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原　　著

Cultivation Methods for Achieving Both High Sugar Content and High Yield in Tomatoes Irrigated with High-Salt Hot Spring Water

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高塩泉灌漑トマトの高糖度化・高収量化の両立を目指した栽培方法の検討

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要　　旨

地域農業の特色を促進する仕組みとして地理的表示保護制度が注目されている．温泉と農業が連携した地域ブランド農作物を創出することは，温泉地の活性化につながる．著者らは高塩泉・亀山温泉「白鳥の湯」を利用したトマトの高品質化と商品化のための栽培方法の検討を行っている．先行研究により，限定的な条件調整が可能なポット栽培による実験の結果，高塩泉の高頻度の灌漑によって，トマトが明確に高糖度化することが示されたが，十分な収量が得られなかったため，一般的なトマト栽培方法としてよく使用される雨除け露地栽培による実験を行った．実験の結果，雨除け露地栽培では十分なトマトの十分な収量は得られたものの，果実糖度はポット栽培に比べて低いという結果となった．土壌pHや土壌中ナトリウム蓄積量の化学分析から，雨除け露地栽培では灌漑水が流出してしまい，土壌中に高塩泉に起因する塩分が保持されていないこと，またそのことが十分な塩ストレス効果を与えられず，果実糖度の向上を導かない結果となっていることが推測された．このことから今後は，適度に根域を広げることで十分な収量を獲得しながら，同時に適度に根域を制限し十分に果実糖度を向上させる，という相反する事象を両立させた栽培方法の検討を要する．具体的には，根域を適度に制限できる袋培地栽培の導入検討，ならびにトマト果実の小玉化が商品価値の低下につながらないミニトマトを用いた栽培実験の有用性が示唆された．

キーワード：トマト，雨除け露地栽培，ポット栽培，高糖度化，収量，高塩泉

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Abstract

The Geographical Indication (GI) protection system is attracting attention as a mechanism for promoting the distinctive features of regional agriculture. Creating regional brand agricultural products that combine hot springs and agriculture may contribute to the revitalization of hot spring resorts. The authors are currently investigating cultivation methods that utilize high-salinity hot springs to improve tomato quality and enable commercialization using high-salt hot spring water, Kameyama Onsen Shiratori no Yu. Results from pot cultivation experiments, which allowed limited adjustment of growing conditions based on prior research, showed that frequent irrigation with high-salt hot spring water increased tomato sugar content but resulted in low yields. Therefore, in this study, we conducted experiments using field cultivation, a common method for tomato production, to establish practical cultivation techniques. Although field cultivation produced sufficient yields, fruit sugar content was lower than that obtained with pot cultivation. Chemical analyses of soil pH and sodium accumulation suggested that irrigation water leached away during open-field cultivation, preventing the retention of salt from the high-salt hot spring water in the soil. This likely prevented the application of sufficient salt stress, thereby failing to enhance fruit sugar content. Therefore, future research should explore cultivation methods that reconcile these conflicting objectives : achieving sufficient yields by moderately expanding the root zone, while simultaneously restricting it to adequately enhance fruit sugar content. Specifically, this study suggests the potential benefits of introducing bag cultivation systems that moderately restrict the root zone and conducting cultivation experiments using mini tomatoes, for which the smaller fruit size does not diminish commercial value.

Key words : Tomato, rain-sheltered field cultivation, pot cultivation, high sugar content, yield, high-salt hot spring water

1. Introduction

To revitalize hot spring areas and ensure their sustainable development, it is essential to explore new approaches to utilizing hot springs. Hot springs are deeply embedded in the local climate and culture. Similarly, agriculture is also closely tied to the local climate and culture. By linking hot springs with agriculture, we aim to create regional agricultural brands that represent the area. Examples of the agricultural use of hot springs include those reported by Sugimori et al. (2017, 2018, 2019) and Ezaki et al. (2010). Furthermore, the Geographical Indication (GI) protection system is gaining attention as a mechanism for promoting regional agricultural characteristics. The Basic Action Plan for Food, Agriculture and Rural Areas in FY2010 defines the GI system as "a designation for agricultural, forestry, and fishery products produced in a specified region, where the designated variety, production methods, and production period are appropriately managed" (Ministry of Agriculture, Forestry and Fisheries, 2010). The use of hot springs in agriculture aligns well with the core principles of the GI system.

Currently, the demand for high-quality regional-brand agricultural products is increasing. For example, tomatoes are the most widely produced fruit vegetable in Japan, and many regional brands have been developed. As the quality of tomatoes considerably varies depending on the cultivation method, it is easy to differentiate them from tomatoes produced in other regions. Enhancing fruit sugar content under controlled salt stress is essential for producing high-quality tomatoes. Tanaka et al. (2000), Kawai et al. (2002), Oka et al. (2004), Nishimura et al. (2011), and

Ito and Hirozumi (2017) reported cultivation experiments on high-sugar tomatoes produced using seawater and high-salt solutions. For example, in Kumamoto Prefecture, high-sugar tomatoes were grown under salt stress on reclaimed land. As a result, they were registered under the GI system as "Kumamoto Shio Tomato" (Ministry of Agriculture, Forestry and Fisheries, 2024). These can be regarded as successful examples of regional branding.

Our research group is conducting cultivation experiments with the aim of developing a technique for cultivating high-sugar content tomatoes using high-salt hot spring irrigation. As a preparatory step before introducing this method to agricultural fields, it was necessary to confirm the appropriate cultivation conditions. Therefore, the experiment was conducted using pot cultivation, which allowed limited adjustments to cultivation conditions (Hirozumi et al., 2025). The results showed that irrigation with high-salt hot spring water significantly increased tomato fruit sugar content. Furthermore, increasing the frequency of high-salt hot spring water irrigation led to an even greater increase in sugar content. Furthermore, soil chemical analysis suggested that the increase in fruit sugar content resulting from high-salt hot spring water irrigation is a physiological response caused by salt stress associated with sodium accumulation in the soil.

The next challenge for our research group is to establish cultivation methods suitable for commercializing tomatoes irrigated with high-salt hot spring water. A high sugar content was achieved in tomatoes irrigated with high-salt hot spring water. However, variability in fruit weight associated with salt stress was also observed. Such variability in tomato quality could pose a significant barrier to practical application and commercialization. Furthermore, because the pot cultivation method used by Hirozumi et al. (2025) is not commonly applied to tomatoes intended for market distribution, commercializing tomatoes irrigated with high-salt hot spring water requires verification using widely practiced cultivation methods such as field cultivation, hydroponics, and greenhouse cultivation.

Therefore, tomato cultivation experiments were conducted using high-salt hot spring water irrigation during rain-sheltered field cultivation. The reasons for selecting rain-sheltered field cultivation as the research subject were threefold : ① Field cultivation is a common tomato cultivation method ; ② although it is not as effective as pot cultivation in a greenhouse, it reduces the impact of rain and allows irrigation to be controlled ; ③ rain-sheltered field cultivation is low cost and easier to implement than greenhouse cultivation. The results of this experiment yielded important findings that contribute to the practical application and commercialization of high-quality tomatoes grown using high-salt hot spring water irrigation.

2. Methods

2.1 Cultivation examination

Two rain shelters were prepared for this experiment in the experimental field at Yokkaichi University, Yokkaichi City, Mie Prefecture, Japan. The rain shelters measured 2.2 m (length) × 7.0 m (width) × 2.0 m (height). To ensure sufficient sunlight, the roof of each rain shelter was made of transparent vinyl film, and no shade nets were installed. Photo 1 shows the rain shelters.

Four cultivation areas were established, with two under each rain shelter. Each cultivation area measured 2.0 m in length × 2.0 m in width. One of the two cultivation areas under each rain shelter was designated as the treatment area, and the other as the control area. The layout of the cultivation areas is shown in Fig. 1. Commercially available cattle manure compost (N : 15 g/kg ; P : 19 g/kg ; K : 22 g/kg ; C/N ratio : 158 g/kg) was applied at 24.0 kg per area. After thorough mixing, a black polyethylene film cover was applied.

Four commercially available tomato seedlings (*Lycopersicon esculentum* Mill. "Home Momotaro") were planted in each cultivation area. Tomato seedlings were planted on April 17, 2018, and cultivated till July 30, 2018. During the cultivation period, the minimum temperature in Yokkaichi City was 6.4℃, maximum temperature was 37.7℃, and total precipitation reached 835 mm (Japan Meteorological Agency, 2025). Similar to a previous study by Hirozumi et al. (2025), side branches were removed, and only the main stem was allowed to grow. In addition, the plants were pinched back, leaving only the top two nodes above the third flower cluster. The number of fruits per cluster was limited to four. On April 30, May 30, and June 30, 2018, chemical fertilizers (nitrogen, 100 g/kg ; phosphorus, 80 g/kg ; and potassium, 80 g/kg) were applied at a rate of 0.60 g per plant. Insect nets were installed on May 15, 2018. Photo 2 shows tomato plants bear-

Photo. 1　Test areas in rain shelters at Yokkaichi University (April 18, 2018).

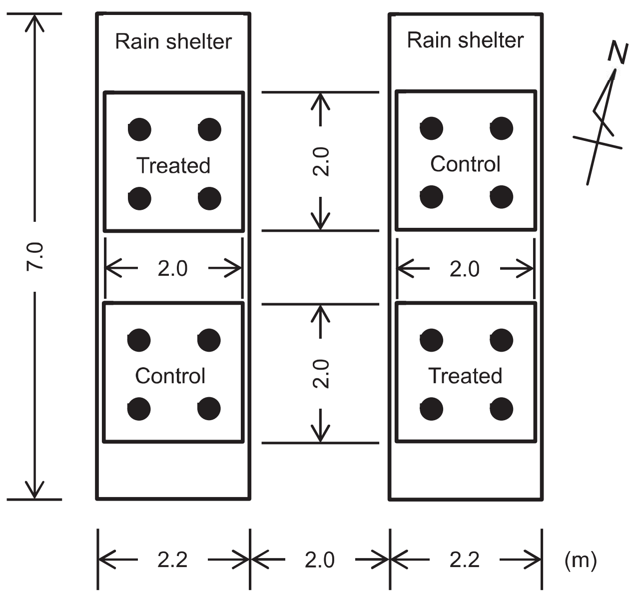

Fig. 1　Location of treated and control areas in rain shelters. Filled circles (●) indicate locations where tomatoes were planted.

ing fruit.

2. 2 Irrigation method

Irrigation was performed once daily during the cultivation period. For irrigation water, the treatment plots used "Kameyama Onsen Shiratori no Yu" (Kameyama City, Mie Prefecture, Japan), which is a high-salt hot spring water ($NaCl{\cdot}HCO_3$ type). In the control area, tap water from the Yokkaichi University campus was used for irrigation. The hot spring water used for irrigation in the treatment area was the same as that used in a previous study by Hirozumi et al. (2025), with a pH of 9.7 and a sodium content of 841.8 mg/kg. Other major cations were K^+ 3.9 mg/kg, NH_4^+ 0.7 mg/kg, Mg^{2+} 2.7 mg/kg, and Ca^{2+} 10.8 mg/kg; major anions were Cl^- 734.8 mg/kg, HPO_4^{2-} 0.2 mg/kg, and HCO_3^- 500.5 mg/kg (Mie Prefecture Health and Environment Research Institute, 2018). The tap water had a pH of 7.5 and, sodium content of 1.9 mg/kg. Before fruit set, each cultivation area received 500 mL of tap water per plant per irrigation. After fruit set, the control area received tap water, and the treatment area received hot spring water at 500 mL per plant per irrigation.

Photo. 2　Tomato plants with fruits in the treatment group irrigated with high-salt hot spring water (June 27, 2018).

Plants that died during the cultivation experiment (three plants in total), presumably owing to individual variation in commercially available plants, were excluded from this study.

2. 3 Analysis of soil environment

Soil samples were collected from the surface of each cultivation area before and after cultivation. The collected soil samples were dried in a greenhouse, and those that passed through a 2.00 mm sieve were analyzed.

The methods used to measure soil pH and sodium accumulation followed those described by the Editorial Committee on Soil Environmental Analysis Methods (1997).

To determine pH, 20.00 g of soil was mixed with 50 mL of distilled water, gently shaken, and allowed to stand for one hour. The pH of the resulting extract was measured using a compact pH meter (ASONE AS-712). Sodium ion concentration was determined by adding 100 mL of 1 mol/L ammonium acetate solution to 5.00 g of soil, shaking for 1 h, filtering the extract through 8 μm filter paper, and measuring the filtrate with an atomic absorption spectrophotometer (SHIMADZU AA-6200). Na_2O accumulation was then calculated from the Na^+ concentration of the extract solution using Equation (1) (Hirozumi et al., 2025).

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

$A_{\mathrm{Na_2O}}$: Na_2O accumulation per unit mass in dried soil sample (mg/kg)
$C_{\mathrm{Na^+}}$: Na^+ concentration in the 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. 4　Evaluation of fruit quality

The harvested tomatoes were weighed using an electronic balance. After weighing, the tomato fruits were crushed in a processor, and the juice was extracted. The filtrate was measured using a handheld refractometer (ATAGO N1) to determine fruit sugar content. A refractometer was used to estimate the concentration of soluble solids in fruit juice by measuring its refractive index. As sugars constitute the majority of these solids, they can be used to estimate sugar content (Tateishi, 2013). The main sugars in tomato fruit are fructose and glucose (The Subdivision on Resources the Council for Science and Technology, Ministry of Education, Culture, Sports, Science and Technology, Japan, 2023). Statistical comparisons between groups were conducted using the Wilcoxon rank-sum test, with statistical significance set at $p<0.05$. All data analyses were performed using R version 4.5.1 for i386.

3.　Results and Discussion

3. 1　Changes in Soil Environment and Fruit Sugar Content Due to Irrigation with High-Salt Hot Spring Water

Figure 2 shows soil pH and soil sodium accumulation (Na_2O) before and after cultivation trials in each cultivation area.

The soil pH in the control area fluctuated from 7.3 to 7.5 (range : 0.2) before and after the cultivation trial. In contrast, the treated area showed a fluctuation from 6.8 to 7.9 (range : 1.1). The pH of the hot spring water used in the experiment was 9.7. This indicates that the soil pH in the treated area irrigated with hot spring water became more alkaline.

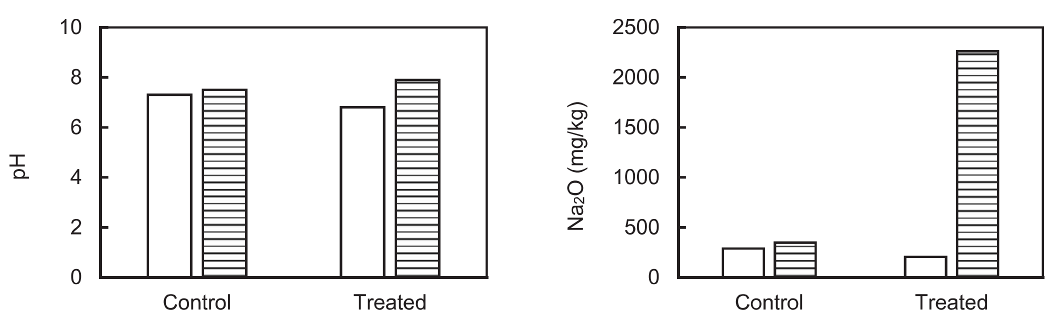

Fig. 2　Soil pH and Na_2O in test areas before and after the experiment (n=2). Unfilled bars (□) indicate data before the experiment, and bars with horizontal lines (⊟) indicate data after the experiment.

The difference in sodium accumulation in the soil was 59 mg/kg (from 288 mg/kg to 347 mg/kg) in the control plots before and after the cultivation test. In contrast, the difference in the treated plot was 2,056 mg/kg (from 204 mg/kg to 2,260 mg/kg), indicating a significant increase in sodium accumulation.

Changes in soil pH and sodium accumulation due to high-salt hot spring water irrigation have also been observed in pot cultivation experiments (Hirozumi et al., 2025). It was clarified that high-salt hot spring water irrigation causes significant soil environmental changes even under the open-field cultivation conditions with rain shelters used in this study, not only in closed growing environments such as pots.

Figure 3 shows the average sugar content and weight of tomato fruits harvested from each test area. The sugar content of tomatoes was 5.42 Brix% in the control area and 5.49 Brix% in the treated area. The weight per fruit was 203.84 g in the control area and 173.12 g in the treated area. A significance test was performed to compare the two groups. No statistically significant difference was observed in sugar content ; however, a statistically significant difference was observed in fruit weight.

3.2 Comparison of Closed Pot Cultivation and Open Field Cultivation

Table 1 shows the results of our pot cultivation experiment in a greenhouse (Hirozumi et al.,

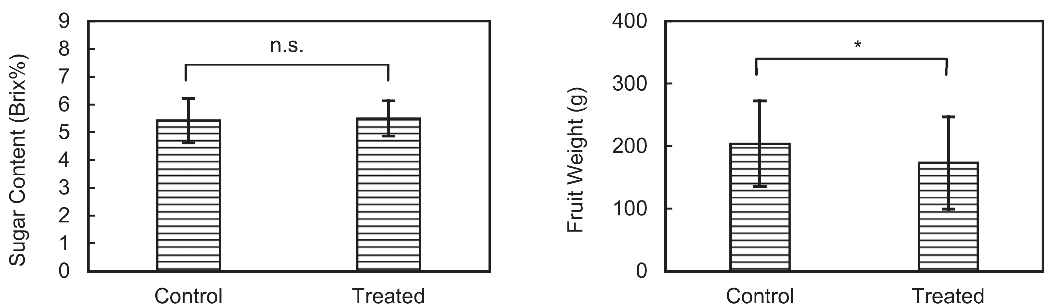

Fig. 3 Comparison of tomato fruit sugar content and weight between treated and control groups. Error bars indicate standard deviations. * indicates a significant difference ($p<0.05$), and n.s. indicates no significant difference by the Wilcoxon rank-sum test.

Table 1 Comparison of soil properties and fruit quality under greenhouse pot cultivation based on the frequency of tap water and hot spring water irrigation (Hirozumi et al., 2025).

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

Table 2　Comparison of soil properties and fruit quality under open-field cultivation under rain shelters based on the frequency of tap water and hot spring water irrigation.

Frequency of irrigation (day(s)/week)		Soil properties			Fruit quality		
Tap water	Hot spring water	n	pH	Na_2O (mg/kg)	n	Sugar content (Brix %)	Fruit weight (g)
7	0	2	7.5	347	51	5.42	203.84
0	7	2	7.9	2,260	63	5.49	173.12

2025). Table 2 shows differences in the soil environment and fruit quality of open-field cultivation under rain shelters based on irrigation frequency in this study.

First, we compared differences in the soil environment caused by different cultivation methods. In pot cultivation, soil pH shifted toward the alkaline side as irrigation frequency increased : 8.1 with weekly high-salt hot spring water irrigation, 8.5 with twice-weekly irrigation, and 8.6 with three-times-weekly irrigation (Table 1). In contrast, in the open field under rain-shelter cultivation in this study, the soil pH remained at 7.9 even after continuous daily irrigation (Table 2). Furthermore, in pot cultivation, soil sodium accumulation was 4,849 mg/kg with weekly high-salt hot spring water irrigation, 7,956 mg/kg with twice-weekly irrigation, and 9,101 mg/kg with three-times-weekly irrigation, indicating an increase with irrigation frequency (Table 1). In contrast, in the open field under rain-shelter cultivation used in this study, even with daily irrigation, sodium accumulation remained at 2,260 mg/kg (Table 2). These results indicate that irrigation with high-salt hot spring water in a closed soil environment, such as pot cultivation, is strongly affected by the chemical properties of the irrigation water, whereas irrigation in an open soil environment, as in this study, is relatively less affected.

In pot cultivation, irrigation with high-salt hot spring water occurred at most three days per week, with a volume of 500 mL per irrigation, totaling 1,500 mL per week. Despite open-field cultivation using 500 mL per day for seven consecutive days, totaling 3,500 mL per week, pot cultivation showed a greater impact from high-salt hot spring water. This indicates that in open soil environments, such as those in this study, sodium from high-salt hot spring water diffuses widely and is not sufficiently retained in the soil. This represents a critical challenge that must be addressed when aiming to increase tomato fruit sugar content through high-salt hot spring water irrigation in open-field cultivation.

Next, we examined differences in fruit sugar content based on cultivation methods. In pot cultivation, fruit sugar content increased with more frequent irrigation using high-salt hot spring water : 8.05 Brix% with weekly irrigation, 8.82 Brix% with twice-weekly irrigation, and 9.64 Brix% with three-times-weekly irrigation (Table 1). In contrast, in the open field under rain-shelter cultivation in the present study, even with daily irrigation using hot spring water, the fruit sugar content remained at only 5.49 Brix% (Table 2). Because the increase in fruit sugar content is thought to correlate with salt stress in the soil, it was inferred that under open-field conditions with rain shelter cultivation, where soil sodium accumulation is low, the plants did not experience sufficient salt stress to significantly increase fruit sugar content. Furthermore, focusing on tap water irrigation, pot cultivation yielded 7.07 Brix% (Table 1), whereas open-field cultivation under rain shelters yielded 5.42 Brix% (Table 2), indicating higher sugar content in pot cultivation. Since fruit sugar content increases are also known to be induced by drought stress (Hayata et al., 1998 ; Hiei et al., 2019), it is inferred that pot cultivation inherently subjects plants to considerable drought stress due to the limited root zone and the irrigation water volume of 3/7. Differences in drought stress induced by different cultivation methods must also be considered.

Third, we examined differences in fruit weight according to the cultivation method. In pot cultivation, the weight per fruit ranged from approximately 30 g to 50 g, regardless of the presence or frequency of hot spring irrigation (Table 1). In contrast, in the open-field under rain-shelter cultivation used in this study, the weight was 203.84 g with tap water irrigation and 173.12 g with hot spring water irrigation (Table 2). The difference was significantly greater in open-field cultivation, achieving yields comparable to those of commercial products.

3.3 Changes in Fruit Quality Owing to Cultivation Method Differences and Future Research

Summarizing the experimental results and discussions presented thus far, we have considered the direction of future research based on the insights gained.

Many studies have been conducted on plant responses to salt stress. It was indicated that salt stress leads to a trade-off between increasing sugar content and maintaining yield of tomatoes (Oka et al., 2004 ; Saito et al., 2006 ; Ito et al., 2017). Therefore, an extremely challenging cultivation technique is required to use salt stress to increase sugar content while maintaining a sufficient yield.

In the open field under rain-shelter cultivation used in this study, sufficient sodium accumulation in the soil was not achieved to induce increased fruit sugar content through salt stress. Open-field cultivation under rain shelters tends to result in more widespread runoff of irrigation water than pot cultivation. Plants flexibly adapt their root zones to their growing environment ; for example, they extend their roots shallowly when moisture is abundant and deeper when the soil is dry (Kroon and Visser, 2008). Furthermore, water uptake is not uniform throughout the root zone, and the amount of water absorbed varies locally depending on the surrounding dryness (Araki, 2002). Because the root zone is not restricted in open fields under rain-shelter cultivation, tomatoes could potentially secure a sufficiently large root zone and avoid salt stress. Saito et al. (2008) also pointed out that even when similar salt stress was applied, the effect of improving sugar content was lower in open-field cultivation where the root zone was not restricted compared to greenhouse cultivation where the root zone was restricted. This study supports the results of our experiment. Therefore, to induce salt-stress effects in tomatoes, even in open-field cultivation, it is necessary to intentionally restrict the root zone area and irrigate it to ensure that sodium salts accumulate uniformly throughout the entire area.

In contrast, in open-field cultivation, tomato fruit weight improved significantly. Unlike pot cultivation, the open-field cultivation method used in this study did not restrict the root zone, which likely prevented poor growth. However, this phenomenon conflicts with the effective induction of salt stress. Cultivation techniques that allow sufficient yield by moderately expanding the root zone while simultaneously restricting it to sufficiently improve fruit sugar content is required in open-field cultivation.

Based on the above discussion, producing high-quality tomatoes with high market value using open-field cultivation requires moderate restrictions on the root zone area. One potential method for limiting the root zone area is bag cultivation. This method, developed by the Aichi Agricultural Research Center, enables sufficient yield using a small volume of cultivation soil (Kaneko et al., 2006). The method of irrigation with hot spring water is also important. Oka et al. (2004) pointed out that the reduction in fruit yield can be suppressed by adjusting the timing of salt stress application. Additionally, the appropriate selection of tomato varieties is necessary. If salt stress inherently causes tomatoes to produce smaller fruits, cultivating mini tomatoes, which maintain their market value despite their lower weight, could be a method to preserve commercial value.

In addition to these issues, unique challenges exist that come with hot spring water being a natural resource. Unlike simple salt water, hot spring water contains various components other than sodium chloride. Moreover, the composition and pH of each hot spring differ. The components and pH of hot spring water can have either positive or negative effects on crops, depending on their properties and amounts. When using hot spring water for agriculture, it is necessary to understand the characteristics of each type of hot spring water and decide how to use it.

We will position these points as future research topics and aim to achieve both enhanced fruit sugar content and stable yields, despite the salt-stress effects of high-salt hot spring water.

4. Conclusion

This study investigated cultivation methods for improving the quality and commercial viability of tomatoes using high-salt hot spring water, with the aim of revitalizing hot spring areas and creating regional-brand agricultural products. Results from pot cultivation experiments, which allowed for limited condition adjustments based on prior research, showed that frequent irrigation with high-salt hot spring water increased tomato sugar content, although yields were insufficient. Therefore, in this study, we conducted experiments using field cultivation, which is a common tomato cultivation method, to establish cultivation techniques.

While open-field cultivation yielded sufficient quantities, the fruit sugar content was lower than that in pot cultivation. Chemical analysis of soil pH and sodium accumulation revealed that in open-field cultivation, irrigation water flowed away, preventing the retention of salts originating from high-salt hot spring water in the soil. This resulted in insufficient salt-stress effects, thereby failing to enhance fruit sugar content.

The results of this study provide new insights into the research questions. Specifically, it necessitates exploring an extremely challenging cultivation method : achieving sufficient yields by moderately expanding the root zone while simultaneously restricting it to sufficiently enhance fruit sugar content.

This highlights the need to investigate bag cultivation systems that moderately restrict root space and conduct cultivation experiments using mini tomatoes, wherein smaller fruit sizes do not diminish commercial value. Therefore, we intend to pursue these studies as future research objectives. Furthermore, by enhancing tomato quality using high-salt hot spring water, we aim to contribute to the future creation of regional agricultural products that utilize hot springs.

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