Review

A Review of Japanese Greenhouse Cucumber Research from the Perspective of Yield Components

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Japanese cucumbers are unique in terms of their production methods, such as steamed cultivation in which the greenhouse is closed to increase the temperature and humidity. Moreover, Japan has strict standards for fruit size. Therefore, most research on greenhouse cucumbers in Japan has focused on pests, diseases and fruit quality, and few studies have focused on increasing yields. Therefore, we aimed to contribute to a yield improvement in Japanese greenhouse cucumber production by considering environmental factors and training methods based on the yield components. Here, we discuss different training systems, pinching and lowering methods, and the effects of environmental factors such as temperature, humidity, CO₂ concentration, irrigation, and nutrition on yield and yield components. Moreover, this paper also proposes future areas of research for Japanese greenhouse cucumbers.

Key Words: Cucumis sativus, dry matter production, lowering cultivation, pinching cultivation, steamed cultivation.

Introduction

Cucumber (Cucumis sativus L.) is an important vegetable in Japan and has a long cultivation history. However, The planted area and yield have fallen to 10,300 ha and 548,100 t, respectively (MAFF, 2020 <https://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_yasai/>). This represents a 23% decrease in planted area (13,400 ha) and a 19% decrease in yield (674,600 t) compared to 15 years ago. On the other hand, the productivity of Japanese cucumbers is low, at 3.4 kg·m⁻² and 10.7 kg·m⁻² for summer-autumn and winter-spring cultivations, respectively (MAFF, 2020 <https://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_yasai/>). This is significantly different in comparison with a productivity of 72.8 kg·m⁻² in the Netherlands, an advanced facility-growing country (FAOSTAT, 2018).

This may be due to the slow spread of high-productivity technologies such as soilless nutrient cultivation and environmental control technology, as well as a lack of progress in developing suitable high yield varieties. However, the most important problem may be the unique Japanese cultivation system known as “Steamed Cultivation”, a characteristic cultivation method used in Japanese greenhouse cucumber production. Steamed cultivation was referred to as a humid culture condition in a previous study (Hirama et al., 2011), and greenhouses are closed to increase the temperature and humidity (30°C and above 70% relative humidity) before noon to promote the development of lateral branches and fruit development. However, this cultivation method promotes plant diseases and may increase workload because the difficult work environment. Furthermore, there are various training methods such as pinching, lowering, and renewed lowering cultivation, which require a lot of time for trimming, training, harvesting, and adjustment. Moreover, Japanese cucumbers have certain strict standards for fruit size: young cucumbers 22 cm long and weighing 100 g are preferred. With this background, past research on greenhouse cucumbers in Japan has been mainly conducted to control diseases, such as downy mildew and powdery mildew, and maintain fruit quality (Sakata et al., 2006; Yoshioka et al., 2014), and avoid bent fruit, bottom-gourd-shaped fruits, poor texture and gloss (Kanahama and Saito, 1989; Hirama et al., 2007; Sakata et al., 2011). In contrast, there is little information aimed at productivity improvements, such as increasing yield.

Therefore, the purpose of this study was to reconsider previous studies regarding the environmental control and training method used in greenhouse cucumber production in Japan from the perspective of yield.
components. We also aimed to acquire knowledge to support future improvement in yields of greenhouse cucumbers by referring to greenhouse production in the Netherlands, which has been actively trying to improve productivity.

### 1. Yield components

In recent years, in major cucumber production areas in Japan, there have been cases where 40 kg·m⁻² per year has been achieved by improving environmental control and cultivation techniques. In order to achieve higher yields in the future, it is necessary to conduct quantitative analysis from the perspective of dry matter production. Higashide and Heuvelink (2009) evaluated the differences in tomato productivity by analyzing the yield components, as shown in Figure 1. The yield components have a hierarchical structure; the elements in the lower layer determine the elements in the upper layer; the fruit yield fresh weight can be expressed as a product of fruit yield dry weight and fruit dry matter content. Thus, it is possible to clarify the factors contributing to the difference in yield.

According to studies by Higashide et al. (2012a) and Iwasaki et al. (2014), the light extinction coefficient of cucumber defined by Monsi and Saeki (1953) ranged from 0.8 to 1.69, while that of tomato was in the range of 0.6 to 1.0 (Higashide and Heuvelink, 2009; Higashide et al., 2012b), so cucumber has a higher light extinction coefficient than tomato. This indicates that the amount of intercepted light varies even with the same leaf area index (LAI) management.

The fruit distribution rate of cucumber varies throughout the growing season due to different female flowering rates and occurrence of fruit abortion in different cultivars. In fact, Heuvelink and Marcelis (1989) and Marcelis (1992, 1993a, b, 1994) developed a model to predict variable fruit distribution. This suggests that the number of fruit set and fruit distribution rate interact with each other. Data generated regarding the parts of the yield components that are affected by cultivars and cultivation systems in other crops as well as cucumbers can be used effectively for further technological development.

### 2. Environmental factors

In Japanese cucumber production, the relationship between environmental control and yield is not yet clear. Research has been conducted on the relationship between environmental factors and the occurrence of lateral branches. However, very little quantitative analysis has been conducted, making it difficult to detect the yield component that has affected the yield. In other words, it is difficult to evaluate the factors that result in a high yield due to the variation in LAI, the number of nodes with different plant densities and trimming methods. Here, we discuss the results of research on each environmental factor.

#### 2.1 Temperature

Temperature is closely related to the growth rate, having a strong influence on the rate of increase in the number of nodes and the rate of fruit growth (Marcelis, 1993c; Marcelis and Baan, 1993). This indicates that temperature affects the intercepted light caused by increased LAI in the yield component.

The development rate is related to the day and night temperature, and therefore, to the 24-h mean temperature, as observed for cucumber (van Uffelen, 1989). The high temperature and humidity during steaming cultivation in the morning are not suitable for workers. Kawashiro et al. (2010) found that the workload was greatly reduced by maintaining a target temperature of

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Fig. 1. Components contributing to fresh fruit yield in cucumber (Higashide et al., 2012a): total dry matter production (TDM), light use efficiency (LUE), and leaf area index (LAI).
25°C in a greenhouse for 2 hours from 9:30 to 11:30 a.m. which is the harvest time, and then 33°C for 2 h until 13:30 p.m. In this study, it was found that the same yield (16.8 kg m⁻²) and quality were obtained by maintaining the temperature at the same level compared with steaming cultivation: the maximum temperature was 28°C, and the harvesting operation in the greenhouse could be made more comfortable. Ehara et al. (2017) investigated the effect of a higher afternoon temperature followed by a quick temperature drop in the early evening on the growth of cucumbers. They found that this treatment reduced the days required for harvesting (13.6 days to 12.8 days and 13.0 days to 12.0 days in the fruits that flowered on December 2 and February 2, respectively) and increased the average fruit weight (89.7 g to 93.6 g) due to increased fruit surface temperature, which promoted fruit growth. It was evident that the treatment suppressed leaf growth and lateral branching and reduced the number of harvested fruits in the low sunshine period; therefore, no difference in total yield was observed with this treatment. This result suggests that dry matter production mostly depends on the average daily temperature. On the other hand, at different temperatures, Marcelis (1994) estimated that the whole plant potential vegetative growth rate of cucumber increased from 7.8 to 9.3 g d⁻¹ when the temperature increased from 18 to 24°C.

Temperature greatly influences the leaf appearance rate (Baker and Reddy, 2001; Marcelis, 1993c). Therefore, methods that increase the average temperature are useful for securing LAI and increasing the amount of integrated light by accelerating the development of the number of leaves. Similarly, high temperature management to increase the number of nodes (improving the number of fruits) could be also be considered.

However, in Japan, temperature is controlled at lower than the optimum temperature to reduce energy costs. This may cause the reduction in plant vigor due to low temperature management, and the inability to secure LAI in the spring when solar radiation improves. Furthermore, at present, growth characteristics at low temperatures have not been modeled. Therefore, it is necessary to investigate the effect of dry matter production on the critical temperature, and to manage the temperature appropriately, balancing the cost-effectiveness.

2.2 Humidity

Humidity levels generally affects diseases and pests; high humidity promotes downy mildew and brown spots, and low humidity promotes powdery mildew (Sun et al., 2017; Whipps and Budge, 2000). On the other hand, extremely low humidity (excessive transpiration) leads to a decrease in photosynthetic rate and leaf area. However, there is no literature indicating that increased humidity directly promotes photosynthesis and improves yields. Nevertheless, in actual production sites, there have been several cases where suitable humidity control affected stomatal conductance and improved yields by promoting photosynthesis.

Very few studies have investigated the relationship between humidity and dry matter production in greenhouse cucumber production. In previous studies, Bakker (1991) observed no clear effects of vapor pressure deficit (VPD) varied from 0.3 to 0.9 kPa on fruit dry matter content in tomato and cucumber. However, the VPD value is expected to be higher than that mentioned above because of the higher temperature in Japan. Sakiyama et al. (2002) reported the effect of humidity conditions (RH40, 60, 80%; 1.1 to 3.4 kPa) at 35°C on young plants, and the relative growth rate of dry matter production and leaf area were higher at RH60 and 80% than 40%, which suggests that an increase in LAI contributed to the increase in the amount of integrated light and to the dry matter growth. Therefore, it is desirable to maintain the relative humidity at 60% or more at higher temperatures. On the other hands, Hirama et al. (2002) stated that the number of harvested fruits increased (43.0 to 50.2 per plant) due to the enhancement of second and subsequent lateral branching at 25°C and 40% RH compared with 30°C and 60% RH, suggesting that steaming cultivation (high humidity and temperature) may not be the optimal cultivation method in terms of the environmental conditions. Based on these results, it is necessary to analyze the effect of humidity on dry matter production in cucumbers.

2.3 CO₂

CO₂ is commonly used in greenhouse cucumber production, and its effectiveness is known to be superior to than that on tomatoes and bell peppers (Nederhoff, 1994). Nederhoff (1994) found that in the 200 to 1,100 ppm CO₂ concentration range, cucumbers had an increased fruit distribution rate and light use efficiency (LUE) was also increased by 10 to 15%. Kawashiro et al. (2009) reported that CO₂ application at 500 ppm (7 h application) or 1,000 ppm (3 h application) increased fruit yield by 39 to 55% compared with non-application. Further applying 500 ppm CO₂ for 7 h was more effective at increasing the yield of cucumber than 1,000 ppm for 3 h. In this research, a higher LAI, net assimilation rate and relative growth rate were observed, suggesting that the synergistic effect of the increase in the amount of interception light caused by increased LAI, and the LUE due to CO₂ supply induced a higher total dry matter (TDM) and yield. In addition, Iwasaki et al. (2014) analyzed the yield increase with CO₂ supply (800 ppm) and humidity control (RH70–80% when the temperature was above 25°C) based on the yield components in three different cultivars. As a result, the increase in LUE (11–19%) was due to increased photosynthetic rate, and fruit distribution due to a reduction in fallen and aborted fruit.

These results suggest that CO₂ supply is necessary to
increase yield in cucumber production. However, in a number of scenarios in Japanese greenhouse cucumber production, it is not cost-effective to supply high CO$_2$ on cloudy days and before the plant community has formed. Therefore, to achieve high productivity in cucumbers, it is important to create an optimal environment for dry matter production by appropriate supply of CO$_2$ along with ensuring a suitable amount of light reception.

2.4 Irrigation & Nutrition

Nutrient and water management are indirectly closely related to dry matter production. In soil cultivation, even if the same nutrient and water management are conducted with similar control of environmental factors such as temperature, humidity, and CO$_2$, the growth will be different due to differences in the physical, chemical and biological properties of the soil, which makes it difficult to conduct research while maintaining the same water content in different soil conditions. On the other hand, growers are reluctant to actively irrigate because of concerns about disease caused by high humidity, and in many cases they do not irrigate properly. Insufficient irrigation not only causes a reduction in photosynthesis due to stomatal closure, but also leads to a reduction in the amount of light interception due to a decrease in leaf area and lateral branch development. Although, management with a pF meter and a soil moisture sensor using the time domain reflectometry method or the amplitude domain reflectometry method is increasing, there is no clear standard for soil conditions. Therefore, in the future, it will be important to develop a model that can quantitatively determine the water management required by plants based on environmental and biological information.

On the other hand, the use of bloomless rootstock makes plants susceptible to disease and pests, resulting in low silicon content (Hasama, 1992; Hasama et al., 1993). Therefore, it is necessary to determine the range of silicon fertilization that does not cause blooms while maintaining the silicon content, or to select varieties that do not cause blooms. In recent years, there has been a growing interest in the nutrient cultivation of cucumbers, but most cultivars have been selected and bred by soil cultivation with an emphasis on the water deficit tolerance, nutrient stresses and diseases, rather than yield. Therefore, it is necessary to breed and research cultivars suitable for hydroponic cultivation to improve yield and productivity.

3. Training methods

In Japanese cucumber cultivation, there are two major cultivation methods, the pinching and lowering methods, and the pinching method is the most common because of the structural limitation of greenhouses with low eaves. In this method, the lateral branches developing from the axillary buds are repeatedly pinched to increase the number of lateral branches, which is important to increase the yield. However, the method of plucking differs depending on the producer and variety, which causes significant differences in plant vigor and LAI, leading to differences in yield. On the other hand, lowering cultivation is often used in employment-type production such as large greenhouses because of the ease of understanding in terms of the training method. A high rate of female flower setting, a so-called predominantly female type, is required because the method involves setting fruits on the main stem for a long period of time.

Isomura et al. (2001) selected cultivars of the predominantly female type and used low lateral branch development. They compared the harvest time in lowering cultivation with that of pinching cultivation and found that the time required per fruit was shorter (8.0 to 11.7 and 8.8 to 12.3 seconds for lowering and pinching, respectively) for lowering than pinching, and that lowering was less labor-intensive. In addition, Ota et al. (2005) stated that it is easier to maintain plant vigor in lowering cultivation at low temperatures and irradiation, and that it is possible to expand the scale of greenhouses using simple plant management. However, lowering cultivation is disadvantageous in that the total working time is increased (10%) in comparison with pinching cultivation. Hiramai et al. (2011) revealed that the lowering method with some lateral branches and three branches with non-training had higher numbers of fruits and marketable yields that was less labor-intensive than the pinching method by testing different training methods. Considering this result from the viewpoint of the yield component, the increase in the number of fruits due to the increase in the number of nodes, and the increase in the amount of light reception due to the increase in the LAI caused by extending the side branches are the causes of the increase in the yield.

Higashide et al. (2012a) analyzed the effects of the lowering and pinching methods on dry matter production and yield in short-term cultivation from the yield components, and found that the pinching cultivation had a higher yield than that of lowering. They stated that the result was due to a higher proportion of fruit dry matter and total dry matter. Moreover, there are relationships between total dry matter and light use efficiency in the total cultivation period, and the amount of light reception and total dry matter up to 40 days after planting. Further, Iwasaki et al. (2014) investigated the difference in yield between pinching cultivation and lowering cultivation in Japanese and Dutch cultivars in terms of yield components. As a result, Dutch cultivars had higher yields than the Japanese cultivars because of a lower light extinction coefficient and higher fruit distribution due to differences in sex expression. In addition, the yield was higher in pinching cultivation than in lowering cultivation caused by a lower light extinction coefficient and superior light use efficiency. Recently,
an increasing number of producers have adopted the “renewal lowering method”, which involves extending the newly lateral developed branches after promoting fruit growth at trained branches. Although this method has been shown to be effective in improving fruit quality and regulating harvest workload, it is still unclear whether the method is effective in dry matter production and yield potential. Therefore, it is necessary to conduct further research into this cultivation system in the future.

As described above, in greenhouse cucumber cultivation, there are differences in yield and workability according to the various cultivation methods, and the most suitable method for cucumber cultivation has not been determined. However, in terms of yield components, it is possible to clarify differences in yield, and the pinching method is more efficient than the lowering method in terms of the light extinction coefficient and fruit distribution. However, these results must be considered while acknowledging that the plants were cultivated for a short period and that cultivars with non-predominantly female plants were used.

In other words, the initial increase in LAI is directly related to the yield in short-term cultivation, but the planting density results of Higashide et al. (2012a) were 1.48 plants·m\(^{-2}\) and 0.99 plants·m\(^{-2}\) using the lowering and pinching methods, respectively, suggesting that the lowering method may not be suitable for short-term cultivation. In addition, Japanese cultivars have a low rate of female flowering on the main branches. Iwasaki et al. (2014) reported that Japanese cultivars are suitable for pinching cultivation. Therefore, in the future, it will be necessary to use cultivars with predominantly female plants and to consider cultivation methods for long-term cultivation. In Japan, short-term cultivation of two crops per year is common, and for material production, it is important to ensure community formation, i.e., an increase in LAI in the early stages of cultivation, but there are no reports that investigated changes in LAI over time. Therefore, in the future, more detailed studies are needed on cultivation methods to investigate changes in LAI over time and yield components.

**Future research**

We have discussed the influence of environmental factors and cultivation methods in terms of yield components. Environmental control has been carried out to enhance the lateral branches of the non-predominantly female plants. Furthermore, Dutch tomato cultivars have been improved to have higher LUE (Higashide and Heuvelink, 2009). In order to improve productivity, similar breeding approaches can also be expected to be effective in Japanese cucumber, and it is necessary to re-evaluate the response of various types of Japanese cucumber plants to environmental factors in (Sakata et al., 2011) based on dry matter production.

On the other hand, various models have been developed to predict and analyze many factors that affect growth and yield, and simulation models are also useful for quantitative analysis. Several models have been developed to predict yield and dry matter production in tomato (Dayan et al., 1993; Vanthoor et al., 2011; Lin et al., 2019), and efforts have also been made to analyze the potential yields in these models and the measured yield to analyze the reduction (Van Ittersum et al., 2013).

However, the yield model may require some important parameters that are difficult to estimate in an actual greenhouse environment, such as the potential growth rate and fruit distribution rate. Therefore, deep learning may be useful for more accurate predicted results. In fact, some models have been developed to predict yield and dry matter production in tomato (Lin and Hill, 2008; Ehret et al., 2011; López-Aguilar et al., 2020) by machine learning, and a product that predicts disease (Plantect, Bosch, Japan) has also been developed. On the other hand, it is extremely difficult to obtain accurate data to create a prediction model using deep learning. Especially in Japan, it is difficult to obtain accurate data because there are various cultivation methods, greenhouses structures, monitoring sites, and environmental control instruments. Therefore, it is necessary to develop a model for greenhouse cucumber production in Japan with high prediction accuracy, even if relatively less data is available, and to fine-tune the parameters for each greenhouse. On the other hand, simulation models may require plant information such as leaf area. Advances in sensing technology have made it easier to obtain plant physiological and morphological information. In fact, real-time monitoring technology for the photosynthetic rate in communities has been developed (Shimomoto et al., 2020).

Therefore, it is necessary to measure and analyze the causal relationship between growth and the environment in cucumber in more detail. Cucumber has a higher growth rate than that of other fruit and vegetables, which suggests that it should be easier to estimate the dry matter production than that of tomatoes and bell peppers. In addition, in order to obtain higher yields in the future, it will be essential not only to breed new cultivars, but also to construct new cultivation systems with quantitative analysis research in terms of dry matter production. We conclude that consistent management of cultivation, labor and distribution based on evaluation is essential for future Japanese greenhouse cucumber production.

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