Invited Review

Protected Horticulture after the Great East Japan Earthquake in Iwate Prefecture

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Agricultural lands in the Kesen area, which is located in the coastal area of Iwate Prefecture, were severely damaged by the Great East Japan Earthquake on March 11, 2011. Empirical research was undertaken to promote agricultural restoration and reconstruction. This project was conducted to realize low-cost protected horticulture utilizing local resources effectively. In this area, where forestry was popular, there was abundant unnecessarily thinned timber. Three types of low-cost greenhouses were developed, including a wooden frame house built using lumber derived from thinning. A stove to use thinned timber as a fuel was also developed. To establish protected horticulture at a low cost, greenhouses that could be constructed with accessible materials were developed along with a device for sterilizing nutrient solutions using charged plasma. An environmental control program was developed based on a “ubiquitous environment control system (UECS)” for small-scale facilities. Disease control using hot water for long-term cultivation was carried out. Strawberry and tomato production was conducted to demonstrate the use of these developed elements and resulted in yields significantly higher than those obtained for these crops before the disaster.

Key Words: protected horticulture, strawberry, tomato, wood-burning stove, wooden frame plastic greenhouse.

Introduction

The Great East Japan Earthquake had a magnitude of 9.0 and occurred at 14:46 on March 11, 2011. The Kesen area of Iwate Prefecture, comprising the cities of Rikuzentakata and Ofunato, and the town of Sumita, was struck by a tsunami with a maximum wave height greater than 18 m (Mori et al., 2012). In the Kesen area, the total number of confirmed deaths was 2023, with 282 people missing, and agricultural damage amounted to 29 million dollars over 460 ha. Greenhouses with a total land area of 5.9 ha were damaged by the tsunami.

The Southern Region Horticulture Research Section (Nanbu Section) of the Iwate Agricultural Research Center was destroyed by the tsunami. It was redeveloped and reopened on January 6, 2013 as an open laboratory to promote agricultural restoration and reconstruction in the area, as well as to provide support for the affected agricultural lands and facilities. Efforts concerning rehabilitation of facilities for horticultural production in this area were implemented mainly from this base.

The Kesen area is located in the coastal part of Iwate. In this area, winter is relatively mild and there is abundant sunshine (more than 140 h of sunlight per month). Summer is cool because of sea fog, named “Yamase” locally (Kanno, 1997; Takai et al., 2006). These conditions create a climate suitable for protected horticulture. However, the Rias coast has mountains approaching the shore and little flatland. Many areas are limited in terms of setting up large-scale greenhouses. Therefore, an appropriate greenhouse size was thought to be between approximately 3000 and 10000 m². The tsunami caused salt damage in the fields containing the greenhouses. Salt stress is known to reduce strawberry (Kaya et al., 2002) and tomato (Cuartero and Fernández-Muñoz, 1999) yields. After the disaster, it became necessary to introduce cultivation in beds that were isolated from salt-contaminated soil to rapidly reconstruct protected horticulture in the area. Empirical research for tomato and strawberry production in isolated beds was under-
taken to promote agricultural restoration and reconstruction. The concept of this research was to realize low-cost protected horticulture facilities by utilizing local resources effectively.

The protected horticultural techniques used in Iwate Prefecture are described in a pamphlet that can be downloaded from the website of the Agriculture, Forestry, and Fisheries Research Council (http://www.affrc.maff.go.jp/docs/sentan_gijyutu/sentan_gijyutu.htm). This document is written in Japanese so this review aims to introduce the reconstruction efforts following the disaster more widely.

**Low-cost greenhouse construction**

“Mokkotsu house” (wooden frame greenhouse) utilizing local natural resources

Large quantities of cedar lumber are produced in the Kesen area, so this plant resource could be an alternative material for the construction of greenhouse frames. Wood is a natural byproduct of thinning and is generally under-utilized. The use of wooden frames reportedly enables the construction of buildings with lower CO₂ emissions than those built with reinforced concrete (Gustavsson et al., 2006). Thus, a prototype wooden frame greenhouse was constructed, and practical strawberry production was achieved.

At first, different base structures for constructing greenhouses were developed by a local vendor (Kirakusouken Co., Ltd., Ofunato, Japan). Several types of base structure were tried and a basic structure consisting of two pillars, four beams, and eight bolts was ultimately adopted (Fig. 1). This frame is a simple structure that can be assembled by a farmer, can withstand snow accumulation of ≥50 kg·m⁻², and is wind resistant up to ≥50 m·s⁻¹. A wooden frame greenhouse was constructed using this type of frame (Fig. 2).

The light transmission rate of a Japanese-style large-scale greenhouse was 50–60% of the outside solar radiation (Higashide et al., 2014); light utilization in a wooden frame greenhouse was slightly higher at 61% (Matsuda et al., 2017) and was almost equal to that of a steel-frame plastic greenhouse (Fig. 3). The light conditions were therefore considered practical, but not excellent.

One advantage of wooden frame greenhouses is that it has a relatively low frame-surface temperature in hot weather compared with steel-frame greenhouses. It is also easier to control temperature rises in the greenhouse because of the lower radiant heat from the frame (Suzuki et al., 2016). Additionally, the environmental load for constructing greenhouses with wooden frames is lower than that for steel-frame greenhouses because the CO₂ emitted during the manufacture of the greenhouse is 4.4% that of a steel-frame greenhouse of the same size (Ohta, 2017). Furthermore, frame refuse is decreased in a wooden frame greenhouse because it can be dismantled after use and the wood used as a biomass fuel. Wooden frame greenhouses are attracting attention from farmers in Japan and 11 have been built as of January 2018.

**New energy-saving pipe-frame greenhouse (double-arched greenhouse) and a plastic greenhouse using scaffold materials for cold regions**

Two types of greenhouses have been developed by
the Western Region Agricultural Research Center, National Agriculture and Food Research Organization (WARC/NARO). This center has conducted many agricultural studies in relatively confined farming areas surrounded by mountains in warm regions and has determined that double-arched greenhouses and plastic greenhouses using scaffold materials have characteristics suitable for building in such areas. These greenhouses may be suitable for construction in the Kesen area after slight improvements to render them appropriate for colder climates.

The first type of greenhouse had double-arched frames and foundations anchored with screw piles (Fig. 4). This frame contributes to durability against both snow and wind at low cost. To improve thermal conditions and reduce heating costs, multilayered thermal curtains and a water heat storage system were installed (Kawashima, 2015; Kawashima et al., 2013). A manual concerning the thermal insulation curtain and heat storage system was published in Japanese (http://www.naro.affrc.go.jp/publicity_report/pub2016_or_later/files/warc_man_nikouonnshitupanfu201604shuseiban.pdf). A reduction in running costs for heating is currently being demonstrated in Iwate Prefecture (unpublished). This multilayered thermal curtain was developed by WARC/NARO et al. and is lightweight with a low heat transmission coefficient. This type of greenhouse is thought to be suitable for construction in small spaces. Insulation is important in small greenhouses, so a windbreak, which was made with scaffold materials, was constructed to reduce heating costs (Moriyama et al., 2017).

The second type greenhouse is characterized by a frame constructed using steel pipes with a diameter of 48.6 mm (Fig. 5) joined together using clamps. These pipes and clamps are often used as temporary frames for the scaffolding used at construction sites and can easily be obtained inexpensively. Screw pipes for the greenhouse foundation had been developed previously (Nagasaki et al., 2010). Large amounts of materials are likely to be needed for the reconstruction of various buildings in the afflicted area so constructing greenhouses with easy-to-obtain and inexpensive materials will be advantageous for the reconstruction of horticultural production. A 3200 m² greenhouse of this type was built at Rikuzentakata to confirm the strength of the structure and its snow endurance. A design load of 338.8 N·m⁻², based on the 20-year probability of maximum snow depth (25.6 cm) gave sufficient margin for the actual designed load of 50 cm snow depth (Yoshikoshi et al., 2015). The maximum snowfall of 18 cm in 2014 did not cause any problems. This green-

![Fig. 3. Transmission of solar radiation in each greenhouse and outside solar radiation.](image)

![Fig. 4. Double-arched Greenhouse. (A) screw pile for the foundation, (B) double-arched frame, (C) exterior of the greenhouse.](image)
The greenhouse was designed to withstand wind speeds of up to 35 m·s$^{-1}$; and speeds of over 35 m·s$^{-1}$ were not encountered. This greenhouse can be used for tomato production for approximately 3 years.

**Development of a horticultural wood-burning stove**

Wood pellets are a well-known source of wood-based biomass fuel. It is necessary to continuously supply pellet fuel to heat greenhouses because air temperature below the optimum range can negatively affect greenhouse production. A stable supply of pellets is difficult to obtain in the Kesen area. Therefore, a new wood-burning stove (SuperGoronta; Ishimura industrial Co., Ltd., Kamaishi, Japan) that can utilize thinned wood and lumber remnants as fuel was developed (Fig. 6). Using this stove, it was possible to continue burning fuel for 12 h after the fuel was ignited. Under extremely cold conditions, in which the combustion efficiency may be a problem and where a decrease in heating capacity may result from continuous burning, the efficiency can be improved by introducing air intake quantity control. Under such circumstances, it may be better to use this stove in combination with another heating system using kerosene as fuel. This heating unit showed great potential as an effective method of using wood from tree thinning in the Kesen area. Ninety-five of these stoves have already been sold.

**Efficient control using the ubiquitous environment control system (UECS) for medium/ small sized greenhouses**

In Iwate Prefecture, small-scale pipe-houses account for 97.6% of the cultivation facilities. It is difficult to install general environmental control systems in small-scale greenhouses because these systems are very expensive so they have not been widely used. The effect of integrated environmental control on both the yield and quality of agricultural products has been recognized throughout Japan, so it was necessary to develop an environmental control method suitable for the weather conditions in the Kesen area.

A ubiquitous environmental control system was developed for installation in small- to medium-scale greenhouses (Hoshi et al., 2004). In this system, all the environmental control devices are connected to a local area network (LAN) and environmental control is implemented for communication of relevant information. The UECS uses an open-source protocol for communicating with and controlling these devices (nodes) and anyone is able to develop hardware and software for environmental control in accordance with the rules of the system (Hoshi et al., 2018). The specifications of the communications protocol for UECS can be obtained from the UECS website (http://www.uecs.jp/en/protocol-e.html). Some producers are personalizing this system and implementing advanced control at low costs. In the previously mentioned double-arched greenhouse, a commercially available controller (Fujitsu Ltd., Kawasaki, Japan) that communicated in
In accordance with the UECS protocol was installed (Fig. 7). A number of devices made by the project researcher were installed on the same LAN and were connected to a commercial controller. The software for calculating the greenhouse interstice ventilation rate based on the nocturnal time course of inside and outside CO$_2$ concentrations was installed in the LAN (Yasuba et al., 2017). Environmental conditions and actuators to control information were monitored by free UECS logging software (Yasuba et al., 2012). Various information on environmental control can be monitored by inexpensively installing the UECS.

**Strawberries**

The strawberry cultivation area in Iwate Prefecture is currently 874 a and has decreased by almost 40% over the past 10 years. Strawberries have been predominantly cultivated in open fields (not greenhouses) and small-scale greenhouses. Strawberries were generally planted in soil and cultivated in winter conditions until they were exposed to the chilling required to break endo-dormancy. After that, greenhouses were covered with plastic film for heat insulation. The yield using an ever-bearing cultivar was generally about 2 kg·m$^{-2}$ from the summer to autumn, and that of a semi-forcing culture using June-bearing cultivars was about 1.5 kg·m$^{-2}$.

These yield levels were not high compared with those in other areas. Our study therefore aimed to improve strawberry yields by developing a forcing culture with isolated beds instead of semi-forcing with exposure to the cold climate of the Kesen area.

We considered two production models for strawberry production and evaluated their relevance. The first model was constructed by effectively utilizing the by-products generated during the production of timber, which is a specialized product in this area. The second model was a long-term cultivation method using the cool weather conditions in the Kesen area.

**Development of a root zone heating technique and construction of a cultivation method for strawberries using cedar byproducts.**

While heating devices are necessary for the introduction of a forcing technique, it is important to decrease heating costs for commercial production. Strawberry plants are very compact, so it was thought that heating costs could be reduced by introducing root zone heating. A local heating system using thinned wood as fuel was therefore developed. This system was constructed with the “SuperGoronta” stove described in the previous section. In this system, hot water at about 30–50°C produced by the stove was circulated through pipes at the root zone (Chiba et al., 2016a). Elevated beds with a bilayer hammock-type construction were used for strawberry cultivation (Fig. 8). Pipes were set in elevated beds and the root zone heated locally.

Cedar bark was used as the culture medium. Slow-release fertilizer was dressed in the medium, and water without added nutrients was applied through drip irrigation. The strawberry ‘Benihoppe’ was grown with this system in a forcing culture. The yield following root zone heating was 4.9–15.7% higher than without treatment and was almost the same as that obtained using the general crown heating method (Table 1; Chiba et al., 2016b). Once the tubes of the root zone heating system were installed, they remained in place, which resulted in lower labor costs to implement this system.

The target yield was 5.5 kg·m$^{-2}$ while the actual yield was 5.9 kg·m$^{-2}$. Cedar, which is a specialized product of the Kesen area, was used in the main parts (wooden frame greenhouse, cedar bark as cultivation medium, and thining wood as fuel) of the system.

**Development of a method for long-term cultivation**

The climate of the Kesen area is characterized by a large amount of solar radiation enabling cultivation in winter and cool temperatures in the summer. This climate may be suitable for strawberry production because strawberry plants have low resistance to high temperatures and decreased fruit yields under low light condi-
Taking advantage of this climate, a method to continue cultivation for more than one year was developed. The cultivation system was constructed using elevated beds with the cedar bark medium in the wooden frame greenhouses (Ohta et al., 2015). This system was similar to that described in the previous section. Liquid fertilizer was applied instead of slow-release fertilizer as it was considered more suitable for long-term cultivation. Both June-bearing ‘Benihoppe’ and ever-bearing ‘Natsuakari’ were used to test long-term cultivation. The first cultivar is a high-yield cultivar and the second is an ever-bearing type with good taste characteristics. Several technologies were introduced to realize long-term cultivation.

A day length of 24 h was obtained using artificial lighting on the ever-bearing cultivar ‘Natsuakari’ to promote flower initiation. A crown temperature controlling system was installed to promote flower initiation and maintain plant vigor in the high-temperature season and for low-cost heating in the low-temperature season (Fig. 9; Ohta et al., 2017; Yamazaki et al., 2017).

It is difficult to control diseases and pest damage during successive long-term cultivations because the number of applications is restricted for each type of agricultural chemical, regardless of the length of the cropping period. Additionally, chemical-resistant powdery mildew is expanding in this area. Recently, heat shock treatment using hot water was shown to be a potential alternative to chemical protection against powdery mildew (Ogawara et al., 2012; Sato et al., 2018). This treatment was adapted to long-term cultivation (Fig. 10) and was found to control powdery mildew.

The yield of long-term cultivation was 16.0 kg·m⁻² over 2 years, or an average of 8.0 m⁻² per year. This was higher than the average level found in this region, confirming the benefits of the new technologies such as elevated bed cultivation, environmental control, and Integrated Pest Management (IPM).

<table>
<thead>
<tr>
<th>Year</th>
<th>Heating treatment¹</th>
<th>Total fruit yield (g/plant)</th>
<th>Treatment period (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014–2015</td>
<td>Control</td>
<td>578.8</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Water tank</td>
<td>607.1</td>
<td>104.9</td>
</tr>
<tr>
<td></td>
<td>Crown</td>
<td>599.2</td>
<td>103.5</td>
</tr>
<tr>
<td>2015–2016</td>
<td>Control</td>
<td>630.1</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Water tank</td>
<td>725.1</td>
<td>115.7</td>
</tr>
<tr>
<td></td>
<td>Crown</td>
<td>741.5</td>
<td>117.7</td>
</tr>
</tbody>
</table>

1 control; no regional heating: water tank; root heating using “SuperGoronta”. Crown; crown heating.

![Fig. 8. Cultivation methods and scheme of the closed-elevated bench.](image-url)
Tomatoes

In the Kesen area, tomatoes have been conventionally cultivated in greenhouses to shelter the fruit from rain. However, the yield obtained using this type of cultivation was not particularly high (ca. 12 kg·m⁻²). In this area, the temperature is not lower than inland and there is little snowfall in the winter season. If a yield of 30 kg·m⁻² was obtained, a heating device could be introduced to the greenhouse. Soil culture was used in this area for tomato production. Isolation bed cultivation was expected to be effective for avoiding salt damage and help to quickly resume the production of tomatoes in the area damaged by the tsunami.

Initially, a simple cultivation system was constructed using a combination of coated fertilizer and isolation beds for small-scale greenhouses. The coated fertilizer was immersed in a hydroponic tank and water eluted from the coated fertilizer was used as a nutrient solution (Kinoshita et al., 2014a, b, 2016). This method is a simple means of producing a nutrient solution but it was difficult to adapt to large-scale cultivation because a large tank was needed. An isolation bed was made using a polystyrene box and cedar bark was used as the cultivation medium. Introduction of interplanting may be effective to improve yield as it is difficult to cultivate over long periods in small greenhouses. Tomatoes were cultivated in wooden frame greenhouses as described in the above method (Fig. 11). The yield was 24 kg·m⁻² from March to the following January. The effect of the fertilizer management remains to be determined. It was difficult to control the nutrition using coated fertilizer and more work will be required to establish a reliable protocol. The work involved in the long-term production of tomatoes using interplanting could be simplified.

Next, a cultivation system was developed for greenhouses on a larger scale than those in the previous section. While an environmental control technique was effective for improving tomato yields in large-scale production (Higashide et al., 2015), it is difficult to construct many large greenhouses in the Kesen area. It is important to introduce environmental control technology suitable for small- and medium-sized greenhouses to improve productivity. A system for long-term tomato production was therefore constructed. This system was composed of a combination of rockwool culture and environmental control.

Quantitative control of the amount of fertilizer was conducted using recirculating hydroponic culture with a low amount of fertilizer (Nakano et al., 2010). Two kinds of stock solutions are generally mixed to prepare the nutrient solution. In recent years, liquid fertilizers that can meet plant demands with only one stock solu-
tion have been developed. A method for controlling nutrients quantitatively using this type of fertilizer for rockwool culture was developed (Fujio et al., 2017). The amount of fertilizer supplied was calculated based on the photosynthesis of the plant community (Fujio et al., 2015; Higashide et al., 2011). Sterilization of the nutrient solution is important for this recirculating type of hydroponic culture. A new solution-sterilization device using discharged plasma was developed to sterilize the nutrient solution (Fig. 12; Okumura et al., 2016; Saito et al., 2016, 2017; Takahata et al., 2015; Takano et al., 2015). The whole hydroponic system can be constructed at low cost as only one liquid fertilizer-incorporating machine is needed.

High temperatures in summer restricted tomato yield. Fogging systems effectively decrease the temperature in greenhouses. Recently, a fogging system that sprays mist with high water pressure in plant factories has been introduced. However, this system is too expensive to introduce to greenhouses in the Kesen area. A fogging system using low water pressure was therefore developed. The spray droplets in this system are larger than those in the high-pressure type, resulting in the plants tending to get wet. To prevent plants from excessive wetness, a controller was developed to fog water at low water pressure. The controller calculates the vapor pressure deficit and determines the amount of water for fogging corresponding to the environmental factors. Consequently, it can decrease the air temperature in greenhouses and avoid excessive water fogging.

By introducing both rockwool culture and environmental control, especially temperature control by means of fogging, it was possible to increase the yield of tomatoes to 30 kg·m⁻².

Conclusion

Restoring facilities in the confined land space of the Kesen area has proven difficult. Development of greenhouses and equipment using specialized regional products and accessible materials was implemented and cultivation methods for tomatoes and strawberries were developed. In the areas of the region that have not yet completely recovered as of 2018, research to promote more advanced protected horticulture will need to be carried out continuously.

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