REVIEW
Current Usage of Air Circulators in Greenhouses in Japan

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Abstract

In the last decade, air circulators have been widely used in greenhouses and high tunnels in Japan. The main purpose of air circulation is to provide uniformity in temperature, humidity level, and carbon dioxide concentration in greenhouse air. In addition, empirical knowledge that air circulation prevents hygrophilous diseases increased among growers, together with the inference that air circulation reduces the fuel consumption required for heating. Although the benefits of air circulation remain uncertain, some empirical evidence has been obtained from horticultural and engineering studies in Japan. In this review, the results of these investigations are summarized on the basis of five aspects: performance indicators for circulators, microclimate uniformity, crop yield, suppression of hygrophilous diseases and possible mechanisms. Practical issues regarding the installation of air circulators for greenhouses and high tunnels are also discussed.

Introduction

In many areas of Japan, greenhouses and high tunnels are often unventilated even during the early summer rainy season. Many crops thus face unventilated conditions coupled with the stagnation of air, resulting high humidity and dew formation in late stages of the crop. These conditions trigger the incidence of hygrophilous diseases such as *Botrytis cinerea* (gray mold), *Passalora fulva* (tomato leaf mold), and *Pseudoperonospora cubensis* (downy mildew). The combined operation of heating and ventilation can prevent unfavorable conditions, but such environmental control systems are not typically installed for small greenhouses and high tunnels in Japan due to the high cost involved. Instead of heating and ventilation, growers often create air circulation in the greenhouses by using plastic film ducts and forced-air heating equipment without fuel combustion (Kanaiso 2000, Ushio & Takeuchi 2006). As an alternative means of such forced-air heating equipment, the use of air circulators has spread widely in the last decade due to their reasonable installation cost.

Given the lack of related statistics, it is unclear when and how the widespread use of air circulators occurred in Japan's protected cultivation setting. The handbook of the Japan Greenhouse Horticulture Association (JGHA) did not include items regarding air circulation in protected cultivation until the fifth revision in 2003 (JGHA 4th ed. 2001, 5th ed. 2003). According to the articles of a public relations magazine (JGHA 2005), demonstration experiments of air circulators were apparently conducted at agricultural extension centers in some prefectures from 2000 to 2002.

Air circulation provides uniformity in temperature, humidity level, and carbon dioxide concentration in greenhouse air (Fernandez & Bailey 1994), and possibly reduces the fuel consumption required for heating, promotes photosynthesis, and mitigates summer heat damage in crops and among workers (Baba 2010). The installation of an air circulating fan system, which is regarded as an energy-saving measure, has been eligible for a subsidy from Japan's Ministry of Agriculture, Forestry and Fisheries since 2012. However, some benefits of air circulation remain uncertain, whereas others have yet to be confirmed. This review introduces horticultural and engineering studies that have investigated the performance of circulators and the effect

of air circulation on the microclimate and crop health in greenhouses and high tunnels.

Performance indicator

Various types of air circulators are available in Japan, and the differences among the products are based on their size, design, and performance. Such aspects of performance as airflow rate and coverage are generally specified. However, there is no standard procedure, even for measurement of the airflow rate of air circulators. The airflow rate of some domestic products is measured based on the JIS C 9601 standard (1990), whereas that of others is measured in accordance with ANSI/AMCA 230-99 (2000). The procedure under the JIS standard is based on the measurement of horizontal distribution of air velocity at three times the distance of the fan diameter from the outlet, whereas the procedure under ANSI/AMCA 230-99 is based on the measurement of thrust and ambient air density, and the impeller's physical diameter. Therefore, a comparison of commercial air circulators based on the airflow rates listed in the specifications is inadequate.

The air circulation coverage of six commercial fans was previously investigated using an identical protocol (Kuroyanagi 2013a). Airflow created by each fan was measured in a closed and empty garage (8.5 m in width, 33.6 m in depth, and 6.1 m in height). A 6 m × 25 m horizontal grid pattern with 1-m spacing was marked on the floor, and air velocities were measured at each intersection using four hot-wire anemometers at heights of 0.5 m, 1.0 m, 1.5 m, and 3.0 m; that is, air velocities were measured at 728 points for one circulator. The results showed that the percentage of measurement points varied among the circulators in a 6 × 25 m grid where the airflow generated by each circulator was observed. For data analysis, the range of air circulation was defined as the percentage of points where the measured air velocity was greater than 0.2 m s^{-1}. The power consumption correlated significantly with the range of air circulation observed (R = 0.84, P < 0.05), but the airflow rate listed in the specifications was not (R = 0.36, N.S.). It has thus been concluded that power consumption is a valid evaluation indicator for the performance of air circulators, although highly inefficient circulators are hardly distinguishable.

Uniform air temperature and humidity

The spatial gradient of air temperature in greenhouses affects the uniformity of crop growth. An investigation in a greenhouse with a 1.3 ha cultivation area showed that the stems of tomatoes became thicker and shorter in the area with a lower air temperature (Takayama et al. 2014).

Uneven growth is undesirable for not only the yield but also for crop management such as training or artificial pollination. In particular, protected horticulture in Japan largely depends on small-scale greenhouses and high tunnels, which often generate a gradient of air temperature between the center and alongside the walls or ceiling in all seasons. Therefore, the effect of air circulators on the uniformity of air temperature has been confirmed in small-scale greenhouses and high tunnels.

The effect of air circulation on the distribution of wind speed and air/leaf temperature in the daytime and in the heating hours at night was investigated for a double span greenhouse (Ishii et al. 2012). The greenhouse (14.4 m in width, 60.0 m in length, 4.2 m in height) was separated by plastic film into four compartments (7.2 m × 29 m). The circulators used in the study were axial fans (AB353a, Fulta Electric Machinery, Co., Ltd.; airflow rate of 79 m^3 min^{-1}) that provided horizontal airflow. Forced air heating (GPN25M, Fulta Ennetsu, Co., Ltd.; heating capacity of 53.4 kW, unknown airflow rate) was applied using a plastic film duct. The circulators were positioned at a height of 2.1 m for the compartment where tomatoes were cultivated (crop height of 1.8 m). During the daytime in winter, at least two circulators were necessary to provide a wind speed of at least 0.5 m s^{-1} above the crop, and at least 0.3 m s^{-1} in the crop canopy. The arrangement of circulators provided uniform air temperature with a standard deviation of 0.6°C or less, whereas the deviation was ca. 1.1°C without air circulation. The authors suggested that the effect of air circulation on leaf temperature was negligible because solar radiation had a greater impact on leaf temperature. During the heating hours, operation of the circulator decreased the standard deviation of air and leaf temperature at 1.5°C or less, whereas the standard deviation was 2.5°C and more without air circulation.

The effect of air circulation on the hygrothermal conditions was investigated for single-span high tunnels (Matsuura et al. 2004). Two high tunnels used in that study were of identical size (6 m in width, 15 m in length, 3.6 m in height) relative to the heating equipment. One high tunnel was equipped with an air circulator 2 m from the end panel at a height of 2.2 m. The type of circulator used in that study was an axial fan (280B, Vornado Air LLC; unknown airflow rate) that provided horizontal airflow. Forced air heaters (KA-321, Nepon Inc.; heating capacity of 37.2 kW; airflow rate of 60 m^3 min^{-1}) with plastic film ducts were used. The heaters maintained air temperature in the high tunnel at higher than 12°C. Non-grafted tomato seedlings (*Solanum lycopersicum*, cv. House Momotaro, Takii Co., Ltd.) were transplanted into fertilized soil (N:P:K = 2.0, 1.7, 2.0 kg a^{-1}) on November 2, 2001 and cultivated until June 2002 when the

fruit reached the 11th truss. The plant density was ca. 1.5 plant m^{-2}. The circulator created a wind speed of 0.5-1.3 m s^{-1} above the canopy, and 0.1-0.2 m s^{-1} in the canopy, whereas calm conditions were observed in the high tunnel without the use of any air circulators. Air circulation decreased the vertical air temperature gradient between inside and above the canopy, with values of 2.8°C for the control tunnel and 0.8°C on average for the high tunnel with the fan from January to February of 2001. A decrease in the vertical gradient of relative humidity was also observed, from 3.6% for the control tunnel to 0.1% for the high tunnel with the fan. The authors did not discuss the reason why horizontal airflow reduced the vertical gradient of air temperature and relative humidity. It could be explained by a circulation of airflow along the gable end wall of the high tunnel because airflow from a commercial air circulator reaches 20 m and more ahead (Kuroyanagi 2013a).

Yield and photosynthesis

Matsuura et al. (2004) also reported that air circulation significantly increased the yield in January from 369 g m^{-2} for the control tunnel to 622 g m^{-2} for the tunnel with the fan (P = 0.0047). In contrast, the total yield was 9.1 kg m^{-2} for the control tunnel and 9.3 kg m^{-2} for the high tunnel with the fan. There was no significant difference between both tunnels for the total yield (P = 0.9892) and unmarketable yield (P = 0.7353).

Matsuura et al. (2004) suggested that the increased yield at an early period resulted from higher temperature within the canopy for the high tunnel with air circulation. Their assumption is supported by the dependence of progress of an initiated fruit towards ripeness on temperature (Heuvelink 2005). On the other hand, the increase in yield might be related to the enhanced gross photosynthesis of leaves due to the supply of airflow around 0.5 m s^{-1} (Yabuki & Miyagawa 1970). Shibuya et al. (2006) confirmed that the relationship between the enhancement of photosynthesis and the airflow supply for tomato seedlings that were raised at ambient carbon dioxide (CO_2) concentration, whereas air circulation did not change the total dry matter production and cumulative fruit growth for mature tomatoes raised at an elevated CO_2 concentration. (Elings et al. 2007). Therefore, the increased yield at an early period in Matsuura et al. (2004) might be mainly attributable to the rise in air temperature around the first truss of tomatoes. Further studies should be conducted to deepen understanding of the relationship among air circulation, canopy photosynthesis, and crop yield at ambient CO_2 concentration.

Support pest management

Some growers believe that air circulation in greenhouses creates an aerial environment that prevents or delays the incidence of hygrophilous diseases. This effect may be related to the acceleration of evaporation and transpiration in crops. A few reports have struggled to verify the effect of air circulation on the suppression of diseases in high tunnels as shown in Fig. 1.
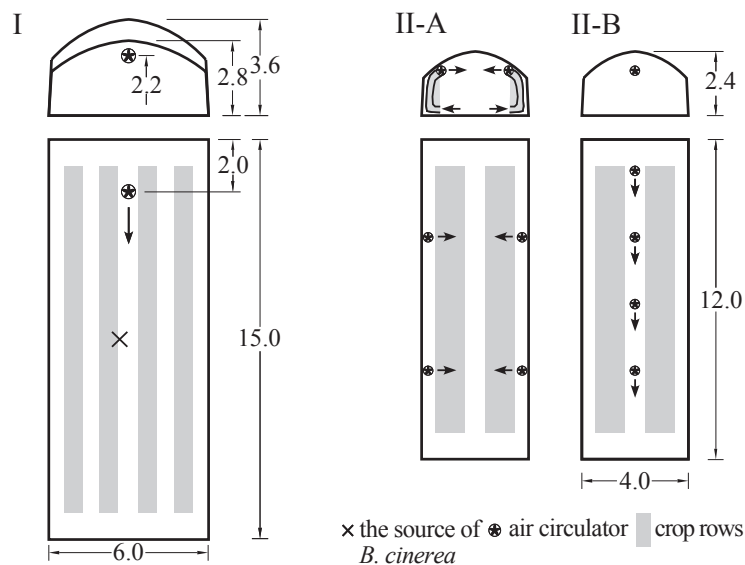

Fig. 1   Schematic diagram of the high tunnels in I) Matsuura et al. (2004), and II) Sekine et al. (2007)

The effect of air circulation on the incidence of *B. cinerea* (gray mold) and *P. fulva* (leaf mold) in tomato was investigated for single-span high tunnels (Matsuura et al. 2004). The tunnels and cultivation conditions of tomato are described in the section titled "**Uniform air temperature and humidity.**" The source of *B. cinerea* with fungicide resistance (phenotype RSS) cultivated using potato dextrose agar was placed at the center of each tunnel on April 8 (157 days after transplantation), whereas the source of *P. fluva* was not introduced artificially to both tunnels. The number of leaves infected with *B. cinerea* and *P. fluva* was counted every 10 days after inoculation. The numbers of total fruits and those infected with *B. cinerea* were counted on the last day (May 22) of the investigation. During the investigation from late April to late May, air temperature and relative humidity above the crops were 19.8 °C and 84.8% on average in the high tunnel with the fan, and 19.9 °C and 85.3% in the control tunnel, respectively. The first incidence of *B. cinerea* was observed on April 25 (17 days after inoculation) in the control high tunnel, and on May 14 (36 days after inoculation) in the high tunnel with the fan. The *B. cinerea* infection expanded more quickly in the control tunnel than in the high tunnel with the fan. The final proportion of leaves infected with *B. cinerea* in the control tunnel and air-circulated high tunnels was 11.3% and 0.6%, respectively. The difference in infection rate between high tunnels was significant (P = 0.00001). The final proportion of fruits infected with *B. cinerea* in the control and air-circulated high tunnels was 1.7% and 0%, respectively. In contrast, there was no significant difference in the infection rate of *P. fluva* between both high tunnels. Microclimate measurements showed that air circulation did not reduce relative humidity in the canopy, but did reduce the amount of water droplets on the fruits and increased evaporation from the wet plastic plates. Thus, it was suggested that suppression of the incidence of *B. cinerea* was associated with reduced wetting on the leaves and fruits.

The effect of air circulation on the incidence of *B. cinerea*, *P. fluva*, and *Oidium neolycopersici* (powdery mildew) in tomato was investigated for single-span high tunnels (Sekine et al. 2007). The three tunnels used in that study were of identical size (4 m in width, 12 m in length, ca. 2.5 m in height) and without heaters. Two tunnels were equipped with four fans (Fig. 1), whereas the other tunnel had no fans. Axial fans (MRS18V2-B, Oriental Motor Co., Ltd; airflow rate of 11.0 m³ min⁻¹) that provide horizontal airflow were used. For one tunnel (A), two couples of fans were positioned above the crop canopy, and the intakes of each fan were positioned near the ground using 1.7-meter-long flexible ducts (ca. ϕ200

mm). The fans of one couple faced each other and generated a head-on collision and vertical stirring of air at the center of the tunnel. For the other tunnel (B), four fans were positioned in series above the crop canopy. Thus, there was a difference in the range of air circulation between tunnels A and B. In the three tunnels, grafted nursery tomato (*S. lycopersicum*, cv. Momotaro 8, Takii Co., Ltd.) was grown in soil culture at plant density of 1.6 plant m⁻² from April to September 2006. After June 9, the tunnels were ventilated naturally through the side vents for 24 hours, and air was circulated from 6 p.m. to 6 a.m. The relative humidity in the tunnels exceeded 90% with considerable frequency during the night and on rainy days. Artificial inoculations of *B. cinerea*, *P. fluva*, and *O. neolycopersici* were not conducted. Three types of fungicides were used three times (74, 88, and 101 days after transplantation). The number of leaves infected with *B. cinerea*, *P. fluva*, and *O. neolycopersici* was counted every week. The number of fruits infected with *B. cinerea* was counted every three days. For *B. cinerea*, the first incidence was observed on the same day (56 days after transplantation) in all tunnels, and then its expansion in tunnel A was lower than that in tunnel B and the control tunnel. For *P. fluva*, the situation was almost the same as that for *B. cinerea*. For *O. neolycopersici*, the incidence was only observed in tunnel A. The proportion of leaves infected with *O. neolycopersici* reached 35% at the first incidence (73 days after transplantation), and then decreased due to the usage of fungicide. The authors suggested that the expansion of *B. cinerea*, *P. fluva*, and *O. neolycopersici* was associated with the hours when the leaves were wet with dew. The expansion of such hygrophilous diseases as *B. cinerea* and *P. fluva* in the control tunnel and high tunnel B was faster than that in high tunnel A. In contrast, the incidence of *O. neolycopersici* (a xerophilic fungal disease) in tunnel A was supported by the fact that the duration of wetting on the leaves in tunnel A was shorter than that in the control tunnel and tunnel B. The results obtained from tunnel B appear to be inconsistent with the investigation by Matsuura et al. (2004), where horizontal airflow suppressed the incidence of *B. cinerea*. This may be explained by the difference in airflow rate between the air circulators; that is, the air circulators used in tunnel B were insufficient to generate air circulation inside because they only had a fraction of the airflow rate of commercial air circulators.

Matsuura et al. (2004) and Sekine et al. (2007) similarly showed that the use of air circulators could suppress the incidence and expansion of *B. cinerea*. In contrast, there was a discrepancy regarding the effect of air circulation on the outbreak of *P. fluva*. This discrepancy may be associated with sensitivity to the duration of wetting

for the infection of *B. cinerea* and *P. fluva*. The incidence of *B. cinerea* can be suppressed when the duration of dew formation in the greenhouse is less than 5 h (Tezuka et al. 1983), whereas *P. fluva* can be induced by 30 min of wetting after inoculation (Abiko et al. 1986). Air circulation may be effective in the suppression of certain hygrophilous diseases due to the reduced presence of water droplets on crops resulting from the acceleration of evaporation, transpiration, and heat exchange between the crops and air. The next section briefly discusses the mechanism that explains the results of Matsuura et al. (2004) and Sekine et al. (2007).

Reduce wetness on crops

The effect of air circulation on the appearance of wet leaves and fruits was investigated for single-span high tunnels (Sekine et al. 2007). The tunnels, the equipment used, and the cultivation conditions for tomatoes are described in the section titled "**Support pest management.**" In these experiments, two couples of fans were positioned above the crop canopy in one tunnel (A), and the intakes of each fan were positioned near the ground. In the other tunnel (B), four fans were positioned above the crop canopy. A control tunnel was also prepared. The authors measured the temperature of the leaves and fruits, and regarded temperatures lower than the dew point as representing the appearance of wetting on the surfaces of leaves and fruits. The observation results indicated that at the first incidence of *B. cinerea*, the hours when wetting on the leaves occurred in all tunnels were 1 h, 12 h, and 5 h for tunnel A, tunnel B, and the control tunnel, respectively, on June 30. The same conditions were observed from June to July. Why the hours when leaves wetted in tunnel B were longer than in the control remains unclear. The authors suggested that air circulation in the vertical direction could reduce the duration of wetting on leaves and fruits and delay the expansion of *B. cinerea*.

The effect of air circulation on wetting and transpiration of tomato leaves was investigated using the chamber test (Kuroyanagi et al. 2013). Non-grafted tomato plants (*S. lycopersicum*, cv. Reiyo, Sakata Seed Corporation) grown in a container were separately placed in a darkened and constantly humidified growth cabinet (680 mm × 680 mm × 1990 mm), and then exposed to saturated humid air (relative humidity of 100%) and three levels of air circulation intensity (wind speeds of 0.05 m s^{-1}, 0.16 m s^{-1}, and > 0.29 m s^{-1}). The air circulation was created by the combination of eight axial fans (ASEN 60511, Panasonic Corporation; airflow rate of 0.26 m^3 min^{-1}). An electric balance was used to measure the transpiration rate automatically, whereas wetting on the leaves was

manually measured using several dozen pieces of cotton. The measurements indicated an increased evaporation rate in direct proportion to air velocity around the plants. In contrast, the wetting on the leaves was completely suppressed under well-circulated conditions (i.e., velocity of > 0.3 m s^{-1}). This study indicates that air circulation reduces the wetting of plants by guttation under dark and high-humidity conditions, which is likely to suppress the secondary spread of pathogens.

The wetting of crops results from three factors associated with the high humidity of greenhouses: (1) condensation falling from greenhouse covers, (2) condensation on the leaf or fruit surface, and (3) guttation, which is the exudation of drops of xylem sap resulting from root pressure (Kuroyanagi et al. 2013). Sekine et al. (2007) focused on estimating the appearance of wetting resulting from (1) and (2), whereas Kuroyanagi et al. (2013) revealed the effective range of wind speed for suppressing the wetting on leaves resulting from (3). Both studies suggest that the usage of air circulators reduces the wetting on crops. However, the mechanism remains unclear regarding whether air circulation removes water droplets on the crops by promoting evaporation or suppresses the appearance of water droplets by promoting transpiration and heat exchange between the crops and air, or both.

Perspective

Solar radiation and the use of forced-air heating certainly causes a spatial gradient of air temperature in greenhouses and high tunnels. The results of the greenhouse and high tunnel experiments show that the proper usage of air circulators cancels the gradient and provides uniform air temperature. In contrast, there is an opposing idea of creating a gradient of air temperature between the upper and lower parts of greenhouses to reduce the fuel consumption of heating and increase the commercial fruit yield (Kawasaki et al. 2011). For other aspects such as pest management, there is evidence that air circulation suppress the incidence and expansion of *B. cinerea*. However, the mechanism remains unclear. Apparently, air circulators do not provide a panacea for uneven crop growth and crop disease. Thus, the installation of air circulators should be determined based on the conditions of greenhouses and crops on a case-by-case basis.

The number and position of circulators providing the desired conditions depend on the location, size, and shape of greenhouses, the capacity of the heating equipment, the performance of the circulators, and the type of crop. Thus, it is difficult to determine the optimum arrangement of air circulators based on available literature. Currently, computational fluid dynamics (CFD) is used

in predicting the distribution of air velocity in greenhouses (Kuroyanagi 2013b). The CFD approach may be a common procedure that provides the ideal arrangement of air circulators in various types of greenhouses.

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