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REVIEW

Development of Cooling Techniques for Small-scale Protected Horticulture in Mountainous Areas in Japan

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Abstract

Small-scale protected horticulture is carried out in mountainous areas, such as in the sloping terrain and highlands of Japan. Given the cooler climate in mountainous areas, agricultural products can be produced there during summer, which is the off-crop season in the flatlands. However, the effects of global warming are making it harder to produce vegetables in summer, even in mountainous areas. Therefore, cooling techniques have been developed and improved for small-scale protected horticulture in mountainous areas. Intercepting solar radiation is an effective way to limit temperature rise in greenhouses. By using a computer program responsive to solar radiation intensity controlling a motorized movable shaft system with a shading material, it is possible to reduce the temperature in greenhouses caused by excessive-solar radiation without affecting photosynthesis. Such evaporative cooling techniques as the fog cooling and the pad and fan cooling systems were previously too expensive and complex to install in small-scale greenhouses. These systems have now been simplified with the costs reduced. Local cooling techniques are efficient for summer production. These techniques can locally and directly cool the specific parts and ambient temperature of a plant. In strawberries, for example, the formation of flower buds will be accelerated by locally cooling the crown or the root zone, thereby accelerating the harvest period.

Discipline: Horticulture
Additional key words: automatic shading, evaporative cooling, fog cooling, local cooling, pad and fan cooling

Introduction

In Japan, mountainous areas account for about 40% of all cultivated lands, and a corresponding proportion of growers use those areas (Ministry of Agriculture, Forestry and Fisheries 2015, Statistics Bureau, Ministry of Agriculture, Forestry and Fisheries 2015). But given the narrow and sloping terrain in these situations, it is challenging to pursue agriculture profitably. On the other hand, agriculture in rural communities is expected to drive regional revitalization.

Mountainous areas offer certain advantages over flatlands regarding agricultural production. In Japan, highlands are generally defined as regions at an altitude higher than 500 m and with summer temperatures of less than 25°C (Hamashima 1970). As the lapse rate from June to September is about 0.57°C•100 m^{-1}, the climate in summer is cooler in the highlands than on the plains (Fukuoka 1966). Therefore, agricultural products can be produced in the highlands during the off-crop-season of summer (Nagasaki et al. 2005, Kawashima 2015a). Many mountainous areas also feature sloping terrain, and slopes can positively influence plant growth processes, such as photosynthesis. For example, on sloping land facing east, south or west, the amounts of light intercepted by the middle and lower leaves in tomato plants and the amount of photosynthesis per plant were estimated to be higher in sloping lands with a 20° angle of inclination than in flatlands with a 0° angle of inclination (Higashide 2010).

In the 1970s, rain shelters were developed for vegetable production to improve yield and quality in

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mountainous areas, especially on sloping lands (Futatsudera et al. 1976, Yukitake et al. 1982). Although the rain shelters helped improve vegetable productivity, they could not completely protect the vegetables against rain, wind, insects, and disease (Sakoda 2009). In addition, typhoons caused severe damage to the shelter structures and the crops inside. However, relatively few greenhouses and tunnels have been introduced due to the difficulty of building such facilities on sloping land. Practical techniques for protected horticulture are required to enable year-round and reliable crop production in mountainous areas. Therefore, a flat-roof sloping greenhouse, which can be built on sloping and irregularly shaped fields, has been developed (Nonaka et al. 2001; Nagasaki et al. 2005; Kawashima et al. 2007a, 2007b, 2011, 2015a; WARC/NARO 2008, 2017).

The flat-roof sloping greenhouse has adequate wide-open ventilation and is thus suitable for agricultural production in summer (Kawashima 2015a). A thermal environment-control technique for flat-roof sloping greenhouses has also been developed (Kawashima 2015a). In a conventional greenhouse, a thermal gradient will occur during heating. This problem cannot be overcome, even with the proper installation and use of heaters, circulating fans, and warm air ducts. Thus, small-scale growers in mountainous areas can practice protected horticulture with a flat-roof sloping greenhouse and suitable techniques.

The air temperature has been rising in recent years due to global warming (Akiyama 2007, Kawaguchi 2016, Abdureyim 2019). Vegetable production is thus becoming increasingly difficult in summer, even in mountainous areas. Therefore, cooling techniques have been developed to facilitate reliable vegetable production in summer. Although such techniques were initially expected to be simple and cheap, most of the existing cooling methods are too expensive for small-scale growers (Yamanaka & Kawashima 2019). In this review, we describe trends in the development of cooling techniques for small-scale growers who practice horticultural production in mountainous areas (Table 1).

Intercepting excessive solar radiation

Of the components of solar radiation, light ranging from 400 nm to 700 nm (Photosynthetic Photon Flux (PPF)) and that from 700 nm to 800 nm (Far-red light) are essential for plant growth processes, such as photosynthesis and photomorphogenesis. However, radiation longer than 800 nm (infrared radiation) is not necessary for plant growth. Infrared radiation has high thermal energy and causes temperatures to rise. On sunny days in summer, there can be enough light to sustain photosynthesis even in the presence of shade. Therefore, shade is an effective way to prevent solar radiation from causing a temperature increase in greenhouses.

In order to shade against solar radiation only on sunny days, an automatic shading system has been developed (Kawaguchi et al. 2017, Yano et al. 2020). This system consists of a computer with an irradiance sensor and a motorized movable shaft system with a shading material (Fig. 1). The computer controls the motor. When an amount of solar radiation measured by the irradiance sensor exceeds the set value, the motor with the movable shaft system rolls down the shading as instructed by the computerized control program. The plants are then protected against excessive solar radiation. When the amount of solar radiation measured by the irradiance sensor is less than the set value, the program instructs the motor to roll up the shading material to promote photosynthesis as much as possible. This technique has been successfully demonstrated for tomato and strawberry production.

Table 1. Cooling techniques for small-scale protected horticulture

Categories	Techniques	Years
Preventing thermal energy	Automatic shading system '*Nissya-sousa kun*'	Kawaguchi et al. (2017)
	Automatic shading system with multi-layered thermal curtain made of nanofiber controlled by 'YoshiMax'	Yano et al. (2020)
	Water curtain in summer	Iwasaki et al. (2007)
Evaporative cooling techniques	Low-cost fog cooling system	Shibata (2012)
	'*Cool Sat*' system	Tokujyu-Kogyo Co, Ltd. (2018)
	Simply installed pad and fan cooling system	Watanabe et al. (2013)
	System design by simulating using computation fluid dynamics (CFD)	WARC/NARO (2019)
Local cooling techniques	Medium-temperature cooling system using evaporative cooling	Yamazaki et al. (2007)
	Crown-temperature cooling technique	Okimura (2009)

A water curtain (thermal screen) can also prevent thermal energy from solar radiation. Water transmits PPF but absorbs about 45% of the infrared radiation (ranging from 800 nm to 1,000 nm) that causes temperature increases in greenhouses (Iwasaki et al. 2011). The water curtain needs sufficient cold water, which is sprayed on the internal thermal screen. In a greenhouse with the water curtain, the air temperature, leaf temperature of strawberry, and medium temperature of high-bench culture are also cooled (Mihara 1972; Iwasaki et al. 2007, 2011). In this way, the water curtain maintains conditions suitable for plant growth (Ibuki & Iwasaki 2010). This technique requires a large amount of cold water in the summer. As many mountainous areas are blessed with abundant groundwater, this technique could be easy to adopt in such places.

Evaporative cooling techniques

Evaporative cooling techniques can effectively lower greenhouse temperatures. However, their cooling efficiency depends on the humidity or vapor pressure deficit (VPD) in greenhouses. Fog cooling and pad and fan cooling systems are examples of such techniques. These systems are expensive and complicated. A fog cooling system inhibits a temperature rise in greenhouses by fogging from overhead nozzles installed in the greenhouses over a constant time interval (Hayashi 1998). The cost of introducing a fog cooling system is too high for small-scale greenhouses of less than 300 m^2, and the nozzles require time-consuming and labor-intensive maintenance. There are also concerns about the fog generated by this method in making the leaves wet and causing plant disease. To overcome the above problems, a low-cost fog cooling system has been developed (Shibata 2015). This system utilizes a circulating fan with mist nozzles (Fig. 2). The mist nozzles are attached on the blower side of the circulating fan. This system thus offers a significant reduction in the required number of nozzles, the introductory cost, and the time needed for nozzle maintenance. The initiation of fogging is triggered in this system by a change in VPD during an arbitrary time (ΔVPD) calculated by the difference between the dry-bulb air temperature and wet-bulb air temperature in the greenhouses. The fogging time and interval time are used to control the fogging volume. Both fogging time and interval time are determined according to the relationship between ΔVPD in real time and their set values.

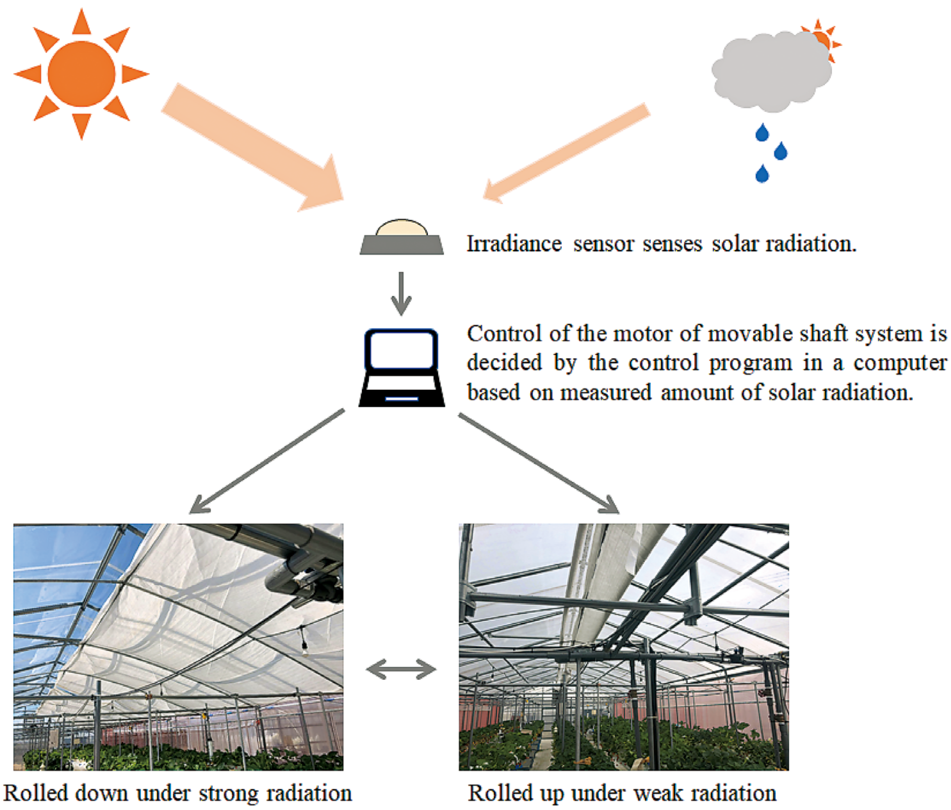

Fig. 1. Automatic shading system under strong radiation (left) and weak radiation (right)
When the control program is used to control the motor of a movable shaft system in response to the strength of solar radiation, the shading material attached to the movable shaft is rolled down (left) or up (right).

This system reduces excess water and does not wet the leaves. A demonstration study to evaluate the effects of this low-cost fog cooling system was conducted in an area at an altitude of 400 m (Shibata 2015). The study compared the marketable fruit yield from July to November produced by a cooled greenhouse with a low-cost fog cooling system and a conventional greenhouse without cooling. The results showed that the fruit yield in a very hot summer was approximately 13% to 15% higher in the cooled greenhouse than in the conventional greenhouse, while the fruit yield in a less hot summer was only 5% higher in the cooled greenhouse than in a conventional greenhouse. Therefore, the low-cost fog cooling system would be suitable for hot regions. However, a few problems were noted with this system. When relative humidity (RH) is less than 50% in this low-cost system, the cooling effect may decrease due to the lack of fogging volume. And although it was difficult to avoid the incidence of wet leaves completely, the demonstration study conducted over three years found that wet leaves caused no diseases.

A cooling and saturation deficit system, namely the '*Cool Sat*' system, is a recently developed fog cooling technique (Tokujyu-Kogyo Co., Ltd. 2018). This system consists of a greenhouse with exhaust fans and nozzles to produce mist in the periphery of the greenhouse (Fig. 3). The greenhouse space in this system is separated into upper and lower areas by an internal screen with some holes. The lower area is open, with an insect screen to cover the side ventilator, while the upper area is enclosed without exhaust fans. Fogging on the periphery of the greenhouse is used to cool the outside air. When the air is removed from the greenhouse by the exhaust fans, cooled and humidified outside air is drawn inside the greenhouse through the side ventilator covered by the insect screen. When the flow of air passing through the holes in the internal screen is temporarily aggregated, the ventilation efficiency of the greenhouse increases. This is how '*Cool Sat*' cools and humidifies the inside of the greenhouse. For example, from 10:00 to 16:00 on July 24, 2018, the air temperature and RH were 4.5°C to 8.5°C lower and 23% to 28% higher, respectively, than in a conventional greenhouse (Tokujyu-Kogyo Co., Ltd. 2018). In addition, the incidence of wet leaves is completely avoided because fogging is done outside of the greenhouse. Although the original version of '*Cool Sat*' required a special greenhouse structure, the newly improved system can be installed in existing greenhouses at an appropriate cost.

A pad and fan cooling system consists of large ramified-cellulose pads and big fans (Hayashi 1998). The large pads are installed on one side of the greenhouse, and the big fans are placed on the opposite side (Fig. 4 (A)). The pads are made wet, and then the fans draw outside air into the greenhouse through the pads. The air is cooled by evaporation as it passes through the large, wet pads. This is how a pad and fan cooling system cools and humidifies the inside of a greenhouse. However, this system is not suitable for small-scale greenhouses because it is expensive and requires a robust structure. Most small-scale greenhouses lack the required strength

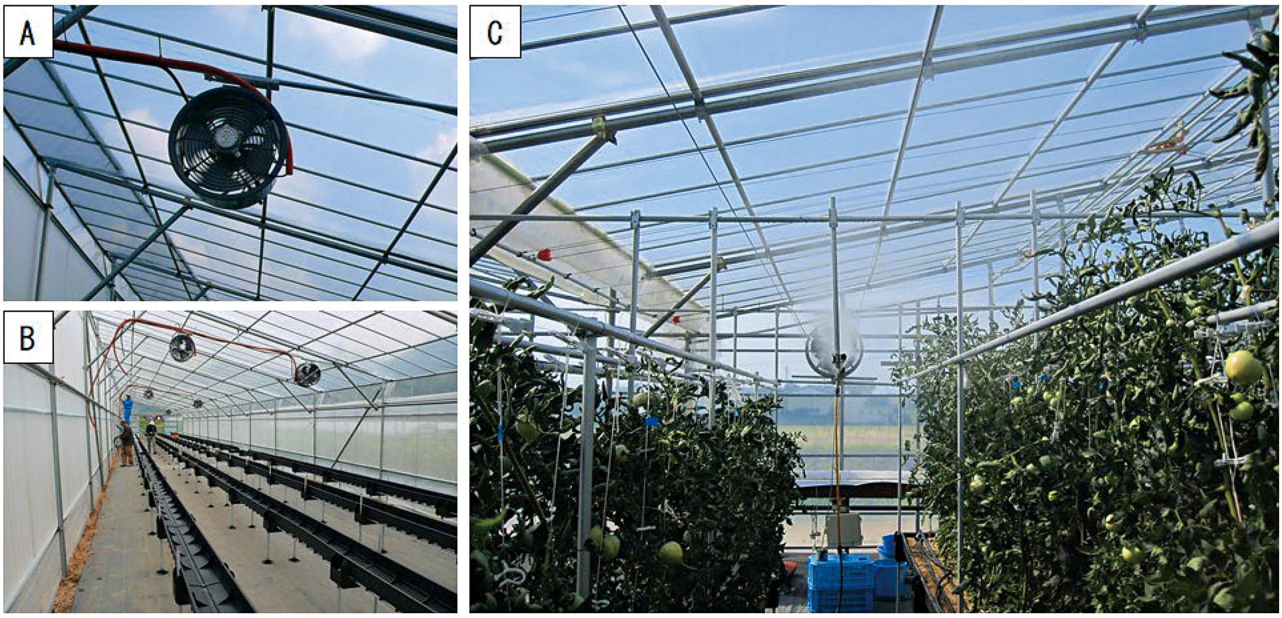

Fig. 2. Low-cost fog cooling system
Circulating fans equipped with a mist nozzle (A) are installed in a greenhouse (B).
Each fan sprays water and cools the greenhouse internally by evaporative cooling (C).

and wall size. Moreover, a thermal gradient may occur in greenhouses with this system. Therefore, a simple pad and fan cooling system has been developed as an alternative (Shimazu 2013, Watanabe et al. 2016, Murakami et al. 2018). This system is suitable for small-scale greenhouses, especially those ranging from 100 m^2 to 300 m^2. In this system, a unit consisting of a small fan and a small ramified-cellulose pad with an irrigation tube is installed in a greenhouse (Fig. 4 (B)). This system even works with quite simple structures. Air is blown into the small wet pad and is cooled and humidified. The cooling effect of this system is enhanced by wind from the small fan and is most efficient at wind speed of 1 m•s^{-1}. Given the unit's limited cooling area, four units are required every 100 m^2. This system can efficiently cool the inside of a greenhouse with a thermal gradient occurring less frequently. In the daytime, the maximum and average air temperatures will be 5°C and 1.3°C lower in a greenhouse cooled with a simple pad and fan cooling system than in a conventional greenhouse without cooling, and VPD will also be smaller in the cooled greenhouse than in the conventional greenhouse (Watanabe et al. 2016). As a result, the marketable fruit yield per a tomato plant will be 45% higher in a greenhouse cooled by this method than in a conventional greenhouse. Some small pads can also be installed in an air duct with a fan. Using the fan to blow air into the duct will generate cooled air from the small pads. In this case, only one fan controls some pads. System performance has been evaluated for improvement by simulation using computational fluid dynamics (CFD) (WARC/NARO 2019, Kuroyanagi & Yoshikoshi 2019).

Local cooling technique

While standard cooling techniques cool the whole greenhouse space, local cooling techniques directly cool the specific part of a plant, such as a shoot apex or rhizosphere. Many studies have shown that plant growth can be managed by local temperature control techniques. Moreover, local cooling techniques have less cooling load in summer than standard cooling techniques.

Local cooling techniques have been mainly developed for strawberry forcing culture, a major type of cropping in Japan. In a forcing culture, strawberry fruits are produced from November to May. Nowadays, the air temperature in fall is increasing due to the effects of global warming, thereby making it difficult to induce flower bud differentiation at low temperatures as required in strawberry. Therefore, cooling techniques are required. Local cooling techniques have been shown to reduce the resting phenomenon of yield in forced strawberries. This is the non-harvesting period from the end of harvesting

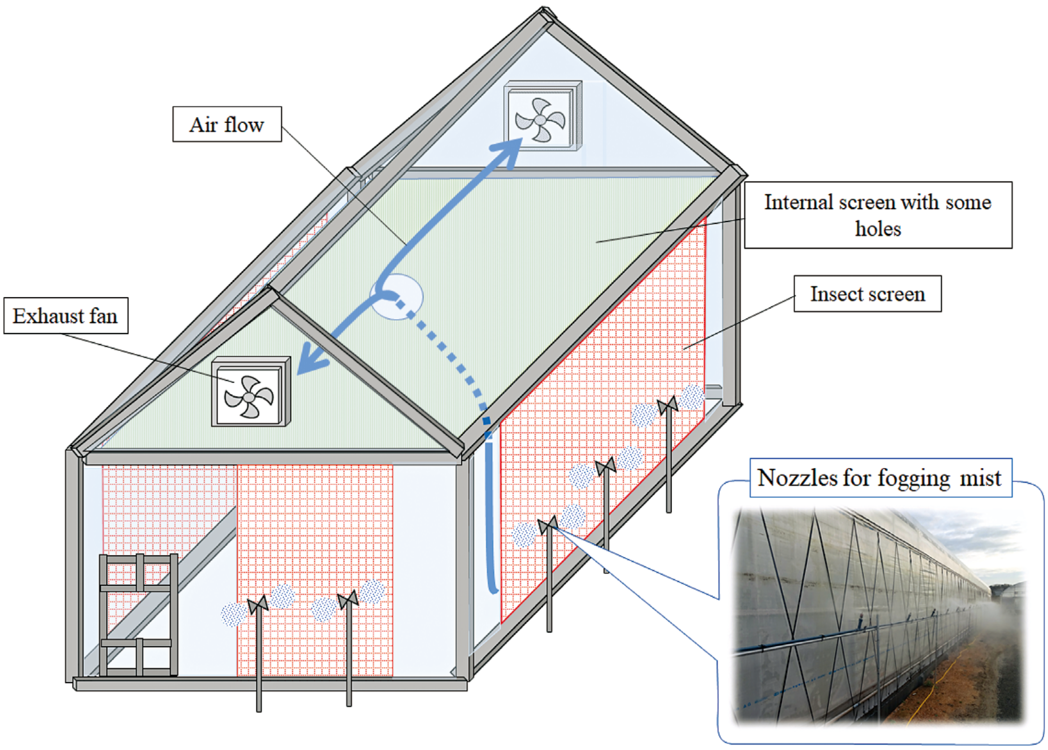

Fig. 3. Schematic graph of Cool Sat
In the periphery of the greenhouse, air is cooled and humidified by fogging mist. The cooled and humidified air is drawn into the greenhouse by exhaust fans via the side ventilator covered by an insect screen.

the fruits of terminal fruit clusters to the start of harvesting the fruits of the second fruit cluster (Yamazaki et al. 2007, Hidaka et al. 2017). Conversely, strawberry fruits are mainly produced in such cold regions as Hokkaido, Tohoku, and the highlands of Japan using summer and autumn culture. In the future, however, global warming will make such cultivation and production difficult. Therefore, local cooling techniques can be used for summer and autumn strawberry culture.

For high-bench strawberry cultivation, a medium-temperature cooling system using evaporative cooling has been developed (Yamazaki et al. 2007, WARC/NARO 2013). In this system, a waterproof sheet covers a hammock-type bed made of non-woven fabric. This allows a pool of redundant water to form on the waterproof sheet by irrigation. Once the redundant water evaporates under fan-blown air, the bed's growth media are cooled. In the daytime, the temperature in the media is about 5°C cooler with this system than with a non-cooled system, and flower bud differentiation of the secondary flowers will be accelerated by about 5 to 10 days (Yamazaki et al. 2007). The system is also expected to improve root growth by lowering the root zone temperature to below 25°C.

A crown-temperature cooling technique has also been developed (Okimura 2009, Hidaka et al. 2017). In this technique, the crown is cooled locally by feeding cold water into a pipe placed near the crown (Fig. 5). Flower bud differentiation of the secondary flowers may be accelerated by about 10 days when using water at 20°C for the crown cooling from August 19th to September 30th (Hidaka et al. 2017). Although a chiller is needed to generate cold water, it is too expensive for small-scale greenhouses. Therefore, the setup and running costs are more expensive in the crown-temperature cooling technique than in the above medium-temperature cooling

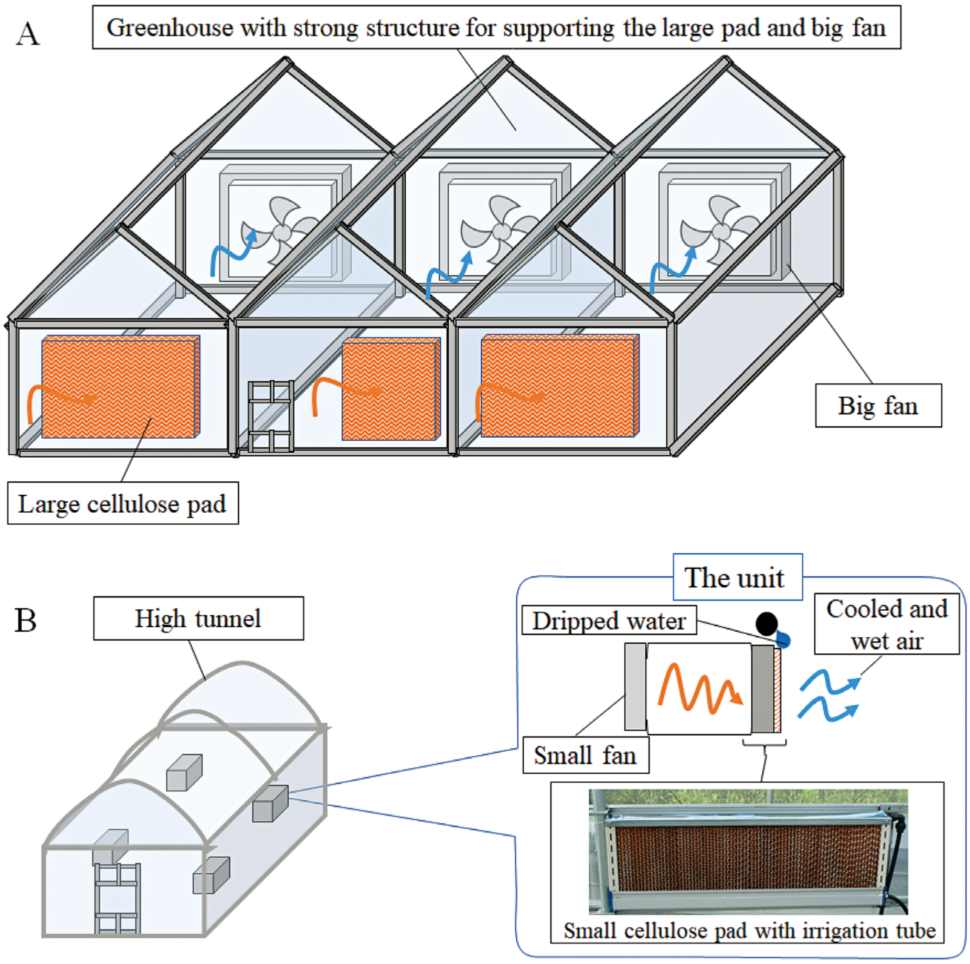

Fig. 4. Schematic graph of conventional pad and fan cooling system (A) and simply installed pad and fan cooling system (B)
In the conventional pad and fan cooling system, a greenhouse built with a strong structure is required to support the large ramified-cellulose pads. Conversely, the simply installed pad and fan cooling system can be installed in high tunnels.

system using evaporative cooling. However, it may be possible to reduce the chiller costs in areas with abundant cold groundwater ranging from 15°C to 20°C, so as to make the system more convenient for small-scale growers. Moreover, assuming operation in summer, the crown-temperature cooling technique could surely accelerate flower bud differentiation as compared with in the medium-temperature cooling system. The cooling effect of the crown-temperature control technique is hardly influenced by ambient temperature, whereas the cooling effect of the medium-temperature cooling system is certainly influenced by ambient temperature. When choosing between these two local cooling techniques, it will be important to consider the climate, the local resources, and the operating costs.

Conclusion

The mountainous areas of Japan have a complex geography and experience diverse weather conditions, but also possess valuable resources such as cool air temperature, inclination, and water. Hence, there are a variety of cooling techniques for small-scale protected horticulture in mountainous areas. A specific technique can be chosen according to the needs of the region (Kawashima 2015b). All of these techniques must be both effective and low cost. These techniques increase a grower's profits by extending the harvesting period or improving such crop qualities as weight and appearance. Because these techniques can increase the productivity of narrow fields, they are suitable for small-scale growers who cannot extend their agricultural land.

The diversity and flexibility of these cooling techniques will prove advantageous for small-scale protected horticulture when employed in hot zones, such as member countries of the Association of Southeast Asian Nations (ASEAN). Moreover, the varied demands of many growers for cooling techniques would likely be satisfied. Therefore, these cooling techniques should be useful in many countries apart from Japan.

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Fig. 5. Strawberry crown-temperature cooling technique
Chiller-cooled water or cold groundwater is passed through a tube installed near the strawberry crown.

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