drastically when the ratio was higher than 20% to 25% (Akl et al., 2003; Hartman et al., 1986; Ikeda and Osawa, 1988). Therefore, the difference in the incidence of BER between treatments in the current study probably originated as a result of differences in Ca deficiency caused by the high NH₄-N ratio in CRF.

Increase in the NH₄-N concentration led to a decrease in the Ca concentration in the petiole juice under first truss during both seasons (Table 4). Thus, Ca uptake was probably suppressed by high NH₄-N uptake in those trusses. Conversely, there was no significant difference in NH₄-N concentration in the petiole juice and no relationship with Ca concentration at the other trusses. From these results, it may be difficult to conclude that BER incidence and Ca deficiency were caused by high NH₄-N uptake.

In contrast, there was little difference in the apparent nutrient uptake between CRF-applied treatments. BER incidence was remarkable on only the lower trusses with very little incidence on the upper trusses. Therefore, Ca uptake probably only differed between the treatments during the first half of the growing season.

Expt. 3: Uptake ratio of NH₄-N/NO₃-N and nitrogen conversion of the supplied fertilizer. The concentration of each N form in the xylem exudates is shown in Table 5. NO₃-N concentration was lower in PF and TF than in MF, whereas NH₄-N concentration was almost the same between the treatments. Organic N concentration was the highest of the three N forms in each treatment and higher in PF and TF than in MF. In general, with increase in the NH₄-N ratio in the fertilizer, decrease in the NO₃-N concentration and increase in the concentration of amino acids in the xylem exudates were observed (Bialczyk et al., 2004; Lorenz, 1976; Lu et al., 2009). This is because the rate of NO₃-N reduction at the roots is very low, and NO₃-N is mainly reduced to NH₄-N and amino acids in the leaves; the rate of NH₄-N reduction at the roots is comparably high (Lorenz, 1976). From these results, the ratio of NH₄-N uptake to NO₃-N uptake was probably higher in PF and TF than in MF.

15N concentration in each N form in the xylem exudates is shown in Table 6. Conversion from NH₄-N to the anion or cation form can be calculated by deducting 15N concentration in each form from that in whole N. In each treatment, the conversion rate of NH₄-N to the cation form was higher than that from NH₄-N to the anion form because the 15N concentration in the anion
form was lower, whereas $^{15}$N concentration in the cation form was higher than that in whole N. Therefore, NH$_4$-N in the fertilizer would mostly be converted to organic N such as amino acids, because NH$_4$-N concentration in xylem exudates was very low in each treatment. This result matches the high concentration of organic N in the xylem exudates.

From these results, the following mechanisms are suggested as possible causes of the difference in BER incidence between the treatments of Exp. 2: 1) in MF, it is difficult to induce Ca deficiency and increase BER incidence because the nitrification rate of the fertilizer is high and the rate of NH$_4$-N uptake is comparatively low; and 2) in PF and TF, it is easier to induce Ca deficiency and increase BER incidence because the nitrification rate of the fertilizer is low and the rate of NH$_4$-N uptake is comparatively high.

### Conclusion

Efficient nitrification of the fertilizer from NH$_4$-N to NO$_3$-N is possible by combining the addition of bark compost (for the rest of nitrifying bacteria) and aeration of the water (to improve oxygen supply). Fruit yield was lower in TF and PF than in MF, but promoting nitrification in the water reserve tank in TF increased fruit yield to the same level as that observed in MF. Besides, the substrates treated by TF may have high reusability. The uptake ratio of NH$_4$-N/NO$_3$-N was estimated to be lower in MF than in PF and TF. Therefore, compared with PF and TF, it would be difficult to induce Ca deficiency and increase BER incidence in MF. Thus, the technique of “tank fertilization” of CRF in the root-proof capillary-wick irrigation system of tomato is possible by promoting nitrification in the water reserve tank.

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