# High-Quality Tomato Seedling Production System Using Artificial Light

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We have developed a closed system for growing tomato seedlings using LEDs as the main light source. Although closed production systems reduce the risk of pest infection without using pesticides, tomato seedlings grown under artificial light for a long time are subject to physiological disorders. Our production system suppresses this problem and grows uniformly large seedlings, thereby shortening the cultivation period between seeding and harvesting. This paper describes how the system suppresses physiological disorders, while controlling air flow for uniform growth. (This research was conducted in collaboration with Chiba University.)

Keywords: artificial light environment, seedling production, tomatoes, physiological disorder, hydroponics

## 1. Introduction

Farming population in Japan is decreasing substantially and aging rapidly. Under this situation, to ensure stable domestic food supply and enter the overseas food market, which is expected to grow in the future, it is necessary to help farmers boost their incomes and increase the number of new willing farmers. We have developed a technology that features an improved bottom-watered sand cultivation system (New Sandponics) to enable harvest of 22 tons per year and 1,000 $m^2$ of popular tomatoes with a sugar content of more than 6 degrees.(1) At these quality and crop yield levels, a farming family is considered to be able to achieve sales of about JPY 80 million/year and profits of about JPY 10-20 million/year from a growing area of 1 ha, an area deemed to be able to be operated.

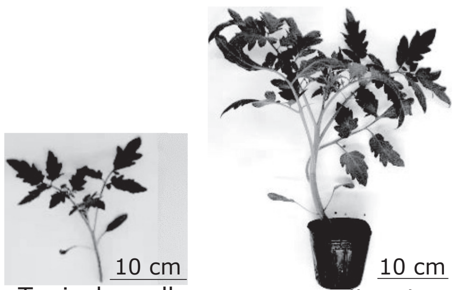


Photo 1. Typical small seedling (left) and large seedling produced by Sumitomo Electric (right)

To realize this model, it is necessary to ensure a stable supply of large seedlings that can be harvested about one month after transplanting them in a farming field. Currently, the only practical way is to purchase about three-week old small seedlings and grow them in the farming field for another 2-3 weeks to obtain large seedlings (Photo 1). Issues associated with this include the resulting decrease in the available farming field area and the cultivation cost. Moreover, in the farming field, small seedlings are exposed to pests and diseases, and may be wilt before transplanting (Table 1). To address these issues, we have developed a technology that grows sprouting seeds to large seedlings in an artificial light environment protected from pests and diseases.

Table 1. Advantages and challenges of different seedling production environments

| | Greenhouse | Facility for Artificial Environment | |
|---|---|---|---|
| | | Existing System | Sumitomo Electric's Seedling Production System |
| Advantages | • Low equipment cost<br>• Low running cost | • Low pest and disease risks<br>• Pesticide-free<br>• Easy to ensure uniform quality | • Low pest and disease risks<br>• Pesticide-free<br>• Easy to ensure uniform quality<br>• **Capable of producing large seedlings** |
| Disadvantages/ Challenges | • Difficult to ensure uniform quality<br>• High pest and disease risks<br>• Farming field required for secondary seedling production | • High initial cost<br>• Limited output<br>• Capacity only suitable for small seedlings<br>• **Prone to physiological disorders** | • High initial cost<br>• Limited output |

## 2. Common Cultivation Method for Super Sweet Tomatoes and Cost of Large Seedlings

Transplanted tomato seedlings set flowers and fruits in clusters (1st, 2nd, etc.). When super sweet tomatoes, which are preferred in Japan, are subjected to stress, the yields decrease for the 3rd and subsequent clusters. Therefore, it is a general practice to transplant as many seedlings as possible in a unit area and growing them up to the 3rd clusters (low node-order pinching). For example, in the case of few-cluster close planting up to the 3rd cluster and using small seedlings, harvest is possible about 8 weeks after transplanting in a farming field and cultivation ends in 14 weeks. After the maintenance of the culture medium, small seedlings are transplanted again in the 15th week. Accordingly, tomato growers have 3.5 crop cycles (from transplanting to harvesting) every year; that is, 12 clusters a year (3 clusters/crop cycle × 4 crop cycles). Assuming that 1 cluster (3-4 tomatoes) weighs 500 g, the yield is expected to reach 20 t/1,000 $m^2$ based on a general transplanting density of 4,000 plants/1,000 $m^2$. If large seedlings are available, harvesting can begin 6 weeks after transplanting, enabling the tomato grower to transplant seedlings for the next crop cycle 13 weeks after transplanting. In this system, the yield will be: 500 g/cluster × 3 clusters × 52 weeks/13 weeks × 4,000 plants/1,000 $m^2$ = 24 t/1,000 $m^2$. The average wholesale price of tomatoes is JPY 350/kg. Accordingly, sales will increase by JPY 1.35 million/year if large seedlings are used. The number of required seedlings is 4,000 × 52/13 = 16,000. If a large seedling is JPY 50 more expensive than a small seedling, the resultant increase in profits will be JPY 560,000 per year and 1,000 $m^2$.

## 3. Issues in Artificial Light-Based Seedling Production

One major issue in raising large tomato seedlings under artificial light is that during cultivation the leaves can develop physiological disorders. This issue emerges about 15 days after sowing. In the early stage, bumpy calluses occur on leaf surfaces and veins, as shown in Photo 2. In an advanced stage, whole leaves die, eventually resulting in the death of the entire plant. This physiological disorder rarely occurs in greenhouses, but tends to develop in an artificial environment. Moreover, the tendency to develop physiological disorders differs between tomato varieties.[2]

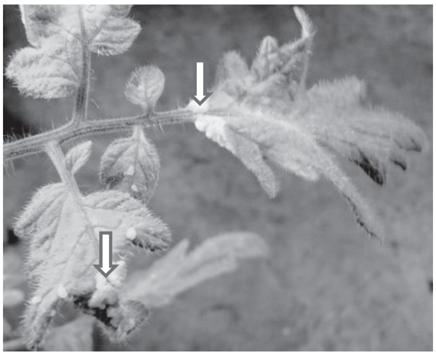

Photo 2. Physiological disorders (calluses) on a tomato seedling raised in an artificial environment

The variety we choose for its high disease resistance, which is an important factor during cultivation, is relatively prone to physiological disorders and dropped several lower leaves before the seedlings became large.

Meanwhile, it is also an important challenge to raise seedlings with uniformity. When growing seedlings, closed environments are more advantageous than open environments in that: they require less resource; flower differentiation, node order, and other qualities are stable;[3] and low pest and disease risks enable pesticide-free cultivation.[4] On the other hand, closed environments are disadvantageous in that their initial costs are high, making it necessary to grow seedlings at a high density. If grown at high density, plants receive breeze unevenly. Particularly, if the cultivation period is long, as with large seedlings, seedlings grow to varying heights. Two major environmental factors that affect seedling height are breeze and light. It is relatively easy to make arrangements to provide a favorable light environment by regulating irradiation intensity[5] based on the leaf area index (LAI) and using suitably installed reflectors and light sources. However, to achieve a favorable breeze environment, it is difficult to control the air velocity within a range of 0.3–1.0 m/s ± 0.1 m/s across the entire cultivation space.

## 4. Measures to Counter Possible Physiological Disorders

Using a 12 $m^2$ environmentally controllable closed system constructed at Chiba University, we conducted basic research, which revealed that physiological disorders develop under the following environmental conditions.

(1) Continued high humidity at a relative humidity (RH) of 85% or higher
(2) $CO_2$ concentration level around 1,000 ppm
(3) Use of fluorescent or LED light as the main light source.

### 4-1 Improving high-humidity environment

If exposed to a high-humidity environment, leaves develop bumpy physiological disorders. This has been also reported to occur in grafting,[6] which is a technique used to cultivate different types of plants as one plant by inserting a plant of a variety that has tasty fruit to a base plant of a variety that is highly disease resistant. A common method to raise tomato seedlings is to vary the temperature setting for day (the light period) and night (the dark period). In our experiment conducted in an artificial environment, an air conditioner was installed in the experimental system to control the temperature. The humidity began to increase in the system when the light period was switched to the dark period. During the dark period, a 100% RH environment continued. The plant transpiration rate is about 10 times higher in the light period than in the dark period. Nonetheless, the air conditioner needs to have a dehumidification function even during the dark period. The use of a single air conditioner results in high humidity. The reason is that, during the light period, the air conditioner removes heat from the illuminating light source and also dehumidifies the air, and in the dark period, in which the light source does not generate heat, the dehumidification rate decreases to below the transpiration rate of seedlings (Fig. 1). As a solution, we installed equipment intended for dehumidification to maintain the humidity setting between 60% and 80% RH during seedling cultivation (Fig. 2). The resulting

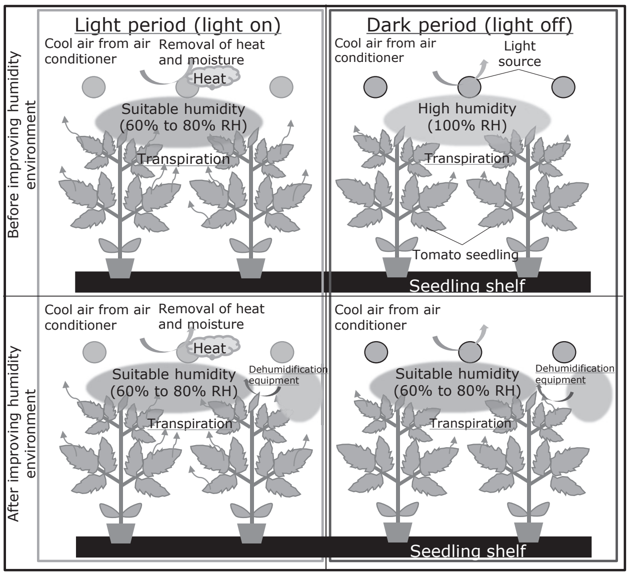


Fig. 1. Schematic diagram of humidity environment in experimental system

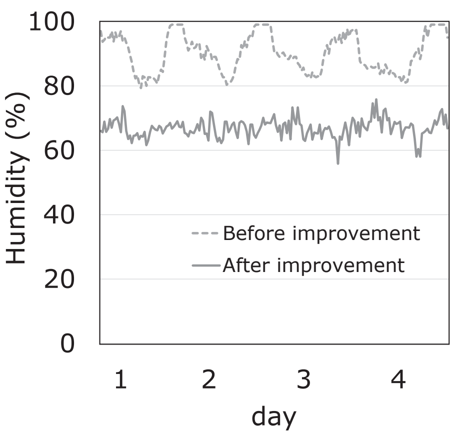


Fig. 2. Actual humidity in experimental system after environmental improvement

increase in equipment cost was 1% of the overall system cost, which is deemed to be within a tolerable range.

In the testing of seedling production before environmental improvement, physiological disorders were observed on lower leaves of 63% of the plants, although the variety was one with a low degree of developing physiological disorders and less likely to turn into severe conditions. The development rate of physiological disorders decreased to 2% after environmental improvement.

### 4-2 Improving high $CO_2$ concentration environment

In an artificial environment, the $CO_2$ concentration is often raised to approximately 1,000 ppm to boost the growth rate. However, it has been reported that in high $CO_2$ concentration environments at 1,200 ppm and higher, physiological disorders occur depending on the plant species.(7) In some cases of long-term cultivation, chlorosis (yellowing or whitening of leaves due to decreased chlorophyll in the leaves) and necrosis (partial discoloration or death of tissue) can occur. For tomatoes, the limits of upper $CO_2$ concentration differ depending on the light environment. Generally, the upper limit is 1,000 to 1,500 ppm under clear conditions and 500 to 1,000 ppm under cloudy conditions.

In the previous seedling production tests, the $CO_2$ concentration was controlled to 1,000 ppm, which potentially was causing physiological disorders as a result of an excessive growth rate, as in the above example. Therefore, as a solution, the $CO_2$ concentration was set to a similar level to the atmosphere of between 400 and 500 ppm. In this environment, the results of a seedling production test showed that the occurrence of physiological disorders was 100% controlled with a variety with a medium level of physiological disorder development rate and 70% with a variety with a high level of development rate. Moreover, the severity of disorders was low. Compared with growth in high $CO_2$ concentrations, the growth in the said environment decreased, which was indicated by the dry matter weight of aerial parts reduced by 21%. With the risk of physiological disorder development taken into account, this decrease is within a tolerable range.

### 4-3 Effective light quality for reducing physiological disorders

It has been reported that, even during LED-based seedling production, similar physiological disorders were reduced by the use of far infrared rays.(8) It is highly probable that light quality control is effective for reducing physiological disorders. According to our findings, white fluorescent lights and white LEDs differ in the degree of physiological disorder development. LEDs have been known to result in a higher rate of occurrence of physiological disorders than fluorescent lights and in a tendency towards severer conditions. LED light is ultraviolet-deficit, while fluorescent light includes some ultraviolet rays. Deducing that this is one factor involved, we radiated ultraviolet rays at an intensity of 0.5 W/m$^2$ using ultraviolet lamps in addition to main light source LEDs (Fig. 3). Incidentally, ultraviolet lamps (Fig. 4) with a narrow wavelength band with a peak at 310 nm were selected so as to make the effect of ultraviolet irradiation.

In the test zone that used LEDs as the main light source and additional irradiation of ultraviolet rays, the occurrence of physiological disorders decreased by 84% in comparison with the test zone that did not use ultraviolet

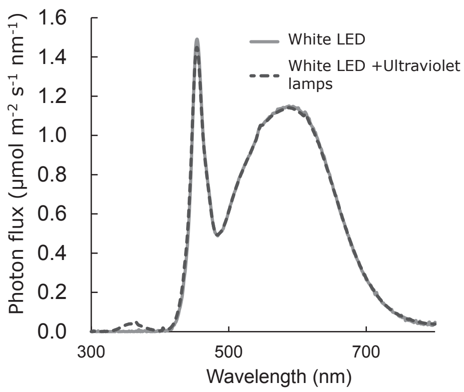


Fig. 3. Quantity of irradiated light for testing with additional ultraviolet lamps

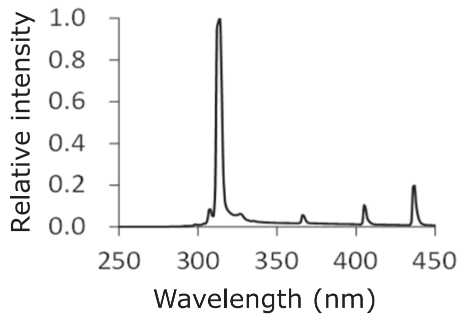


Fig. 4. Spectrum of ultraviolet lamp light

irradiation. When ultraviolet irradiation was discontinued during the growth period, development of physiological disorders was observed 5 days after the discontinuation. Consequently, the test revealed the necessity to radiate ultraviolet rays continuously at least during the light period. Furthermore, raising the irradiation intensity of ultraviolet rays to 1.0 W/m$^2$, twice as high as the aforementioned intensity, resulted in an approximately 30% decrease in dry matter weight of aerial parts, although it was effective in reducing physiological disorders at a similar level to that of irradiation at 0.5 W/m$^2$. The results revealed that excessively intense ultraviolet irradiation retards growth more than necessary and it is important to regulate the irradiation intensity of ultraviolet rays.[9] Furthermore, under identical light conditions, two watering methods were compared: a hydroponic system that provided plants constantly with a nutrient solution and a horticultural soil-based system that provided a nutrient solution several times a day. The results revealed that physiological disorders developed in the case of using the horticultural soil in a fewer number of growth days than in the case of the hydroponic system. This suggests the possibility that greater fluctuations in the moisture content in plant bodies are significantly contributory to the occurrence of physiological disorders.

Plants have a light-sensitive protein to sense ultraviolet and other rays of light[10] and exhibit various reactions to the light received. Their reactions to ultraviolet rays is as follows. In the UV-A wavelength range, reactions include, in addition to reactions produced by UV photoreceptors, those produced by phototropin, which is a blue light-sensitive protein that recognizes visible blue light. Reactions include suppression of spindly growth, floral bud flowering promotion, and promoted synthesis of anthocyanin and other pigments. UV-B is known to retard growth because its energy is stronger than UV-A. Reactions include the promotion of synthesis of antioxidants in plant bodies to remove oxidized substances occurring from ultraviolet irradiation and strengthening cell walls to reduce the amount of ultraviolet transmission into leaves.

It is likely that the aforementioned effects occurred due to the UV-B wavelengths that we used for ultraviolet irradiation. Meanwhile, physiological disorders developed several days after the discontinuation of ultraviolet irradiation during seedling production. Hence, it is highly probable that the occurrence of physiological disorders was reduced by the improved capability of removing active oxygen species (which occur during fast seedling production) owing to the promotion of antioxidant synthesis, rather than by the effect, on disorder reduction, of physical structural changes resulting from strengthened cell walls.

## 5. Measures for Uniform Seedlings

In our system designed to raise large seedlings of tomato in 5 weeks, variations in the raising environment have a substantial influence on the height of the raised seedlings and result in unevenness in quality. Therefore, we improved the air flow environment, a factor affecting seedling height.

### 5-1 Air flow environment around seedling shelves

We conducted simulations and analyses to explore air flow methods to meet both uniformity and air velocity requirements. To achieve uniform velocities of air passing through the tomato seedling production space, we measured actual air velocities in the space, modeled hampered air flow, and worked out an optimum ventilation method.

Ventilation methods are classified roughly into the blowout and extraction methods. Placing importance on a uniform air flow in the seedling production space, we adopted the extraction method that produces a mild air flow. One issue associated with the extraction method is a low air velocity. We examined a system designed to raise the air flow rate without the use of any additional cost-increasing fans. In this novel system, openings were provided near fans to reduce pressure losses of air flow around the fans and to expand the range of air drawn in by each fan. This was effective in avoiding rapid increases in the air flow rate near the fans. Thus, it became possible to maintain the air velocity within a favorable range and improve air velocity uniformity without the use of any additional fans. This technique is also expected to enable enclosure cooling fans to exert energy-saving effects. Moreover, alternate placement of fans in upper and lower positions was effective in improving uniformity in air flow in the upper and lower regions in the wide seedling production space required to raise large seedlings (Fig. 5).

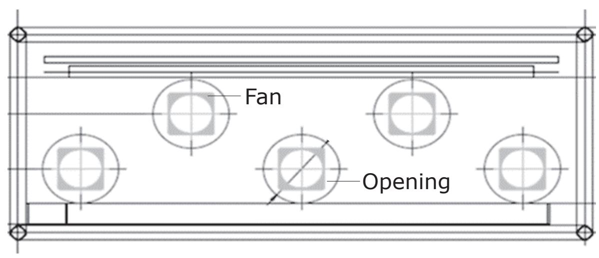


Fig. 5. Placement of fans for seedling shelves

### 5-2 Analysis of ventilation environment in commercial-scale equipment

The system under consideration for commercial-scale equipment connects seedling shelves. Connected seedling shelves require a favorable ventilation environment, for which we worked out a ventilation method through simulations and analyses.

To achieve a uniform air flow in the seedling production space on connected shelves, it is ideal to create a unidirectional breeze without the installation of any fan in the middle of the shelves. Analysis results showed that the air velocity in the seedling production space could be maintained within a favorable range by providing fans at the air outlet and placing the shelves close to each other (Fig. 6). Incidentally, the seedling shelves created 3-tier seedling production spaces. In this configuration, it was possible to avoid stagnant temperature zones in the system by guiding the air flow on the tiers alternately from left to right and then from right to left, which produced an air flow in the overall system (Fig. 7).

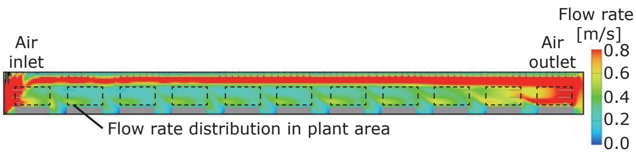


Fig. 6. Air flow analysis results of connected seedling shelves

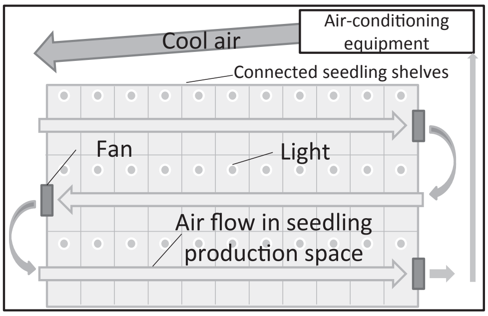


Fig. 7. Schematic diagram of air flow in entire system

## 6. Comprehensive Measures and Cultivation Results

Our artificial light-based large-seedling production system combined the above-described measures to control humidity levels between 60% and 80% RH and $CO_2$ concentration between 400 and 500 ppm, while using a suitable amount of UV-B irradiation in addition to the main LED light source. These measures were effective in reducing physiological disorders at a rate of 100% for varieties with low or medium levels of occurrence of physiological disorders and 94% for those with high levels of disorder development. The artificial light-based large-seedling production system proved itself to be capable of raising tomato seedlings in an artificial light environment in a period of about 5 weeks. Moreover, by adopting the above-mentioned ventilation system, uniformity in seedling height improved by 36% on all seedling shelves.

We cultivated general small seedlings and large seedlings produced by our seedling production system simultaneously in the New Sandponics, a cultivation system developed by Sumitomo Electric Industries, Ltd. The large seedlings grew faster than the small seedlings roughly by 2 weeks. The growth difference continued until the end of cultivation, proving that large seedlings reduce the cultivation period per crop cycle.

## 7. Seedling Production and Operation Using Commercial-Scale Equipment

Lastly, this chapter describes the artificial light-based large-seedling production system that we are currently designing for a 1 ha farming field.

The system uses a 40 feet reefer container used for freight transport on cargo ships. Crop seedling shelves are installed inside the container to enable tomato seedling production. In the container, seedling shelves can be moved and connected. While seedlings are raised, shelves remain connected. When it is necessary to work in the container, seedling shelves can be slid back to allow for a work space. Without the sliding function, the container accommodates 8 groups of seedling shelves (with each group consisting of 3 tiers). In contrast, the above-described structure enables placement of 11 groups of shelves, which means a 38% increase in seedling production area, making it possible to raise about 4,000 large seedlings at once (Fig. 8).

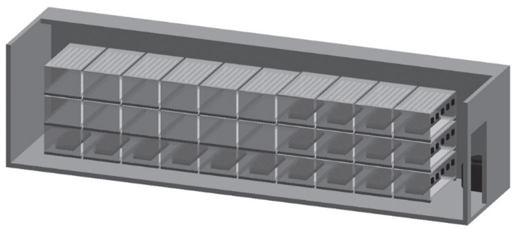

Fig. 8. Schematic diagram of commercial-scale artificial light-based large-seedling production system

To purchase seedlings for transplanting in a farming field, as mentioned earlier, it is a common way to select small seedlings grown for about 3 weeks after sowing. There are reasons for avoiding the transport of large seedlings: it is difficult to perform moisture control during transportation; transportation can subject the plants to shocks, which involves a high risk of damage to leaves; and the cost of transportation is high. By utilizing the seedling production system in a place close to a farming field, it is possible to avoid the afore-mentioned transport risks and to raise the farming field utilization efficiency, eliminating the need for the farming field to be occupied for secondary raising of seedlings. Furthermore, the seedling production system raises seedlings in a favorable environment. This implies that seedling production (from sowing to completing the growth of large seedlings) takes 5 weeks stably throughout the year, facilitating cultivation planning for the farming field. In the case of few-cluster close planting, in which a large cultivation field is divided into several small blocks, the frequency of supplying seedlings to the farming field increases. Therefore, it becomes possible to run the seedling production system constantly at a high rotation rate.

While the target cost is set at JPY100/seedling, the seedling production system takes advantage of a used shipping container in an area-efficient manner and is expected to achieve this target, taking the system cost into account. Furthermore, in comparison with small-seedling production systems on the market, the present system will potentially reduce the system cost to about two-thirds in the case of raising similar small seedlings.

## 8. Conclusion

The artificial light-based large-seedling production system of Sumitomo Electric is capable of raising large tomato seedlings of a high-quality level. The system is isolated from the external environment and provides elements necessary, such as favorable temperature, humidity, light, $CO_2$, and nutrient solutions to produce pesticide-free seedlings with low pest and disease risks. Moreover, the present system reduces the occurrence of physiological disorders regardless of tomato variety, thereby producing evenly grown large seedlings. Specifically, this system runs most efficiently when supplying seedlings regularly to a farming field in which Low Node-Order Pinching of tomatoes is practiced.

## 9. Acknowledgments

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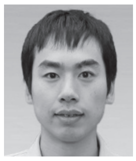

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