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Effects of Application of Low-Sulfate Slow-Release Fertilizer (LSR) on Shoot and Root Growth and Fruit Yield of Tomato (*Lycopersicon esculentum* Mill.)

Akimasa NAKANO[1]*, Akira YAMAUCHI[2] and Yoichi UEHARA[1]

[1] Department of Fruit Vegetables, National Institute of Vegetable and Tea Science (Taketoyo, Aichi 470–2351, Japan)
[2] Graduate School of Bioagricultural Science, Nagoya University (Chikusa, Aichi 464–8601, Japan)

Abstract

Salt accumulation and ion imbalance caused by residual fertilizer in greenhouse cultivation have been serious problems in Japan since the 1970s, when the area of greenhouse cultivation began to increase. Because an excess of sulfate ions was considered to be the major cause of these problems, low-sulfate slow-release fertilizers (LSR) were developed. In a LSR, nitrogen is added in the urea form, and silicate is substituted for sulfate. We investigated the effects of LSR on shoot and root growth and fruit yield of tomato, compared with an ordinary slow-release fertilizer, cyclo-di-urea (CDU) containing sulfate. First, we examined the effects on early growth (for 30 days) and early root distribution in small root boxes. The reduction of shoot and root growth caused by a heavy application of LSR (1.5 g N kg^{-1} dry soil) was smaller than that caused by a heavy application of CDU. Root growth was severely restricted by a heavy application of CDU but only moderately restricted by a heavy application of LSR. Second, we examined the effects of the fertilizers over a longer period of time (84 days) in larger root boxes. In this case, the fertilizer was mixed only in the surface 30 cm. Plants that received a heavy application of CDU were able to grow to some extent, even though root growth in the fertilized layer was reduced, because the same roots extended to the deeper layer, mitigating the stress. With heavy fertilizer application, plants receiving LSR yielded 159% of the fruit weight of plants that received CDU. The sugar content of the fruits decreased from 5.2% ± 0.2% with CDU to 4.8% ± 0.1% with LSR. The sap bleeding rate tended to be higher in the LSR treatment than in the CDU treatment. These results suggest that LSR imposes less osmotic or chemical stress on the root system than CDU.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: protected cultivation, salt accumulation, root system

Introduction

A large amount of chemical fertilizers is used in vegetable production in Japan, especially in protected cultivation, which is carried out under glass or plastic houses. Protected cultivation yields more and higher-quality vegetables than field cultivation, but salt accumulation in soil caused by continuous cropping is a common problem, because leaching by rainfall does not occur. Salt accumulation in soil results in soil degradation and yield reduction[3,13]. The number of reports on soil salinization increased as the area of protected cultivation increased after the 1970s. Excessive amounts of soil nitrate and phosphate were reported all over the country[13,14]. The number of reports on excess soil sulfate also increased, suggesting that this condition is one of the main causes of high soil electrical conductivity (EC)[12]. We collected soil samples from open field culture and protected cultivation in 7 prefectures in Japan from 1996 to 1998 and analyzed the soil chemical properties in 1:5 (H_2O) soil extracts[7]. Our results indicated that about 25% of the soil samples accumulated excessive salt (>1.0 dSm^{-1}). We found that sulfate had accumulated as much as nitrate throughout the protected cultivation area in Japan. To address the problem, desalinization by leaching, soil dressing and cultivation of cleaning crops are practiced, but these methods can cause environmental pollution or are laborious. A new fertilizer with reduced sulfate and chloride contents was developed a few years ago to mitigate salt stress caused by residues of these ions[9]. We have recently showed that this low-sulfate

*Corresponding author: fax+81–569–73–4744; e-mail anakano@affrc.go.jp
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slow-release fertilizer (LSR) improved the soil chemical properties, fruit yield, and quality of tomato in 6 successive crops over a period of 2 years[7].

In this report, we analyzed the effects of LSR on the root form and sap bleeding rate (considered to be an index of root activity[6]), and examined the relationship between these parameters and fruit yield and quality, compared with the use of an ordinary slow-release fertilizer, cyclo-di-urea (CDU) containing sulfate.

Materials and methods

1. Experiment 1

Air-dried Kisogawa sandy loam soil (bulk density 1.2 g cm^{-3}) was sieved through a 2 mm mesh, mixed with fertilizer, and used to fill root boxes (40 cm high × 25 cm wide × 2.7 cm thick; Fig. 1, left). Two fertilizers were used: CDU S222 [N:P:K = 12:12:12] and LSR [N:P:K = 10:11:11] (Table 1). Each fertilizer treatment was supplied at 3 rates: 0.17, 0.50 and 1.50 g of nitrogen per kg dry soil with calcium and magnesium fertilizers at the 3 rates of 0.42, 1.30 and 3.80 g, respectively to balance the application rate of nitrogen with that of calcium and magnesium.

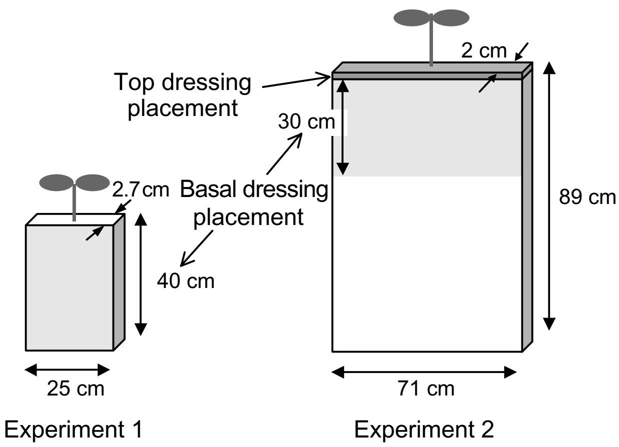

Fig. 1. Schematic design of the root boxes
Not to scale.

Twenty-day-old tomato seedlings grown in plug trays were transplanted to the root boxes. Boxes were irrigated once or twice a day with 100 mL tap water when necessary. There were 3 replications for each treatment.

After 30 days, the shoots were harvested, and the root systems were extracted carefully from the soil according to the needle board method developed by Kono et al.[4] to maintain their original spatial orientation and to minimize damage and disturbance. The root systems were scanned on a flat-bed scanner at a 600 dpi resolution, then their length was measured using root measurement software (Mac Rhizo-a, REGENT Inc., Canada). Shoots and roots were oven-dried at 80ºC for 72 h and weighed.

2. Experiment 2

The same soil as that in Exp. 1 was used to fill larger root boxes (89 cm high × 71 cm wide × 2 cm thick; Fig. 1, right). The fertilizers were mixed in the 30-cm surface layer only. Each was supplied at 3 rates: 0.07 g (Low: L), 0.20 g (Medium: M), and 0.59 g (High: H) of nitrogen per kg dry soil with calcium and magnesium fertilizers at the 3 rates of 0.22, 0.65, 2.00 g, respectively to balance the application rate of nitrogen with that of calcium and magnesium. There were 3 replications for the L and M treatments and 4 replications for the H treatment. The filled root boxes were placed in a tank 50 cm deep, then tap water was poured gently into the tank up to 45 cm. When the water reached the soil surface by capillary action, the water in the tank was discarded.

Thirty-day-old tomato seedlings grown in plug trays were transplanted to the root boxes. The boxes were irrigated daily with 0.5 L of tap water before plant flowering and with 1.0 L after flowering. Since the plants wilted on September 26 and October 13, the boxes were immersed in the watering tank. Top-dressing was added at 51 days

Table 1. Chemical properties of CDU and LSR[a)]

Fertilizers (N-P_2O_5-K_2O)	Fertilizer nutrients (%)									Water-soluble nutrients (mmoLc g^{-1})[b)]									pH[e)]	EC[e)] ($dS\ m^{-1}$)
	N					P_2O_5	K_2O	CaO	MgO	K^+	Ca^{2+}	Mg^{2+}	Na^+	PO_4^{3-}	NO_3^-	Cl^-	SO_4^{2-}	Si		
	Total	NH_4	NO_3	CDU[c)]	UF[d)]															
CDU (12-12-12)	12	4.5	–	7.2	–	12	12	–	4	4.1	0.8	1.8	0.1	1.1	0.0	0.0	4.4	0.0	6.7	7.6
LSR (10-11-11)	10	–	–	–	10	11	11	–	2	0.4	0.2	0.8	0.1	0.4	0.0	0.1	0.5	0.4	8.2	1.3

a): Cited from the data of Nakano et al. (2001).
b): Measured by ICP or ion chromatography (n = 2).
c): CDU, cyclo-di-urea.
d): UF, urea form.
e): Both CDU and LSR (1.2 g) were extracted with 100 mL D.W.

after transplanting for the L and M treatments only.

At 82 days after transplanting, the stems were cut at a distance of 5 cm from the soil surface. Dry cotton (previously weighed) was placed at the cut end, and covered with a vinyl film fixed with a rubber band to collect the bleeding sap for 12 h (from 17:00 on October 14 to 05:00 on October 15), then to weigh it for the calculation of the bleeding rate. At the same time, harvested fruits were weighed, then homogenized for the measurement of the sugar content using a saccharometer.

On October 15 and 16, the root systems were extracted carefully from the soil to maintain the original spatial orientation and to minimize damage and disturbance. The root systems were spread on a black nonwoven fabric and photographed, then they were cut at 8.9 cm intervals from the top. The root length of each part was measured using a root length scanner (HDH, Australia).

Results and discussion

1. Initial response to excessive application of CDU and LSR fertilizers (Experiment 1)

Fig. 2 shows typical root system profiles of tomato plants grown at each fertilizer rate. At higher rates of fertilizer application, root growth was more restricted with CDU than with LSR, especially at a concentration of 1.5 g N kg^{-1} dry soil. Shoot growth was also more restricted with CDU than with LSR (Fig. 3). When the total dry weight was plotted against the estimated EC (calculated from the data in Table 1 and based on the assumption that the soil water content was 0.2 g g^{-1}), the results from both treatments followed the same curve (Fig. 4A). These results indicate that the decrease in the dry weight associated with excessive fertilization was caused by the high salinity of both fertilizers.

Tomato growth was reduced by half at a NaCl concentration of 4,500 ppm[8], which corresponds to an EC of 8 dSm^{-1}. Our experiment showed that the growth was also reduced by half at an estimated soil EC of 10 dSm^{-1}. The shoot-to-root (S/R) ratio was identical for each fertilizer at each concentration. However, when the S/R ratio was plotted against the estimated EC, the values for each

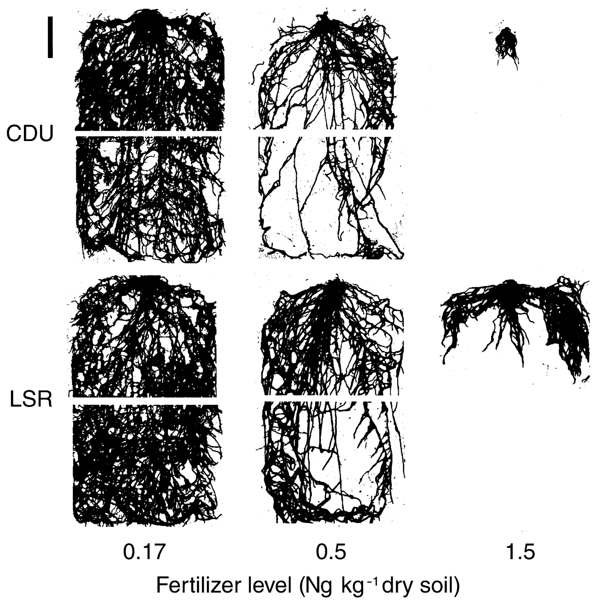

Fig. 2. Digitized images of root systems in the CDU and LSR treatments at different fertilizer concentrations in the short-term (30 days) experiment

Bar represents 5 cm.

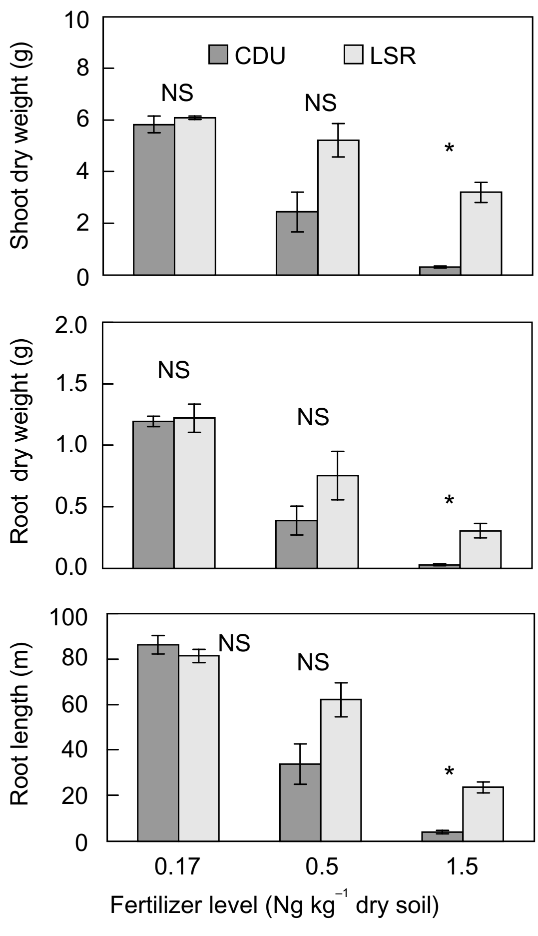

Fig. 3. Shoot and root growth of tomato in the CDU and LSR treatments at different fertilizer levels in the short-term experiment

Basal dressing was applied at the concentrations of 0.17, 0.5 and 1.5 g N dry soil, respectively.
Vertical bars represent SE (n = 3).
NS: Not significantly different at $p<0.05$ of Fisher's LSD.
*Significantly different at $p<0.05$ of Fisher's LSD.

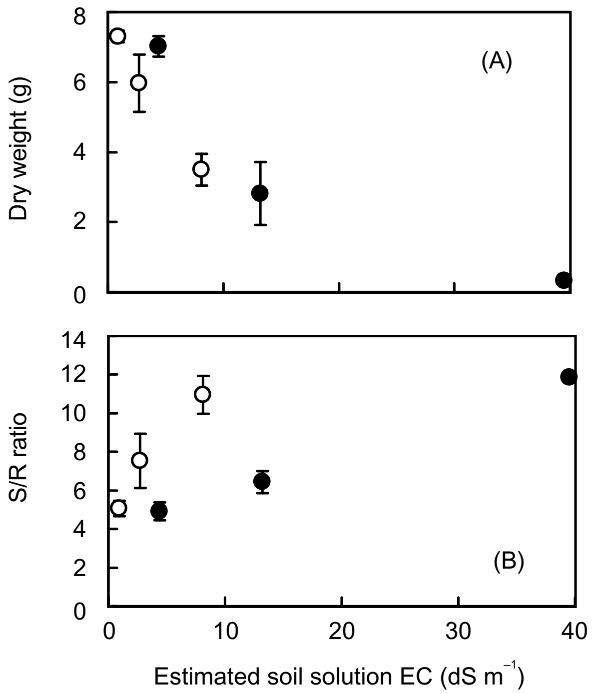

Fig. 4. Relationship between estimated EC of soil extract and dry matter production (A) or shoot/root (S/R) ratio (B) in the CDU (●) and LSR(○) treatments in the short-term experiment

Basal dressing was applied at the concentrations of 0.17, 0.50 and 1.50 g N kg^{-1} dry soil, respectively. Vertical bars represent SE (n = 3).

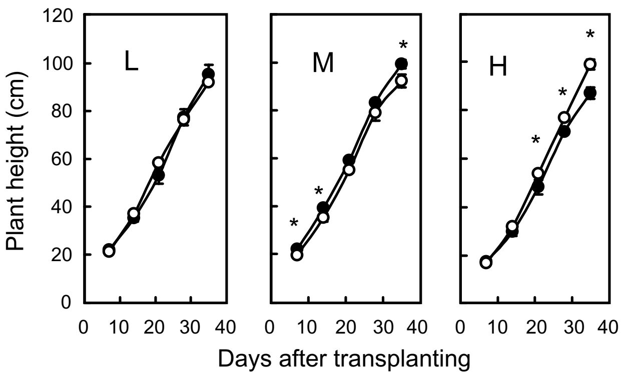

Fig. 5. Changes in plant height in the CDU (●) and LSR(○) treatments at different fertilizer levels in the long-term (84 days) experiment

Basal dressing was applied to the 30-cm surface layer at the rates of 0.07 (L), 0.20 (M) and 0.59 g N kg^{-1} dry soil (H), respectively. Top dressing at the same rate as that of the basal dressing was added in the L and M treatments at 50 days after transplanting. Vertical bars represent SE (L and M: n = 3, H: n = 4).

*Significantly different at p<0.05 of Fisher's LSD. NS: Not significantly different at p<0.05 of Fisher's LSD.

fertilizer lay on different curves (Fig. 4B). These results show that, even though plants were exposed to the same high-salinity stress, the distribution of assimilates differed between fertilizers: more assimilates were transferred to the roots in the CDU treatment than in the LSR treatment. Under stress conditions, for example, salt stress[2], physical impedance[10], and water deficit[11], more assimilates were distributed to the root system than under unstressed conditions. In contrast, our results showed that high-salinity stress induced the distribution of more assimilates to shoots than to roots that is, the S/R ratio increased as EC increased. The S/R ratio increased more in the LSR treatment than in the CDU treatment at the same estimated EC. This result shows that in the CDU treatment, other stresses caused by high salinity, such as an imbalance in ion contents, resulted in the changes in the assimilate distribution.

Muhammad et al.[5] showed that, under the same salinity stress, plants grown under better nutrient conditions distributed more assimilates to shoots. Our results also indicate that, because LSR induced the distribution of more assimilates to shoots than CDU, LSR application mitigated the stress caused by excessive fertilization and created better soil conditions than the CDU treatment.

2. Long-term response to excessive CDU and LSR fertilizer application (Experiment 2)

Plant height in the L and M treatments differed only slightly between the fertilizers applied (Fig. 5). The difference was largest in the H treatment at 35 days after transplanting. This result indicates that the excessive level of CDU application was around 0.59 g N kg^{-1} dry

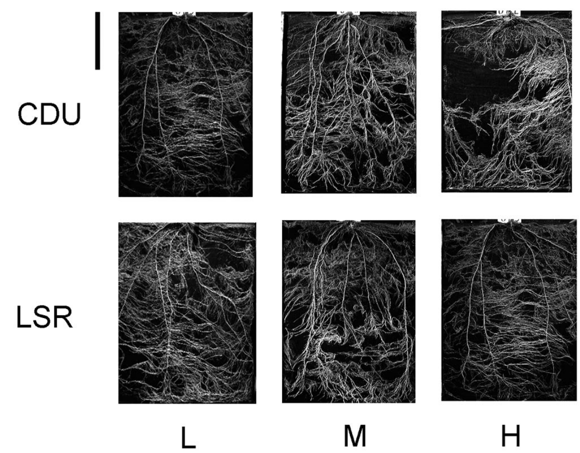

Fig. 6. Photographs of root systems of tomatoes in the CDU and LSR treatments at different fertilizer levels in the long-term experiment

Bar represents 30 cm.

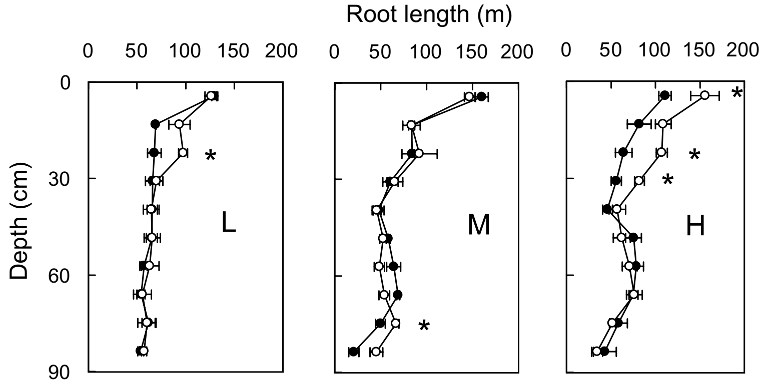

Fig. 7. Vertical distribution of tomato roots in the CDU (●) and LSR(○) treatments at different fertilizer levels in the long-term experiment

Basal dressing was applied to the 30-cm surface layer at the rates of 0.07 (L), 0.20 (M) and 0.59 g N kg^{-1} dry soil (H), respectively. Top dressing at the same rate as that of the basal dressing was added in the L and M treatments at 50 days after transplanting. Vertical bars represent SE (L and M: n = 3, H: n = 4).
*Significantly different at p<0.05 of Fisher's LSD. NS: Not significantly different at p<0.05 of Fisher's LSD.

soil, at which the difference between fertilizers was most significant. The high rate of fertilizer application reduced not only the plant height, but also the root length (Fig. 6). As in the case of the plant height, the root distribution in the L and M treatments was identical visually. However, heavy application of CDU restricted the root distribution, especially in the fertilized soil (top 30 cm) compared with the LSR treatment. The image of the roots with heavy application of CDU shows that only one adventitious root was able to penetrate the fertilized soil to produce lateral roots in the deeper layer. The other adventitious roots could not penetrate the soil and turned brown. Fig. 7 shows the root length distribution. At the lower rates of fertilizer application, there was no significant difference between the fertilizers. The total root length was 690 ± 9 m (CDU) and 754 ± 53 m (LSR) in the L treatment, 699 ± 9 m and 702 ± 53 m in the M treatment, and 690 ± 62 m and 806 ± 22 m in the H treatment. The large difference in H was due to the restricted root length in the locally fertilized soil. Excessive application of CDU restricted root elongation less than in Exp. 1. The results from Exp. 1 suggest that the application rate of 0.59 g N kg^{-1} dry soil may reduce the growth of the CDU-treated plants to less than half of that of the LSR-treated plants. However, the total root length of the same CDU-treated plants in Exp. 2 reached a value of 80% of that of the LSR-treated plants. Stress associated with excessive fertilization with CDU in Exp. 2 was more mitigated than in Exp. 1, because the roots penetrated to the lower soil layer to absorb water and take up nutrients, thus compensating for the stressed roots.

Fig. 8 shows the yield and sugar content of the tomato plants. The yields in the L and M treatments were

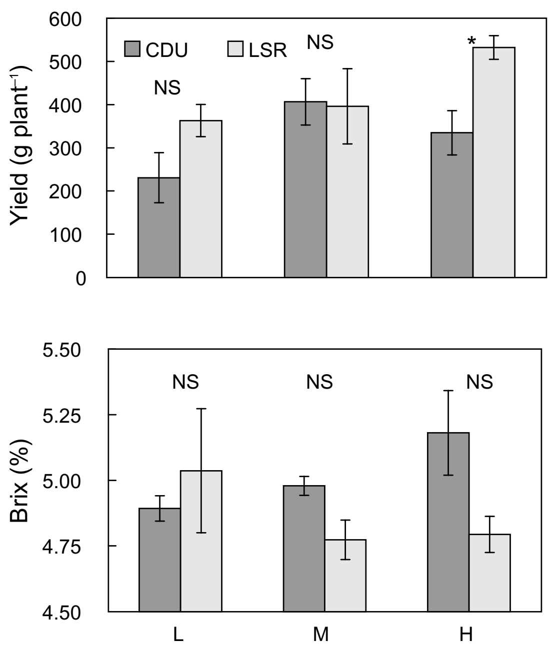

Fig. 8. Yield and sugar content (Brix) of tomato fruits in the CDU and LSR treatments at different fertilizer levels in the long-term experiment

Basal dressing was applied to the 30-cm surface layer at the rates of 0.07 (L), 0.20 (M) and 0.59 g N kg^{-1} dry soil (H), respectively. Top dressing at the same rate as that of the basal dressing was added to the L and M treatments at 50 days after transplanting. Vertical bars represent SE (L and M: n = 3, H: n = 4).
*Significantly different at p<0.05 of Fisher's LSD. NS: Not significantly different at p<0.05 of Fisher's LSD.

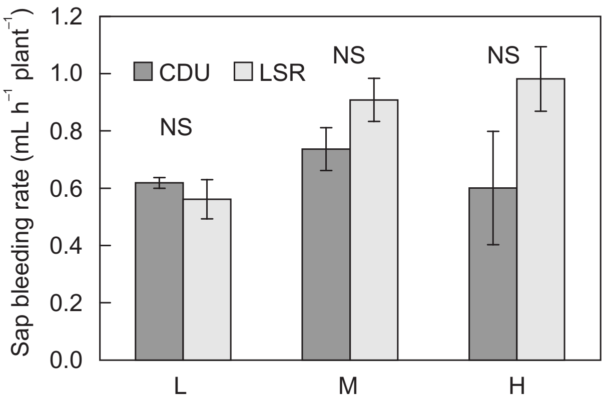

Fig. 9. Sap bleeding rate of tomato in the CDU and LSR treatments at different fertilizer levels in the long-term experiment

Basal dressing was applied to the 30-cm surface layer at the rates of 0.07 (L), 0.20 (M) and 0.59 g N kg^{-1} dry soil (H), respectively. Top dressing at the same rate as that of the basal dressing was added in the L and M treatments at 50 days after transplanting. Vertical bars represent SE (L and M: n = 3, H: n = 4). NS: Not significantly different at $p<0.05$ of Fisher's LSD.

not significantly different between fertilizers, while the yield of the H treatment of LSR was 159% of that in the H treatment of CDU. These results suggest that LSR remained effective as a fertilizer even when it was applied at an excessive level. However, the sugar content tended to decrease as the yield increased. The effect was more pronounced with heavy application of the fertilizer: the sugar content decreased from 5.2% ± 0.2% with CDU to 4.8% ± 0.1% with LSR. Several workers have reported similar results[1,3]. Our results also suggest that the roots experienced a higher water stress with CDU than with LSR.

Fig. 9 supports this assumption, because the sap bleeding rate (an index of root activity[7]) showed the same pattern as that of the increase in yield and decrease in the sugar content.

These results indicate that, in spite of the application of a high dose, LSR reduced the stress in the rhizosphere and led to a higher yield than CDU application, although the sugar content was lower. High yield was incompatible with a high sugar content in this experiment.

Conclusions

LSR (low-sulfate slow-release fertilizer) was developed to prevent the accumulation of residual sulfate. In the short-term experiment, LSR increased the root growth compared with an ordinary slow-release fertilizer, CDU. Because excessive elution was restricted in LSR, osmotic and ion imbalance stresses imposed on the root system were mitigated.

In the long-term experiment, excessive fertilization with LSR enhanced root development in the fertilized soil compared with CDU. This difference in root growth accounted for the increase in fruit yield with LSR to a value 159% of that with CDU. The sap bleeding rate (an index of root activity) showed the same pattern as that of the increase in yield and decrease in the sugar content. These results suggest that the stress on plant roots associated with LSR fertilization was mitigated, compared with the application of CDU.

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