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Original Paper

Effects of Stem Constriction by Washer Ring Treatment on the Growth and Fruit Quality of Tomato

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Abstract

In order to develop a simple and novel technique to improve the soluble solids content of tomato, we cultivated 'ANIMO TY-12 F_1' and 'Momotaro Fight' with the washer ring treatment, and investigated the effect of washer ring treatment on the increase of soluble solids content of tomato fruit. In the washer ring-treated section, 6 mm inner diameter washer ring was passed through the plant at the time of emergence. The treated groups consisted of a 1-ring plot using one washer per plant and a 5-ring plot using five stacked washers per plant in 'ANIMO TY-12 F_1', and 1-ring and 5-ring plots and an additional 10-ring plot using ten stacked washers per plant in 'Momotaro Fight'. Root fresh weight at the end of cultivation showed that the 5-ring plot of 'ANIMO TY-12 F_1' was 52% of that of the control, the 5-ring and 10-ring plots of 'Momotaro Fight' were 32% and 38% of those of the control, respectively. As for marketable fruits, the fruit weight tended to be smaller in treated plots. However, with the exception of first or second truss of 'ANIMO TY-12 F_1' and 1-ring plot of 'Momotaro Fight', in all other trusses, the soluble solids content of fruit increased significantly in all other treated plots. Also, the washer ring treatment did not cause a delay in days to harvest or significant disorder fruits in this experiment. The above results confirm that the washer ring treatment increased the soluble solids content of tomato fruit. Future practical application of the washer ring treatment requires testing under conditions similar to those in production sites, such as planting in fields.

Key Words : root growth, stem diameter, *Solanum lycopersicum*, soluble solids content of fruit

Introduction

One of the principal characteristics of a good quality tomato fruit is a high soluble solids content. Common techniques for producing tomato fruit with a high soluble solids content include deficit irrigation (Johnstone et al., 2005; Nuruddin et al., 2003; Rudich et al., 1977), root restriction (Kawakami and Matsumaru, 2004), and salinity stress (Johkan et al., 2014; Saito et al., 2009; Sakamoto et al., 1999). These techniques aim to restrict water absorption by roots, but also require special equipment, material, and skills, i. e. hydroponic equipment, irrigation control device, irrigation management technology, etc., that are not affordable, simple or easy for farmers to adopt. Takahata and Miura (2014) developed a "wire coil treatment" as a simple cultivation technique to increased soluble solids content of tomato fruit by coiling wire around the lower part of tomato plant stems. The marked reduction in the amount of root tissue in the wire coil-treated plants restricted water absorption by the roots and moisture supply to their fruits, resulting in fruit with an increased soluble solids content. Takahata (2017) subsequently developed the "washer ring treatment" that is cultivated pepino with the stem of the cutting inserted through a washer hole, expecting an effect similar to what was observed with the wire coil treatment, and reported an increased soluble solids content of pepino fruit. Since the washer ring treatment is as simple as the wire coil treatment, it may be a suitable technique for growing tomato fruit with a high soluble solids content if the method can be applied to tomato cultivation. Thus, with the aim of developing a simple and novel technique to improve the soluble solids content of tomato, we cultivated two tomato cultivars using the washer ring treatment to examine whether there was an effect on the soluble solids content of the fruit.

Materials and Methods

Plant culture

'ANIMO TY-12 F_1' (Musashino Seed Co., Ltd.) and

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'Momotaro Fight' (Takii & Co., Ltd.) were the cultivars used in the experiments. The cultivation period was from February 10, 2015 to July 27, 2015 in 'ANIMO TY-12 F_1', and from December 20, 2015 to June 14, 2016 in 'Momotaro Fight'. Plants were cultivated in a glass greenhouse that was ventilated when the temperature inside the greenhouse rose above 25°C and heated when the temperature fell below 14°C. A single tomato seed was sown in each 7.5 cm diameter plastic pot filled with Nippi-Engei-Baido-1gou ($N : P_2O_5 : K_2O$ = 200 : 2500 : 200 $mg \cdot L^{-1}$, Nihon Hiryo Co., Ltd., hereafter referred to as the soil mixture). The plants were repotted in 10.5 cm diameter plastic pots at the 6-leaf stage (March 22, 2015 in 'ANIMO TY-12 F_1' and February 11, 2016 in 'Momotaro Fight'). Subsequently, each of the plants was transplanted (final repotting) to one plant per pot in larger plastic pots (upper diameter: 40 cm, base diameter: 34 cm, height: 30 cm) containing 27 L of the soil mixture on the first day of treatment, which was approximately the day of flowering of the first flower on the first inflorescence (April 8, 2015 in 'ANIMO TY-12 F_1' and February 28, 2016 in 'Momotaro Fight'). The plants were supported by strings hanging down from the ceiling for single-stem training, and pinched (June 12, 2015 in 'ANIMO TY-12 F_1' and April 30, 2016 in 'Momotaro Fight') immediately below the ninth inflorescence and the eighth inflorescence in 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively. A solution of 4-chlorophenoxyacetic acid (4-CPA, 15ppm) was sprayed on the inflorescences to induce fruit setting, up to the eighth truss and the seventh truss in 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively, with each truss thinned to a maximum of four fruits. Once the largest fruit on the first truss reached a diameter of approximately 2 cm, each pot received 500 to 1,000 mL of a 500 to 1,000-fold dilution of liquid fertilizer (Hyponex, Hyponex Japan Corp. Ltd., $N : P_2O_5 : K_2O$ = 6% : 10% : 5%) every ten days, or otherwise irrigated as necessary every day.

Washer ring treatment

Immediately after emergence of cotyledons, a stainless-steel washer (inner diameter: 6 mm, outer diameter: 30 mm, thickness: 2 mm) was placed on the soil surface with the apical hook and the hypocotyl of each plant passing through the hole of the washer; experimental field plots containing these plants were designated as the treated groups. The treated groups consisted of a 1-ring plot using one washer per plant (treatment width: 0.2 cm) and a 5-ring plot using five stacked washers per plant (treatment width: 1.0 cm) in 'ANIMO TY-12 F_1'. The 1-ring and 5-ring plots and an additional 10-ring plot using ten stacked washers per plant (treatment width: 2.0 cm) were used in 'Momotaro Fight'. In the 5-ring and 10-ring plots, the washers were bound together using an adhesive. The day when the stem diameter reached the washer's inner diameter, i.e. when the washers in the 1-ring plot would no longer turn, was defined as the start day of treatment (0 day after treatment: 0 DAT) for the treated groups, on which day all plants were transplanted that is final repotting. Eight and six plants were planted per plot in 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively, with a total of 24 plants, including the control, arranged in two rows of the distance between adjacent pots was 50 cm and the distance between the rows was 80 cm in each cultivar. Plants in each plot were arranged such that the effects of positional variation were minimized for the purpose of treating one plant as one replicate in each plot in the statistical analysis. An extra pot was placed at both ends of each row, using a total of four extra pots in each cultivar.

Adjustment of water quantity

As the plants were the transplanted that is final repotting, a soil moisture sensor (EC-5, Decagon Devices) was inserted in the soil mixture in each pot to a depth of 15 to 20 cm and at approximately 6 cm away from the plant stems. The soil moisture values displayed on a handheld reader (ProCheck, Decagon Devices), which is nominal volumetric water content percentage, were recorded three times (1000, 1200, 1500 HR) daily. After measurement, using 19% moisture as the target value after watering, the amount of water equivalent to the difference between the mean of the plot and 19% was supplied. Plants were watered over the soil surface using a watering can.

In order to investigate the relationship between the soil moisture content (%) and soil moisture retention (pF) values of the soil mixture, a pot similar to the one used for the transplants was filled with the soil mixture without any plants. A soil moisture sensor and a pF meter (DIK-8333, Daiki Rika Kogyo Co., Ltd.) were inserted into the pot, followed by sufficient irrigation. Without further irrigation, multiple measurements were recorded from the soil moisture sensor and the pF meter over a few days (Fig. 1).

Evaluation of plant growth

The diameter of plant stems immediately above the washer ring(s) and at a corresponding position in the control were measured every ten days from the day of transplanting (0 DAT) until 100 DAT. Stem lengths from the soil surface to the apex and the number of topmost unfolded 5 cm or more in size leaves were also measured every ten days until 60 DAT, which was an approximately the day of pinching,

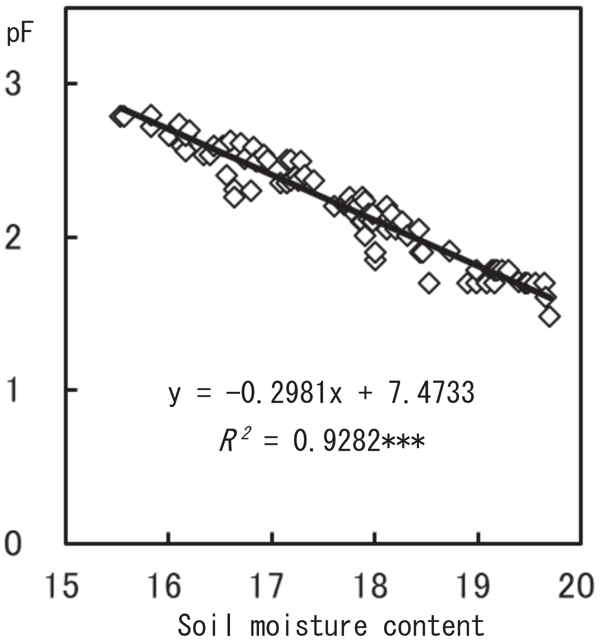

Fig. 1 Correlation between soil moisture content (%) and pF (n = 83).
R^2: coefficient of determination.
***: significant differences at $P < 0.001$

in both cultivars.

At the completion of the experiment (110 and 107 DAT in 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively), the stem diameter was measured at 20, 100, and 180 cm from the soil surface, and shoot and root fresh weights were recorded. Shoot was cut at the soil surface and the weight of shoot without trusses was measured. The root was separated from the mixed soil using of water, and the intact and broken roots from each plant were combined and measured after removing the water with a cloth. The T-R ratio was calculated as the product of the top fresh weight / root fresh weight. For each of the first to fifth inflorescences, the number of leaves below the inflorescence, the number of flowers, and the fruit set ratio were determined. The fruit set ratio was calculated from the number of fruits set on the first to fifth flowers at the time of fruit thinning, which was 2 to 3 weeks after 4-CPA spraying. Two plants in the 5-ring plot in 'ANIMO TY-12 F_1' and one plant in the 5-ring plot in 'Momotaro Fight' broke at the position where the rings were placed just before the end of the experiment. No end of experiment measurements were recorded for these plants.

Evaluation of harvested fruit

For both cultivars, fruits were harvested at fully red stage. Marketable fruits, excluding those that had damage such as blossom-end rot or cracks, were used in the analysis. After removing the calyx, the weight and the height / diameter ratio were measured. The plunger tip which is a cylinder with a 5 mm diameter of a hardness meter (KM-5, Fujiwara Scientific Company Co., Ltd.) was pushed against the fruit skin on the equatorial plane, and the value observed when the plunger broke through the skin was recorded as the fruit firmness. The fruit was then divided longitudinally into four sections, two opposite fruit sections were wrapped in a double layer of gauze, and the fruit was squeezed to release the juice. The soluble solids content of fruit juice was measured using a digital refractometer (PR-101α, Atago Co., Ltd.).

Data analysis and statistics

For evaluation of plant growth during cultivation, the 5% *t*-test was used to examine differences in the mean stem diameter immediately above the washer ring(s) among the control and treated plots, and the 5% Tukey's test was used to examine differences in the means of stem length and the number of topmost unfolded leaves among the plots. To evaluate inflorescences, plant growth at the end of the experiment, and the harvested fruit, the 5% Tukey's test was used to examine differences in the means among the plots. For the fruit set ratio, an angular transformation was calculated.

Results

Moisture content of the mixed soil after transplanting

Each pot was irrigated at 1000, 1200 and 1500 HR when the mixed soil moisture content was below 19%, such that the moisture returned to this level. From 20 DAT, which is the day of the stem diameter immediately above the ring(s) started to enlarge, to the end of the experiment, the mean soil moisture content before irrigation was 17.9, 18.1, and 18.0% in the control, 1-ring, and 5-ring plots, respectively, in 'ANIMO TY-12 F_1', and 17.8, 17.9, 18.2, and 18.1% in the control, 1-ring, 5-ring, and 10-ring plots, respectively, in 'Momotaro Fight'. A significant negative correlation (Fig. 1) was observed between the soil moisture content and pF as expressed by the equation $y = -0.2981x + 7.4733$ ($R^2 = 0.9282$***). Using this regression equation, the pF values corresponding to soil moisture contents of 19.0, 18.2, 18.1, 18.0, 17.9, and 17.8% were calculated to be 1.81, 2.05, 2.08, 2.11, 2.14, and 2.17, respectively.

Plant growth

In 'ANIMO TY-12 F_1', stem diameters immediately above the washer ring(s) (Fig. 2 1-A, B) were significantly larger than the corresponding stem parts in the control plants from 10 DAT onwards. The average diameters in the 1-ring and 5-ring plots reached 144% and 189%, respectively, of the corresponding diameters of the control plants at 100

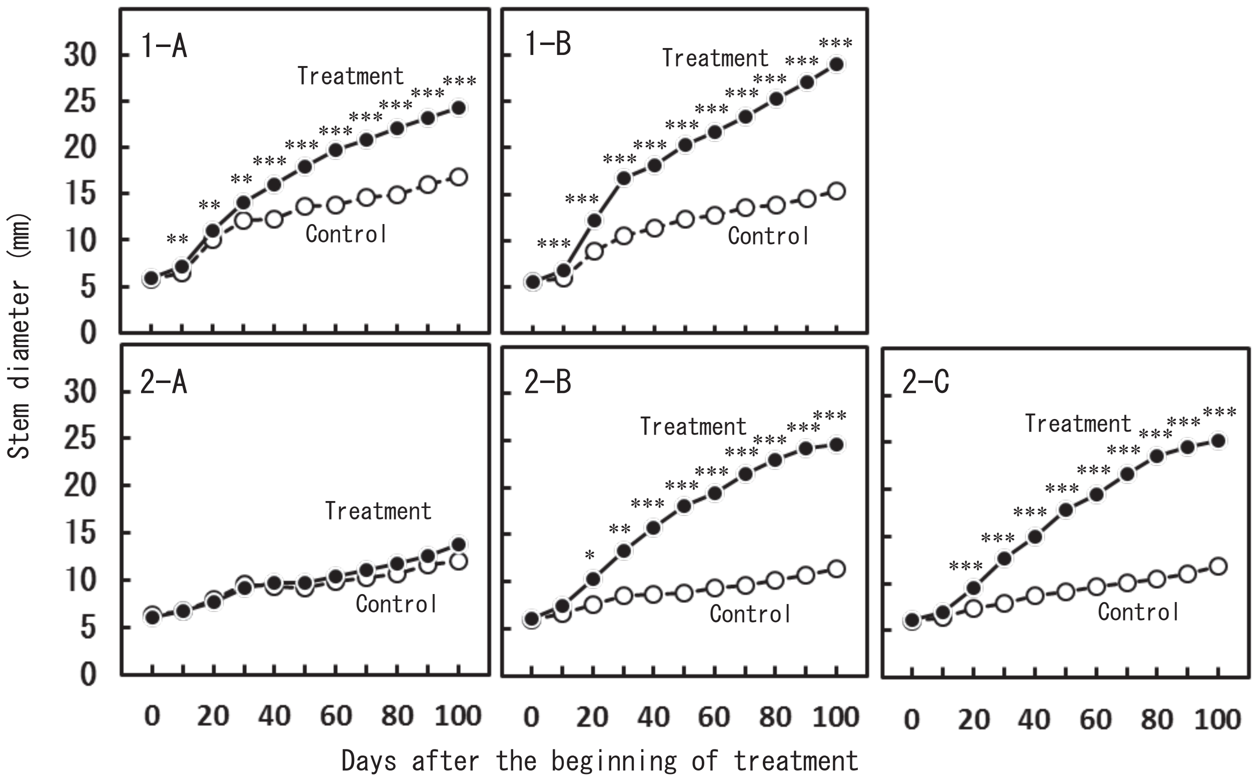

Fig. 2 Effects of the washer ring treatment on tomato stem thickening immediately above the washer ring in 'ANIMO TY-12 F_1' and 'Momotaro Fight' (n = 8 and 6 for 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively).
1: 'ANIMO TY-12 F_1', 2: 'Momotaro Fight'
A: 1-ring plot, B: 5-ring plot, C: 10-ring plot
*, ** and *** indicate significant differences by Student's *t*-test at $P < 0.05, 0.01, 0.001$, respectively.

DAT. Stem lengths (Fig. 3 A-1) were significantly shorter in the 5-ring plot at 50 DAT compared to the control, but there was no difference in the number of topmost unfolded leaves (Fig. 3 B-1) between the control and treated plots.

In 'Momotaro Fight', there was no difference in the stem diameter immediately above the washer ring(s) in the 1-ring plot (Fig. 2 2-A) compared to the control, but the stem diameter was markedly enlarged in the 5-ring (Fig. 2 2-B) and 10-ring (Fig. 2 2-C) plots at 20 DAT onwards compared to the control, with the diameters reaching 215% and 212%, respectively, of the corresponding diameter in the control at 100 DAT. In terms of stem lengths (Fig. 3 A-2) and the number of topmost unfolded leaves (Fig. 3 B-2), there were no differences between the control and treated plots.

Stem diameter above the ring(s) and shoot and root weights at the end of the experiment

Table 1 summarizes the measurements of plant growth at the end of the experiments. Stem enlargement just above the treatment was obvious ('Momotaro Fight', Fig. 4), but in both cultivars, there was no difference in the stem diameter above the ring(s) between the control and treated plots. In 'ANIMO TY-12 F_1', the shoot and root fresh weights in the 5-ring plot were 80% and 52% of the corresponding weights of the control, respectively. In 'Momotaro Fight', the shoot fresh weight in the 5-ring plot was 72% of that of the control, and the root fresh weights in the 5-ring and 10-ring plots were 32% and 38% of those of the control, respectively. The lower panels of Fig. 4 document the markedly reduced root mass produced in the 5-ring and 10-ring plots in 'Momotaro Fight'. In terms of the T-R ratio, the 5-ring plot was 176% of that of the control in 'ANIMO TY-12 F_1', and the 5-ring and 10-ring plots were 306% and 300% of those of the control in 'Momotaro Fight', respectively.

The number of leaves immediately below the inflorescence, the number of flowers, and the fruit set ratio for each inflorescence

In both cultivars, there were no statistically significant differences in the number of leaves immediately below the inflorescence, the number of flowers, or the fruit set ratio for each inflorescence (Table 2) between the control and treated plots.

Table 1 Effects of washer ring treatment on tomato stem diameter, shoot fresh weight and root fresh weight at the end of the experiments (n = 5~8).

Plot	Stem diameters at the soil surface (mm)			Shoot fresh weight[z] (g)	Root fresh weight (g)	T-R ratio[y]
	Above 20 cm	Above 100 cm	Above 180 cm			
‘ANIMO TY-12 F_1’						
Control	13.0	14.9	9.4	1189 a[x]	524 a	2.5 b
1-ring	15.3	15.2	9.4	1245 a	376 ab	3.4 ab
5-ring	16.7	14.2	10.1	957 b	273 b	4.4 a
‘Momotaro Fight’						
Control	11.8	16.0	11.9	994 a	300 a	3.3 b
1-ring	11.2	15.6	13.0	1010 a	257 a	4.0 b
5-ring	11.5	16.2	10.8	715 b	95 b	10.1 a
10-ring	11.4	15.8	11.4	929 ab	115 b	9.9 a

[z] Stem and leaf (all trusses removed).
[y] Shoot fresh weight / Root fresh weight.
[x] Different letters for each cultivar indicate significant differences by Tukey’s test (5%).
There is no significant difference where there is no letter.

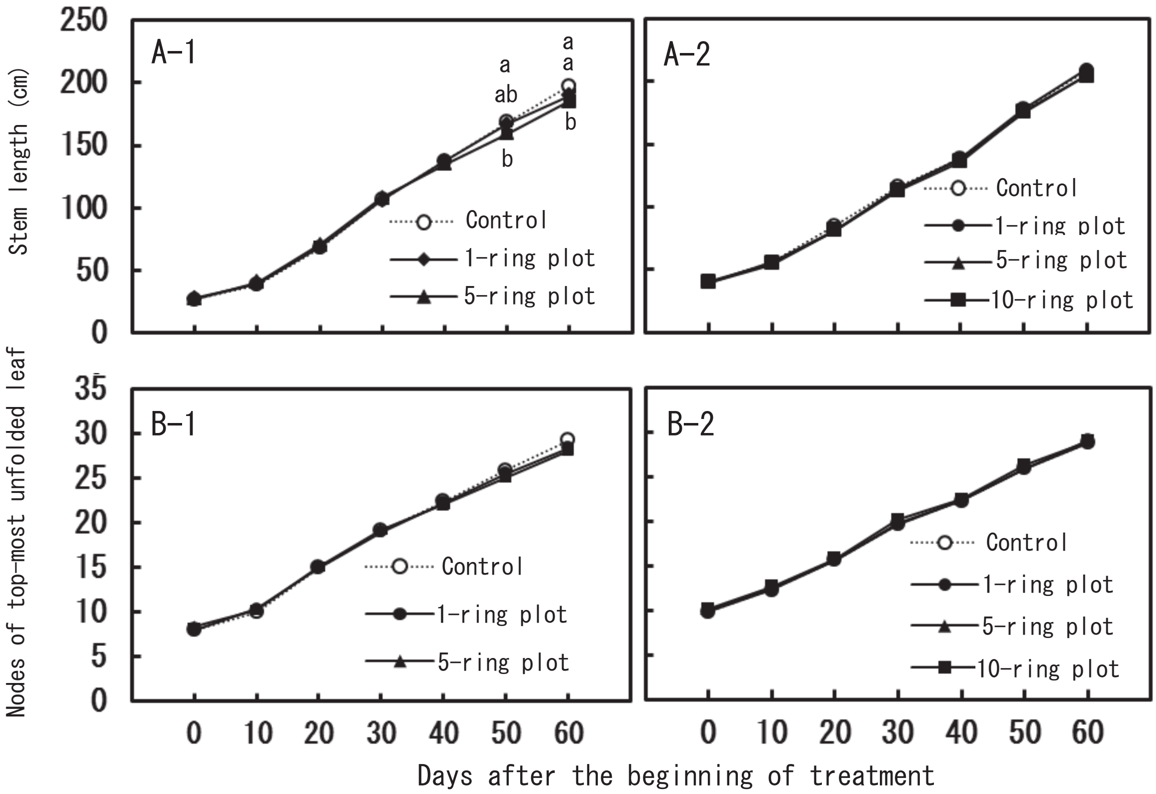

Fig. 3 Effects of the washer ring treatment on tomato stem elongation (A) and leaf unfolding (B) in ‘ANIMO TY-12 F_1’(-1) and ‘Momotaro Fight’ (-2)
(n = 8 and 6 for ‘ANIMO TY-12 F_1’ and ‘Momotaro Fight’, respectively).
Different letters indicate a significant difference by Tukey’s test at $P < 0.05$.

Days to harvest, number, and weight of fruits

There was no difference in the number of days to harvest marketable fruits from the first to fifth trusses (Table 3) between the control and treated plots in either cultivar. A difference in the total number of harvested fruits was observed only in the fifth truss in ‘ANIMO TY-12 F_1’, where the number in the 5-ring plot was 79% of that of the control and 1-ring plot. In terms of the number of harvested marketable fruits, there was a difference only in the second truss in ‘ANIMO TY-12 F_1’, where the number in the 5-ring plot was 67 to 68% of that of the control and 1-ring plot. There was no significant difference in the average weight

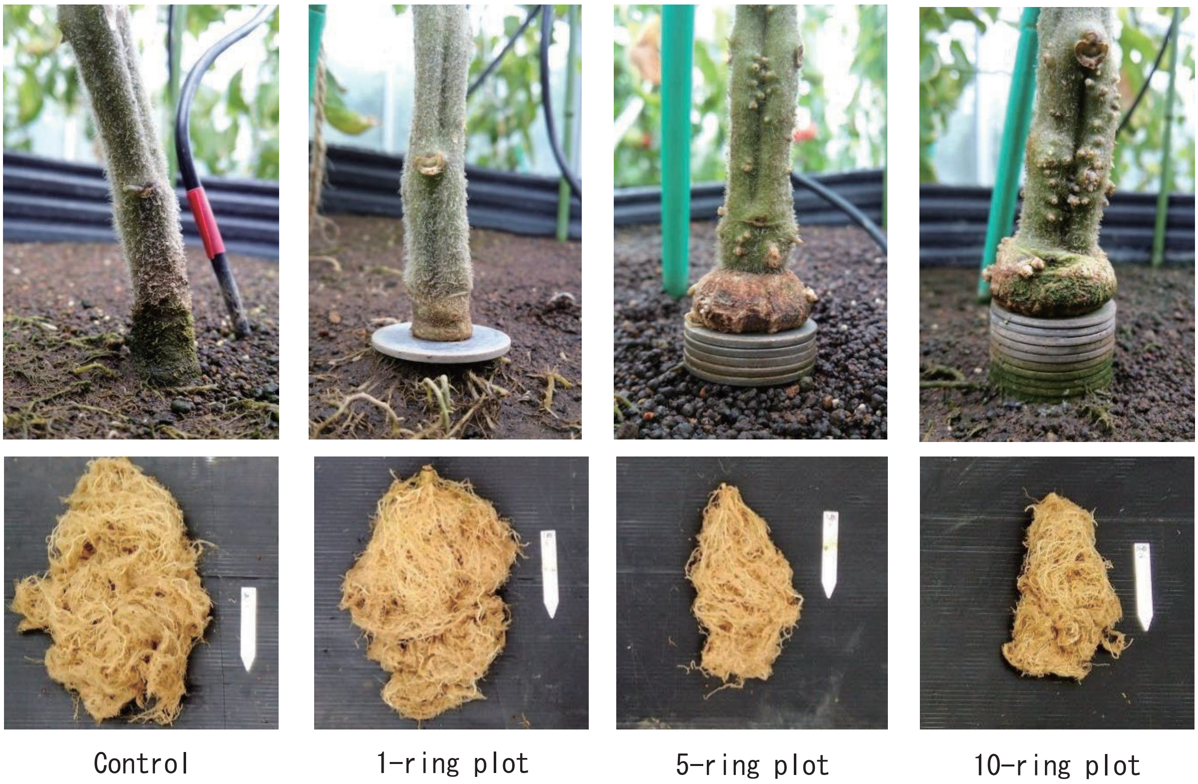

Fig. 4 Appearance of stems immediately above the washer ring(s) and roots of 'Momotaro Fight' at the end of cultivation. All labels in the image are the same size (9 cm).

of fruit among the test plots except for the third truss in the 5-ring plot and the fifth truss in the 1-ring plot in 'ANIMO TY-12 F_1', in which the weights were 83% and 69% of that of the control, respectively, and for the second truss in the 10-ring plot in 'Momotaro Fight', in which the average weight of fruit was 73% of those in the control and 5-ring plot. The yield was reduced in the second and third trusses in the 5-ring plot, and in the fifth truss in the 1-ring and 5-ring plots (59, 58, 67, and 57% of control, respectively) compared to the control in 'ANIMO TY-12 F_1', and in the second truss in the 10-ring plot compared to the control and 5-ring plot (73 to 76%) in 'Momotaro Fight'.

Evaluation of fruit quality

In terms of the quality of the harvested marketable fruits from the first to fifth trusses (Table 4), there was a difference in the fruit shape (height / diameter ratio) only in the fifth truss in 'ANIMO TY-12 F_1', where the ratio was smaller in the control compared to the 1-ring plot. There was no difference in skin firmness among the test plots in all trusses in both cultivars. In terms of the soluble solids content in 'ANIMO TY-12 F_1', the first truss in the 5-ring plot was 109% of that of the control, but there was no significant difference in the second truss. However, the soluble solids content was higher in both the 1-ring and 5-ring plots compared to the control from the third truss upward, where the content was 106% of that of the control in the third truss, 109 to 115% in the fourth truss, and 105 to 109% in the fifth truss. In terms of the soluble solids content in 'Momotaro Fight', there were differences between the control and the 5-ring and 10-ring plots in all trusses. When we compared the soluble solids content in the 5-ring and 10-ring plots with that of the control, the ratio was 107 to 113% in the first truss, 112% in the second truss, 109 to 110% in the third truss, 110 to 113% in the fourth truss, and 114% in the fifth truss. There was no difference in the soluble solids content between the 5-ring and the 10-ring plots.

Discussion

As a preliminary experiment, we grew the two cultivars used in this study in 30 cm diameter pots for single-stem training and observed their growth after treating the seedlings with washers with inner diameters of 4, 5, 6, 8, or 10 mm. As a result, in the treatment with a 4 or 5 mm inner diameter washer, both cultivars broke or died during cultivation. The plants treated with washers with inner diameters of 6 mm or greater were followed up to approximately 120 days after seeding in 'ANIMO TY-12 F_1' and 'Momotaro Fight', but no plants died and both cultivars showed good growth. Among the washer with an inner diameter of 6 to 10 mm, the washer

Table 2 Effects of washer ring treatment on tomato inflorescences (n = 8 and 6 for 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively).

Plot	'ANIMO TY-12 F_1'			'Momotaro Fight'		
	Leaf number[z]	Number of flowers	Fruit set ratio (%)[y]	Leaf number	Number of flowers	Fruit set ratio (%)
			First inflorescence			
Control	7.4	6.4	96	6.3	6.7	93
1-ring	7.4	7.1	91	7.0	5.7	90
5-ring	7.5	6.9	93	6.5	6.3	87
10-ring	-	-	-	6.5	7.7	97
			Second inflorescence			
Control	10.6	7.0	91	9.7	6.5	93
1-ring	10.4	7.0	90	10.2	7.7	97
5-ring	10.8	7.0	86	10.2	6.8	97
10-ring	-	-	-	10.7	6.8	100
			Third inflorescence			
Control	13.5	6.6	79	12.7	6.2	100
1-ring	13.4	6.5	86	13.2	7.3	97
5-ring	13.6	6.4	88	13.2	5.5	100
10-ring	-	-	-	13.7	5.3	100
			Fourth inflorescence			
Control	16.5	5.5	82	15.7	6.0	100
1-ring	16.3	7.1	77	16.2	6.7	93
5-ring	16.6	5.8	81	16.2	5.8	97
10-ring	-	-	-	16.8	6.0	100
			Fifth inflorescence			
Control	19.5	6.3	65	18.7	6.8	73
1-ring	19.3	5.5	76	19.2	7.3	73
5-ring	19.6	5.5	67	19.0	6.8	83
10-ring	-	-	-	19.5	7.0	93

[z] Leaves just below the inflorescence.
[y] Calculated with the first to fifth flowers of each inflorescence: fruit set ratio (%) = number of fruits / 5 × 100.

Table 3 Effects of washer ring treatment on days to harvest, number, and weight of tomato fruit (n = 8 and 6 for 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively).

Plot	'ANIMO TY-12 F_1'					'Momotaro Fight'				
	Time[z] (d)	Total fruit (no. /plant)	Marketable fruit (no. /plant)	Weight (g/fruit)	Total weight[y] (g/plant)	Time (d)	Total fruit (no. /plant)	Marketable fruit (no. /plant)	Weight (g/fruit)	Total weight (g/plant)
					First truss					
Control	114	4.0	3.8	181	677	134	4.0	4.0	148	594
1-ring	114	4.0	4.0	176	705	132	4.0	4.0	139	556
5-ring	114	4.0	3.8	165	616	132	3.7	3.7	141	522
10-ring	-	-	-	-	-	133	4.0	4.0	147	589
					Second truss					
Control	126	4.0	3.9 a[x]	187	723 a	147	4.0	4.0	200 a	798 a
1-ring	125	4.0	3.8 a	164	617 ab	146	4.0	4.0	171 ab	684 ab
5-ring	126	4.0	2.6 b	166	430 b	146	4.0	3.8	201 a	770 a
10-ring	-	-	-	-	-	148	4.0	4.0	146 b	585 b
					Third truss					
Control	136	3.9	2.8	214 a	583 a	158	4.0	3.5	177	632
1-ring	136	4.0	2.8	185 ab	518 ab	157	3.8	3.7	212	771
5-ring	136	3.9	1.9	178 b	339 b	156	4.0	3.2	177	585
10-ring	-	-	-	-	-	158	3.8	3.5	168	591
					Fourth truss					
Control	147	3.9	2.3	221	452	164	3.3	2.5	191	466
1-ring	146	3.9	2.0	173	347	163	4.0	3.7	150	546
5-ring	146	3.8	2.0	194	388	157	3.5	2.3	141	333
10-ring	-	-	-	-	-	160	3.7	3.2	135	444
					Fifth truss					
Control	150	3.8 a	3.4	215 a	715 a	169	2.7	1.5	176	255
1-ring	150	3.8 a	3.3	148 b	477 b	169	3.2	2.5	162	396
5-ring	150	3.0 b	2.3	178 ab	407 b	166	3.7	2.3	132	299
10-ring	-	-	-	-	-	166	3.5	3.0	151	455

[z] Days from seeding to harvest.
[y] Marketable fruit.
[x] Different letters for each truss indicate significant differences by Tukey's test (5%).
There is no significant difference where there is no letter.

Table 4 Effects of washer ring treatment on tomato fruit quality (n = 8 and 6 for 'ANIMO TY-12 F_1' and 'Momotaro Fight', respectively).

Plot	'ANIMO TY-12 F_1'			'Momotaro Fight'		
	Shape (height/diameter)	Firmness (kg)	Soluble solids content (°Brix)	Shape (height/diameter)	Firmness (kg)	Soluble solids content (°Brix)
			First truss			
Control	0.80	1.90	5.4 b[z]	0.81	1.74	5.4 c
1-ring	0.82	1.99	5.6 ab	0.79	1.52	5.5 bc
5-ring	0.81	1.89	5.9 a	0.82	1.66	5.8 ab
10-ring	-	-	-	0.83	1.70	6.1 a
			Second truss			
Control	0.84	2.06	5.5	0.82	2.09	6.0 b
1-ring	0.85	2.10	5.7	0.82	2.02	6.0 b
5-ring	0.86	1.96	5.8	0.83	2.05	6.7 a
10-ring	-	-	-	0.85	2.32	6.7 a
			Third truss			
Control	0.88	1.70	5.4 b	0.84	2.09	6.7 b
1-ring	0.90	1.93	5.7 a	0.81	2.15	6.9 b
5-ring	0.87	1.91	5.7 a	0.82	1.98	7.4 a
10-ring	-	-	-	0.82	2.17	7.3 a
			Fourth truss			
Control	0.86	1.79	5.3 b	0.84	2.29	6.7 b
1-ring	0.88	2.02	5.8 a	0.83	2.15	6.6 b
5-ring	0.87	1.94	6.1 a	0.84	2.15	7.6 a
10-ring	-	-	-	0.83	2.33	7.4 a
			Fifth truss			
Control	0.84 b	1.79	5.5 b	0.77	2.49	6.5 b
1-ring	0.89 a	1.88	5.8 a	0.79	2.43	6.8 b
5-ring	0.87 ab	1.90	6.0 a	0.80	2.59	7.4 a
10-ring	-	-	-	0.83	2.44	7.4 a

[z] Different letters for each truss indicate significant differences by Tukey's test (5%).
There is no significant difference where there is no letter.

that starts applying stress to the seedling earliest is the 6 mm inner diameter washer. If the treatment is started earlier, it is thought that the treatment effect can be expected from the lower fruit trusses. Therefore, it is suggested that a treatment with a 6 mm inner diameter washer would put plants under significant stress while still enabling the production of harvestable fruit. Thus, we used 6 mm inner diameter washers for the washer ring treatments in the present study.

Moisture content of the mixed soil before irrigation was higher in the treated group than in the untreated group. This means that in the treated group, water was present in the mixed soil at the same level as in the untreated group, but the amount of water absorption from there was less than in the untreated group.

In terms of plant growth, enlargement of the stem diameter immediately above the washer ring(s) was observed. Mason and Maskell (1928) girdled cotton plant stems and found in swelling immediately above the treatment and that the cause was due to the accumulation of translocation material at above the treatment. In tomato, stem enlargement has also been observed immediately above plants treated with a wire coiled around the stem base (Takahata and Miura, 2014). The authors discussed that this enlargement may be the result of inhibited translocation of sieve tube sap to plant tissues below the washer ring, leading to the accumulation of carbohydrates and phytohormones immediately above the ring, and resulting in an enhanced growth of callus and activation of cambium cell division compared to the corresponding stem part in untreated plants. Also, similar results have been observed in washer ring-treated pepino plants (Takahata, 2017). In the present study, the stem diameter immediately above the washer ring(s) was conspicuously enlarged except for the 1-ring plot in 'Momotaro Fight' (Fig. 2 and 4), likely due to similar causes. Sitton (1949), Noel (1970), and Richardson (1975) have reported that when the trunk or branches of a woody plant undergoes girdling, the removal of a strip of bark including phloem, the area above the girdle enlarges. Similar results have been reported in the girdling of grape vines (Yamane et al., 2008). In addition, in the stem diameter immediately above the washer ring in the 1-ring plot, 'ANIMO TY-12 F_1' was enlarged, but 'Momotaro Fight' was not enlarged. The reason may be that the treatment with only one washer ring in 'Momotaro Fight' did not inhibit the translocation of sieve tube sap to plant tissues below the treatment part. From the data for the control in Fig. 2, the stem diameter corresponding to the immediately above the washer ring is clearly thinner for ‘Momotaro Fight’ than for ‘ANIMO TY-12 F_1’. The difference between the cultivars may be due to differences in stem cell size and cell division speed near the treatment. Since the stem diameter near the soil surface of ‘Momotaro Fight’ is thin, it seems that treatment with only one washer ring was ineffective. However, in the 5-ring and 10-ring plots of ‘Momotaro Fight’, the stem diameter just above the treatment was enlarged. This is probably because the use of several washers widened the range of treatment and limited the enlargement of a wider range of stems. Stem elongation and leafing were inhibited in washer ring-treated pepino plants (Takahata, 2017) and wire coil-treated tomato plants compared to untreated plants (Takahata and Miura, 2014); washer ring-treated pepino plants had thinner stems compared to untreated plants at the end of experiment. However, the results of the present study did not show similar trends. Observation of the growing plants also failed to confirm any apparent inhibition of shoot growth as a result of the treatment. However, the shoot fresh weight at the end of the experiment was smaller in the 5-ring plot compared to the control in both ‘ANIMO TY-12 F_1’ and ‘Momotaro Fight’. Similarly, the root fresh weight was markedly smaller in the 5-ring and 10-ring plots compared to the control in both ‘ANIMO TY-12 F_1’ and ‘Momotaro Fight’ (Table 1). Girdling of a woody plant has also been reported to decrease the amount of roots, the cause of which is proposed to be the inhibition of photosynthate translocation from shoot to root tissues (Inoue et al., 1991; Yamamoto et al., 1992; Yamane and Shibayama, 2006). This proposal likely explains the notable decrease in root volume observed in the 5-ring and 10-ring plots in the present study (Fig. 4). In addition, as can be seen in Fig. 4, there may be a correlation between the enlargement of the stem diameter just above the treatment and the decrease in root volume. That is, it is considered that whether or not the plant is stressed by the washer ring treatment can be determined by observing the stem immediately above the washer ring.

The T-R ratio was greater in the 5-ring and 10-ring plots compared to the control. This result is consistent with the report that the growth suppressing effects of the washer ring treatment were pronounced in the roots. Impeded photosynthate translocation to the roots by washer ring treatment was responsible for the suppression of root growth. The washer ring treatment was patented as a technique to reduce the root volume of plants (Patent No. 6197257).

Total fruit weight per truss was smaller in some treated plots compared to the control (Table 3). In general, the fruit yield per plant tended to be lower in the treated plot compared to the control. A reduction in yield is commonly seen in cultivated tomato fruit that have a high soluble solids content (Saito et al., 2009; Sakamoto et al., 1999). The fruit soluble solids content increased as a result of the washer ring treatment in both cultivars reported in this study. Particularly in ‘Momotaro Fight’, fruits from the lower trusses also had an increased soluble solids content in the 5-ring and 10-ring plots. As shown in Fig. 4, the amount of root mass was significantly lower in the 5-ring and 10-ring plots. Therefore, with reduced water absorption from the roots and an increase in the T-R ratio, the plant suffered from low moisture, likely resulting in an increase in the fruit soluble solids content. Therefore, it is considered that T-R ratio is increased, the fruit soluble solids content also increases. In addition, in the fourth and fifth fruit truss of ‘Momotaro Fight’, the number of marketable fruits in the control showed a decreasing tendency compared to the treated plot. However, we did not know about this factor.

In the wire coil treatment (Takahata and Miura, 2014), the stem diameter immediately above the coil was approximately 5 to 6 mm at the start of treatment, suggesting that the stem of the treated segment had an equivalent diameter. That is, since the inner diameter of the washer used in this study was 6 mm, the stem-constricting force was likely comparable between the wire coil treatment and the washer ring treatment used in this study. However, if we compare the mean soluble solids content of fruit between the no wire coil treatment and wire coil-treated plants, the soluble solids content in the treated plant was 116% of that in the untreated plant. A tomato cultivar from the same family used in the wire coil treatment was used in the present study (‘Momotaro Fight’), and the mean soluble solids content of fruit produced in the 5-ring and 10-ring plots was 111% of that of the control. Therefore, the degree of increase in soluble solids content of fruit was different between the wire coil treatment and the washer ring treatment. This finding may be attributed to differences in the position at which the treatment was applied, namely the stem segment between the cotyledon and the first leaf in the wire coil treatment and the hypocotyl in the washer ring treatment. However, since the washer ring treatment is simpler to set up, its ease of adoption is likely to be preferred even if the method is slightly less effective. In addition, the washer ring treatment had no disadvantageous effects on fruit production, such as an increase in the number of leaves immediately below each inflorescence, a decrease in the number of flowers, or a decrease in the fruit set ratio (Table 2). Further, within the range of this experiment, the washer ring treatment did not cause significant disorder fruits. The above results suggest that the washer ring treatment may be a simple and novel technique for cultivating tomato fruit with increased soluble solids content. However, to be marketed as a tomato with a high soluble solids content, a soluble solids content of 8° or higher may be required.

With regard to fruit soluble solids content, there was no difference between 1-ring and 5-ring plots in ‘ANIMO TY-12 F_1’, and it increased in 5-ring and 10-ring plots in ‘Momotaro Fight’, but there was no difference between them. In addition, some plants in the present study suffered stem breakage at the position where the washer rings were placed. The practical application of washer ring treatment to tomato culture will require further investigation, e.g., to identify the optimum inner diameter and width of treatment according to cultivars, conditions that further increase the soluble solids content of fruits, fruit yield per unit area, taste survey of harvested fruits, and cultivation management strategies to prevent the stem breakage at the treatment site in order to cultivate under conditions similar to those at production sites. Furthermore, it was considered necessary to elucidate the mechanism of the increase of soluble solids content of the fruits by the washer ring treatment. Therefore, in the future, morphological and physiological investigations will be promoted by observing the xylem and phloem of the stem area treated with the washer rings.

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References

Inoue, H., Y. Ikoma and I. Kataoka. 1991. Effects of ringing and temperature on flower bud differentiation of satsuma mandarin. J. Japan. Soc. Hort. Sci. 60: 275-284. (in Japanese with English abstract)

Johkan, M., A. Nagatsuka, A. Yoshitomi, T. Nakagawa, T. Maruo, S. Tsukagoshi, M. Hohjo, N. Lu, A. Nakaminami, K. Tsuchiya and Y. Shinohara. 2014. Effect of moderate salinity stress on the sugar concentration and fruit yield in single-truss, high-density tomato production system. J. Japan. Soc. Hort. Sci. 83: 229-234.

Johnstone, P. R., T. K. Hartz, M. LeStrange, J. J. Nunez and E. M. Miyao. 2005. Managing fruit soluble solids with late-season deficit irrigation in drip-irrigatied processing tomato production. HortScience. 40: 1857-1861.

Kawakami, T. and T. Matumaru. 2004. Sustainable cultivation of greenhouse fruit vegetables using root-zone restriction 1. Effects of amount of soil on yield in tomato culture under root-zone restriction by use of polyester sheets, and a method of fertilizer application in the cultivation that seated the sheets into the whole area of the greenhouse. Bull. Chiba Agric. Res. Cent. 3: 37-43. (in Japanese with English abstract)

Mason, T. G. and E. J. Maskell. 1928. Studies on the transport of carbohydrates in the cotton plant. I. A study of diurnal variation in the carbohydrates of leaf, bark, and wood, and of the effects of ringing. Ann. Bot. 57: 189–253.

Noel, A. R. A. 1970. The girdled tree. Bot. Rev. 36: 162-195.

Nuruddin, M. M., C. A. Madramootoo and G. T. Dodds. 2003. Effects of water stress at different growth stages on greenhouse tomato yield and quality. HortScience. 38: 1389-1393.

Richardson, M. 1975. Pathway of movement of organic assimilates, p.27-37. In: Translocation in plants, 2nd Ed. Edward Arnold, UK, London.

Rudich, J., D. Kalmar, C. Geizenberg and S. Harel. 1977. Low water tensions in defined growth stages of processing tomato plants and their effects on yield and quality. J. Hort. Sci. 52: 391-399.

Saito, T., N. Fukuda, C. Matsukura and S. Nishimura. 2009. Effects of salinity on distribution of photosynthates and carbohydrate metabolism in tomato grown using nutrient film technique. J. Japan. Soc. Hort. Sci. 78: 90-96.

Sakamoto, Y., S. Watanabe, T. Nakashima and K. Okano. 1999. Effects of salinity at two ripening stages on the fruit quality of single-truss tomato grown in hydroponics. J. Hort. Sci. Biotech. 74: 690-693.

Sitton, B. G. 1949. The effects of different methods of girdling bearing and defruited tung branches. Proc. Amer. Soc. Hort. Sci. 53: 119-124.

Takahata, K. and H. Miura. 2014. Increasing the sugar concentration in tomato fruit juice by coiling wire around plant stems. HortTechnology. 24: 76-80.

Takahata, K. 2017. Effects of stem constriction using steel washer rings on the soluble solids content of pepino (*Solanum muricatum* Ait.) fruit. Hort. J. 86: 470-478.

Yamamoto, K., K. Takahashi and K. Takata. 1992. Techniques of improving grape quality by girdling. Kinki Chugoku Agr. Res. 83: 38-42.

Yamane, T. and K. Shibayama. 2006. Effect of trunk girdling and crop load levels on fruit quality and root elongation in ‘Aki Queen’ grapevines. J. Japan. Soc. Hort. Sci. 75: 439-444.

Yamane, T., Y. Hamana and K. Shibayama. 2008. Effects of taping, branch age, position, and the extent of phloem removal of girdle on healing of the girdle and fruit characteristics in grape. Hort. Res. 7: 57-63. (in Japanese with English abstract)

リング処理がトマトの生育および果実品質に及ぼす影響

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摘　要

トマト果実の糖度を高めるための簡易で新しい栽培技術を開発することを目的として‘アニモ TY-12’および‘桃太郎ファイト’にリング処理を施して栽培し，リング処理がトマト果実の糖度上昇に及ぼす影響を調査した．リング処理区においては出芽時の植物体に内径 6mm のワッシャーをくぐらせた．‘アニモ TY-12’ではワッシャーを 1 枚用いた 1 枚区および 5 枚重ねた 5 枚区を設け，‘桃太郎ファイト’では 1 枚および 5 枚区に加えて 10 枚重ねた 10 枚区も設けた．栽培終了時の根新鮮重は，‘アニモ TY-12’において 5 枚区が無処理区の 52%となり，‘桃太郎ファイト’において 5 枚および 10 枚区はそれぞれ無処理区の 32 および 38%となった．正常果について見てみると，1 果重は処理区で小さくなる果房があったが，糖度は‘アニモ TY-12’の第 1，2 果房および‘桃太郎ファイト’の 1 枚区を除いて，その他の全果房の全処理区において有意に増加した．なお，本実験のリング処理によって，収穫日数の遅れや障害果の著しい発生は見られなかった．以上から，リング処理によってトマトの果実糖度が高まることが確認された．今後，トマト栽培でのリング処理を実用化するためには，さらに果実糖度が高まる条件の検討や地植え栽培などの生産現場に近い条件での調査が必要である．

キーワード：果実糖度，茎径，*Solanum lycopersicum*，根の生長

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