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短　報

Effects of Irrigation with High-Salt Hot Spring Water on Sugar Content in Pot Cultivation Tomatoes

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高塩泉の灌漑がポット栽培トマトの果実糖度に与える影響

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要　旨

本研究では，高塩泉である「亀山温泉 白鳥の湯」の温泉水を灌漑する栽培試験を実施し，トマトの果実品質，とくに糖度について，どのような影響があるかを調べた．栽培実験では，トマトをポット栽培し，灌漑水として高塩泉（ナトリウム―炭酸水素塩温泉）を施用した．栽培実験の結果，温泉水を高頻度に灌漑することによって，トマトの果実糖度が向上したことが明らかになった．この原因としては，温泉水に含まれるナトリウム塩類が土壌中に蓄積し，トマトに塩ストレスを与えたためと考えられる．温泉水灌漑の頻度による果実重量の違いには，統計的な有意差は認められなかった．これらの研究成果を活用することにより，温泉を活用した地域ブランド農作物の創出に貢献できる可能性がある．

キーワード：高塩泉，トマト，塩ストレス，果実糖度

Abstract

In this study, we investigated the effects of irrigation with hot spring water from “Kameyama Onsen Shiratori no Yu”, a high-salinity hot spring, on the quality of tomato fruits, with a particular focus on sugar content. Tomatoes were cultivated in pots and irrigated with either high-salinity hot spring water (NaCl・HCO_3 type) or tap water. Notably, frequent irrigation with hot spring water increased the sugar content of the tomatoes, likely due to the accumulation of Na salts in the soil and the resulting salt stress. Although the difference in fruit weight was not statistically significant, the results indicate that irrigation with hot spring water may enhance tomato sweetness. These findings could support the development

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of locally branded vegetables cultivated using hot spring water.

Key words : high-salt hot spring water, tomato, salt stress, sugar content

1. Introduction

In Japan, hot spring resources are used for bathing and drinking, heat utilization, power generation, and aesthetic purposes (Sasaki, 2013 ; Mori, 2013). Beyond their traditional use for bathing, exploring new applications of hot springs, such as in agriculture, may help revitalize hot spring regions.

To support the growth of these areas in Japan, it is essential to showcase unique food-related attractions that appeal to both locals and tourists. In addition to their health benefits, hot spring resources have potential applications in food production, which could further boost the tourism industry. Furthermore, there is growing public interest in regional branding as a strategy for revitalization (Suzuki and Kiminami, 2009). Integrating local hot springs with agriculture could enhance both regional branding and public awareness.

Improving the quality of agricultural products is also essential for increasing their value in the tourism sector. For instance, high-sugar "fruit tomatoes" sell at higher market prices than conventional varieties (Seto and Tanaka, 1998). Therefore, producing high-quality crops using hot springs may support both food tourism and the sustainable development of hot spring regions.

Several successful cases of vegetable cultivation using hot springs have been reported, including the "Shogawa-Onsen-Vegetables" initiative in Tonami City, Toyama Prefecture (Sugimori *et al.*, 2017, 2018, 2019). Ezaki *et al.* (2010) found that hydroponic cultivation of tomatoes using Yufuin hot spring water (Yufu City, Oita Prefecture) increased fruit mineral content, though it did not improve sugar content. Sugar content is an important factor in determining the quality of agricultural products, and it is well established that salt stress can enhance crop quality, including sugar levels. Several studies have examined the use of saline water in vegetable cultivation. For example, hydroponic experiments have been conducted using seawater (Harada *et al.*, 2006), deep seawater (Nishimura *et al.*, 2011), and salt application (Oka *et al.*, 2004). Additionally, pot and planter experiments have used diluted seawater (Tanaka and Mikubo, 2007), deep seawater (Kawai *et al.*, 2002), and saline water (Tanaka *et al.*, 2000 ; Ito and Hirozumi, 2017) for irrigation. These studies used high salinity solutions to impose salt stress on the crops, and the results indicated that salt stress increases the sugar content of tomatoes (Tanaka *et al.*, 2000 ; Kawai *et al.*, 2002 ; Oka *et al.*, 2004 ; Nishimura *et al.*, 2011 ; Ito and Hirozumi, 2017).

Based on these findings, we hypothesized that irrigation with high-salinity hot spring water could also improve fruit sugar content by increasing salt stress in crops. Therefore, we investigated the effects of irrigating tomatoes with high-salinity hot spring water on plant growth and sugar content through pot experiments. Overall, this study aims to offer insights into the development of high-quality tomato cultivation methods using hot spring water irrigation.

2. Methods

2.1 Hot spring water selection

"Kameyama Onsen Shiratori no Yu" (Kameyama City, Mie Prefecture) was selected for this study (Fig.1).

The physicochemical properties of the hot spring were as follows : the water temperature at the time of emergence was 39.3℃, the pH was 8.1, and the concentration of dissolved substances (excluding gaseous substances) was 2.02 g/kg. A chemical analysis was conducted on February 27, 2018, by the Mie Prefecture Health and Environment Research Institute (2018). Table 1 shows the chemical composition of the hot spring water. The major cation was Na^+ (690.5 mg/kg), while the major anions were Cl^- (734.8 mg/kg) and HCO_3^- (500.5 mg/kg). Thus, the hot spring is classified as NaCl・HCO_3 type. This hot spring is an intermittent power-pumped spring, and its

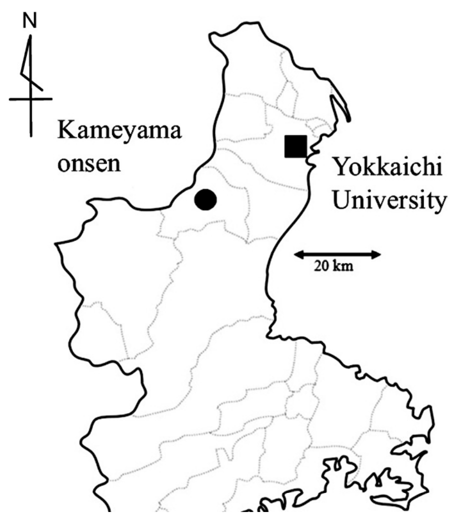

Fig. 1 Location of "Kameyama Onsen Shiratori no Yu" targeted in this study (●), and the cultivation experiment site at the Yokkaichi University greenhouse (■), in the northern part of Mie Prefecture.

Table 1 Chemical composition of the hot spring water used in this study (Mie Prefecture Health and Environment Research Institute, 2018).

Cation	mg/kg	Anion	mg/kg	Non-dissociation component	mg/kg
Na^+	690.5	F^-	1.1	H_2SiO_3	27.6
K^+	3.9	Cl^-	734.8	HBO_2	30.2
NH_4^+	0.7	Br^-	1.5		
Mg^{2+}	2.7	SO_4^{2-}	0.1		
Ca^{2+}	10.8	HPO_4^{2-}	0.2		
		HCO_3^-	500.5		
		CO_3^{2-}	18.0		

chemical composition and pH may vary slightly.

The hot spring is publicly owned by Kameyama City. Given the site's abundant hot spring water supply, it holds strong potential to support large-scale agricultural production using hot spring water in the future.

2. 2 Cultivation examination

A tomato growth experiment was conducted in an experimental greenhouse at Yokkaichi University in Yokkaichi City, Mie Prefecture (Fig. 1). Tomato seedlings were planted on April 18, 2017, and harvested 127 days later, on August 23, 2017. During the cultivation period, the minimum recorded air temperature was 16.8℃ (April 26), and the maximum was 52.3℃ (August 10). To allow maximum sunlight exposure, the greenhouse was not equipped with a shade net.

Photo 1 Tomato plant with fruits irrigated with hot spring water twice per week (June 26, 2017).

Tomatoes (*Lycopersicon esculentum* Mill. 'Home Momotaro') were cultivated in New Wagener Pots (model : NF-5 ; upper diameter: 174.6 mm, lower diameter : 160.4 mm, height : 197.5 mm). Each pot was filled with 1.40 kg of gardening soil mixed with a base fertilizer under natural moisture conditions. Photo 1 shows the tomato plants bearing fruit. Throughout the growth period, side branches were removed to promote the development of a single main stem. The top two nodes of the third flower cluster were retained, and pinching was performed on May 31, 2017. Fertilizer was applied at 27 days (May 15), 41 days (May 29), and 55 days (June 12) after planting, at a rate of 0.60 g per pot each time. The NPK fertilizer used contained 100 g/kg nitrogen (N), 80 g/kg phosphorus (P), and 80 g/kg potassium (K). Pruning and fertilizer applications were carried out uniformly across all test groups.

The number of fruits was limited to four per flower cluster, by removing flower buds beyond the fifth flower. Fruits exhibiting physiological disorders, such as blossom-end rot, were discarded.

2. 3 Irrigation method

The cultivation experiment was divided into four test groups, each following a different irrigation schedule using hot spring water and tap water. Irrigation was conducted three times per week (Monday, Wednesday, and Friday), with each group receiving a specific combination of irrigation days using either hot spring water or tap water. The irrigation protocols for each group are summarized in Table 2. Each treatment was replicated three times (n = 3).

After planting, all test groups were irrigated with tap water three times per week until fruit set was confirmed. Once fruit set was confirmed, the plants received either hot spring water or tap water at a rate of 500 mL per pot.

Table 2　Irrigation schedule for test groups. Open circles (○) indicate irrigation with tap water, while filled circles (●) indicate irrigation with hot spring water.

Test groups	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Tap water only (control)	○	—	○	—	○	—	—
Hot spring water irrigation							
1 day/week	○	—	○	—	●	—	—
2 days/week	●	—	○	—	●	—	—
3 days/week	●	—	●	—	●	—	—

2.4　Analysis and measurement

The pH and Na^+ concentrations of the hot spring water and tap water used for irrigation were measured. The pH was determined using a compact pH meter (ASONE AS-712), and the Na^+ concentration was measured using an atomic absorption spectrophotometer (AAS, SHIMADZU AA-6200).

In addition, soil pH and Na_2O accumulation during cultivation were analyzed. To measure soil pH, 25 mL of distilled water was added to 10 g of surface-layer soil collected from each pot. After shaking, the pH of the soil suspension was measured using the same compact pH meter (ASONE AS-712), following the method described by the Editorial Committee on Soil Environmental Analysis Methods (1997).

For Na_2O accumulation, soil samples collected after dismantling the pots were air-dried and passed through a 2.00 mm sieve. One gram of each soil sample was extracted with 100 mL of 1 mol/L ammonium acetate solution under constant shaking for 30 minutes. The extract was filtered through an 8 μm filter paper, and the Na^+ concentration of the filtrate was measured using AAS. Na_2O accumulation was then calculated based on the Na^+ concentration of the extract solution using Equation (1).

$$A_{\mathrm{Na_2O}} = \frac{C_{\mathrm{Na^+}} \times n(\mathrm{Na_2O/2Na}) \times V_e}{W_s} \quad \cdots (1)$$

$A_{\mathrm{Na_2O}}$: Na_2O accumulation per unit mass in dried soil sample (mg/kg)
$C_{\mathrm{Na^+}}$: Na^+ concentration in extract solution (mg/L)
$n(\mathrm{Na_2O/2Na})$: Molecular weight ratio of 2Na to Na_2O (1.348)
V_e : Volume of extract solution (0.1 L)
W_s : Weight of soil sample (0.001 kg)

2.5　Evaluation of fruit quality

After harvest, fruit sugar content was determined using a handheld refractometer (ATAGO N1), and fruit weight was measured using an electronic balance. A refractometer estimates the concentration of soluble solids in fruit juice by measuring its refractive index. Since sugars make up the majority of these solids, they can be used to estimate sugar content (Tateishi, 2013).

2.6　Data analysis

All data analyses were performed using R 4.0.2 for i386. Statistical comparisons between groups were conducted using Tukey's multiple comparison test, with statistical significance set at $p<0.05$.

3. Results and Discussion

3.1 Chemical characteristics of irrigation water

The hot spring and tap water had alkaline (pH 9.7) and neutral (pH 7.5) values, respectively. Additionally, the Na^+ concentration in hot spring water (841.8 mg/kg) was markedly higher than that in tap water (1.9 mg/kg).

3.2 Fruit quality

Table 3 and Fig. 2 show the fruit sugar content for each test group. It is known that the sugar in tomato fruits consists mainly of glucose and fructose (Kanahama, 2007). Significant differences were identified using Tukey's multiple comparison test ($p<0.05$), with different alphabetical letters in the same frame indicating statistical significance (Fig. 2). Compared to the control group, fruit sugar content increased significantly with the frequency of hot spring water irrigation. Specifically, sugar content followed this order : three times per week with hot spring water＞

Table 3　Comparison of harvested tomato fruits conditions and soil properties at the end of the experiment based on the frequency of hot spring water irrigation.

Frequency of hot spring water irrigation (day(s)/week)	Tomato fruits' conditions			Soil properties (n=3)	
	n	Sugar content (Brix%)	Fruit weight (g)	pH	Na_2O (mg/kg)
0	16	7.07	37.81	7.3	92
1	14	8.05	44.09	8.1	4,849
2	12	8.82	32.22	8.5	7,956
3	14	9.64	35.33	8.6	9,101

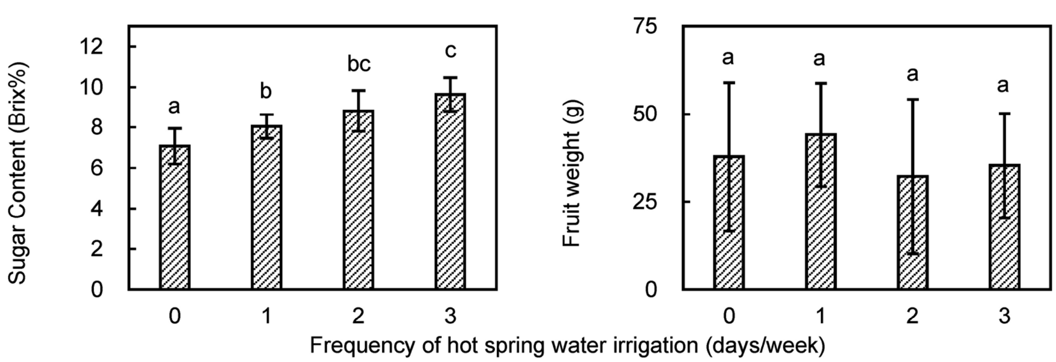

Fig. 2　Comparison of harvested tomato fruits conditions based on the frequency of hot spring water irrigation. Error bars indicate standard deviations. Significant differences were determined using Tukey's multiple comparison test ($p<0.05$) between different alphabetical letters (a, b, c) in the same frame.

twice per week > once per week > no hot spring water. Sugar content was significantly higher in all hot spring water irrigation groups than in the tap water-only group, and the increase was proportional to the frequency of hot spring water application.

Regarding fruit weight, no significant differences were observed among the groups. The fruit weights in the control group and the once-, twice-, and thrice-weekly hot spring water irrigation groups were 37.81 g, 44.09 g, 32.22 g, and 35.33 g, respectively.

3.3 Soil environmental conditions

Table 3 and Fig. 3 present the changes in soil pH and the amount of Na_2O accumulated in the soil for each test group. Significant differences were identified using Tukey's multiple comparison test ($p<0.05$), with different alphabetical letters in the same frame indicating statistical significance (Fig. 3).

At the later stage of cultivation, soil pH was markedly higher in the hot spring water irrigation groups compared to the tap water group. Furthermore, Na_2O accumulation in the soil increased significantly with the frequency of hot spring water irrigation. Specifically, soil Na_2O levels in the control group (tap water only) and the groups irrigated with hot spring water once, twice, and three times per week were 92 mg/kg, 4,849 mg/kg, 7,956 mg/kg, and 9,101 mg/kg, respectively.

3.4 Effects of hot spring water irrigation on tomatoes

As described above, the Na^+ concentration was significantly higher in hot spring water than in tap water. By the end of the cultivation period, soil Na_2O accumulation was significantly higher in the hot spring water irrigation groups than in the tap water group, and it increased with the frequency of hot spring water application. These results suggest that the elevated soil Na^+ concentration in the hot spring water irrigation groups was due to the high Na^+ content of the irrigation water.

Furthermore, fruit sugar content increased with higher irrigation frequency using hot spring water. Previous studies have reported that salt stress can increase tomato sugar content

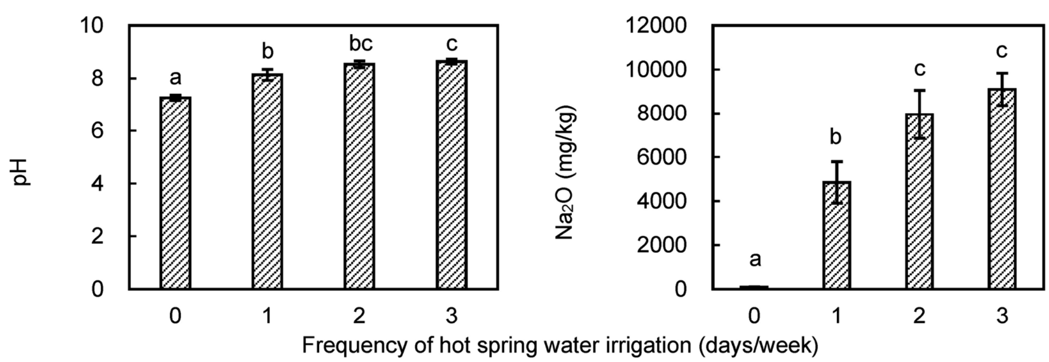

Fig. 3　Comparison of soil properties at the end of the experiment based on the frequency of hot spring water irrigation (n=3). Error bars indicate standard deviations. Significant differences were determined using Tukey's multiple comparison test ($p<0.05$) between different alphabetical letters (a, b, c) in the same frame.

by 1–5 Brix% (Tanaka *et al*., 2000 ; Kawai *et al*., 2002 ; Oka *et al*., 2004 ; Nishimura *et al*., 2011 ; Ito and Hirozumi, 2017). Consistent with these findings, irrigation with hot spring water three times per week increased sugar content by approximately 2.5 Brix% compared to the tap water group. These results confirm that frequent hot spring water irrigation enhances tomato sugar content.

In contrast, fruit weight did not show a consistent trend with irrigation frequency, and the differences were not statistically significant. Salt stress has been suggested to reduce tomato fruit size (Seto and Tanaka, 1998 ; Kawai *et al*., 2002). However, in this experiment, salt stress from hot spring water irrigation did not affect fruit weight. In Japan, tomatoes weighing around 100 g are classified as 'common tomatoes' (Kanahama, 2007). In this study, regardless of irrigation with hot spring water or tap water, fruit weight was less than 50 g, much smaller than that of a typical tomato. In pot cultivation, the limited root zone makes nutrient depletion more likely. It can be speculated that because the fruits did not grow large, the effect of salt stress on size reduction was minimal. These results suggest that using mini tomatoes may allow for increased sugar content while minimizing the impact of salt stress on fruit size.

The increased Na^+ concentration in the soil from hot spring water irrigation likely induced salt stress, which contributed to the rise in fruit sugar content. Sodium salts were the main factor responsible for the observed salt stress in these groups.

Salt stress is known to enhance fruit sugar content and other functional compounds by increasing water uptake, photosynthesis, and sugar accumulation (Harada *et al*., 2006). The observed increase in sugar content following hot spring water irrigation may be explained by this mechanism. This mechanism could also potentially enhance other functional components in tomatoes, such as minerals and antioxidants like lycopene. However, since this study focused solely on sugar content as an indicator of fruit quality, further research is needed to investigate the broader effects of hot spring water irrigation on tomato nutritional value.

3.5 Limitation of hot spring water irrigation

Since hot spring water has a higher pH than tap water, continuous or long-term use for irrigation may lead to an increase in soil pH. Consistent with our hypothesis, soil pH in the hot spring water irrigation groups rose from approximately 8 to 9 by the end of the experiment.

Previous studies have indicated that a neutral soil pH range of 6.8–7.3 is optimal for tomato growth (Kanahama, 2007). An increase in soil alkalinity beyond this range can lead to physiological disorders and hinder plant development. Therefore, when using hot spring water for irrigation, it is essential to implement strategies to prevent soil alkalization. One effective approach is the use of acidic fertilizers to counteract the rise in soil pH.

4. Conclusion

This study examined the effects of irrigating tomato plants with high-salinity hot spring water on fruit quality. Tomatoes were grown in pots and irrigated with hot spring water at different frequencies to evaluate their impact on plant growth and sugar content. The results showed that frequent hot spring water irrigation increased fruit sugar content, suggesting that this method may enhance tomato sweetness.

Since this study was based on pot experiments, open-field trials are necessary to validate the findings. Future research should evaluate the feasibility of using hot spring water at production sites to support its practical application in agriculture.

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