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REVIEW

Trends in the Development of Energy-saving Techniques for Protected Horticulture in Japan

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Abstract

In Japan, several protected horticultural farms depend on nonrenewable sources of energy, such as fossil fuels. However, widespread consumption of fossil fuels causes global warming, and fluctuations in fossil fuel prices may adversely affect farm management. Thus, new low-cost energy-saving techniques have been developed recently. For instance, a multilayered thermal curtain fabricated from nanofiber enhanced the thermal insulation of greenhouses, thereby reducing fossil fuel costs by approximately 35%-51%. Additionally, a local heating technique, which selectively heats areas surrounding the tomato shoot apexes and flower clusters using hanging warm air ducts, has been applied to reduce energy consumption in cherry tomato or tomato cultivation, reducing reduced fossil fuel costs by approximately 10% compared with the conventional method using ground-fixed warm air ducts. Furthermore, a low-cost multivariable environmental control system, "YoshiMax," simultaneously controlled the ambient temperature and CO_2 concentration in a greenhouse along with the frequency of fertigation in response to solar radiation; this improved plant growth and reduced CO_2 and fertilization costs. These and other similar techniques are expected to enable sustainable agricultural management. To increase the efficiency of energy use, it is also effective to increase yield per energy input via high-density planting using a movable bench, etc.

Discipline: Horticulture
Additional key words: local temperature heating, movable bench, multilayered thermal curtain, multivariable environmental control, ubiquitous environment control system

Introduction

Increasing costs of fossil fuels have adversely affected protected horticulture in Japan. In Japan, the area of greenhouses equipped with a heating system accounts for 17,388 ha (41.2%) of the total greenhouse area (42,164 ha) (MAFF 2018). Moreover, most of the greenhouses (89.6%) equipped with a heating system depend on fossil fuels. Given that excessive consumption of fossil fuels may worsen global warming (The Royal Society and the US National Academy 2020), energy-saving techniques for protected horticulture must be developed (Yamanaka & Kawashima 2019). In this study, we summarize the current trends of the development of energy-saving techniques and their characteristics in Japan (Table 1).

Reduction of heat load

To reduce energy consumption, heat load of greenhouses must be lowered. Energy-efficient heating of the interiors of greenhouses is limited by the lack of sufficient thermal insulation because most greenhouses have only a single layer of conventional covering material, such as agricultural polyvinyl chloride or polyolefin films. Moreover, installing simple internal thermal curtains has been proven insufficient in reducing energy consumption.

The use of water curtains (thermal curtains) in winter is an energy-saving technique that entails spraying groundwater over an internal thermal curtain at night (Ogura et al. 1982; Ogura 1983, 1984; Ogura & Mukai 1988). The sprayed water becomes cooler, as the

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Table 1. Low-cost, energy-saving, and/or high-yielding techniques described in this article

Categories	Techniques	Years
Enhancement of heat insultation	Water curtain	Ogura et al. (1982)
	Multi-layered thermal curtain made of nanofiber	*Noshoku-jigyo 27013C* Consortium (2018)
Local temperature control	Strawberry crown-temperature heating	Okimura (2009)
	Local-heating technique of (cherry) tomato around shoot apexes and flower clusters	Kawasaki (2010)
Environment control	Low-cost multi-variable environmental control system 'YoshiMax'	Yasuba (2018)
High density planting	Movable bench system	Nagasaki (2010)

groundwater is generally warmer than the external temperature. Spraying water at an appropriate temperature maintains the geothermal flow, which is the main heat source in nonheated greenhouses at night. The colder the external temperature, more the heat is generated from the sprayed water. Accordingly, water curtains tend to be particularly effective in terms of heat storage performance during very cold nights. For instance, a temperature within an unheated double-roofed greenhouse covered with an external film and equipped with a water curtain ranged from 5.5 to 8.3°C when the corresponding external temperature ranged from −8.6 to −6.8°C (Ogura et al. 1982).

Multilayered thermal curtains, which typically comprise a three- or more-layered structure, improve the thermal insulation of greenhouses (Kawashima 2015). These thermal curtains have a single layer of polyester cotton sandwiched between sheets of woven fabric, and they are often used in countries where the temperature is lower than that recorded in Japan, such as South Korea and China. In recent years, however, Japanese farmers have also focused on the use of such multilayered curtains. Although the thermal insulation provided by these curtains is 2.5-3.0 times greater than that provided by the conventional covering materials, the former tends to be thicker and heavier than the latter. Moreover, when rolled up, the multilayered thermal curtains can reduce solar radiation by up to 20%, thereby inhibiting photosynthesis. Additionally, multilayered thermal curtains are unsuitable for use in movable shaft systems. Accordingly, such curtains warrant structural improvements.

To overcome the aforementioned problems, a novel multilayered thermal curtain fabricated from nanofibers has been developed (*Noshoku-jigyo 27013C* Consortium 2018). This nanofiber curtain (the trial product) is more suitable for use in a movable shaft system compared with the currently used multilayered thermal curtain (the current product). The trial product has almost the same thermal insulation properties as the current product (Kawashima et al. 2017, *Noshoku-jigyo 27013C* Consortium 2018) (Fig. 1). However, the trial product with a thickness of 1.25 mm is approximately 41% thinner than the current product with a thickness of 3.05 mm (Fig. 2). The trial product has the same thermal insulation performance as the current product, whereas the daylighting inside the greenhouse is higher in the trial product than in the current product when they are rolled up during the day (Fig. 3).

The trial product is also more suitable for a 0.0750-mm-thick agricultural polyolefin film. The thermal insulation is much greater in the trial product than in a 0.0750-mm-thick agricultural polyolefin film. Conversely, the amount of solar radiation inside the greenhouse was only 10% lower in the trial product than in a 0.0750-mm-thick agricultural polyolefin film during winter and spring. It was demonstrated that the fossil fuel consumption during winter was reduced by 35%, 38%, and 51% in the trial product compared with a 0.0750-mm-thick agricultural polyolefin film when they

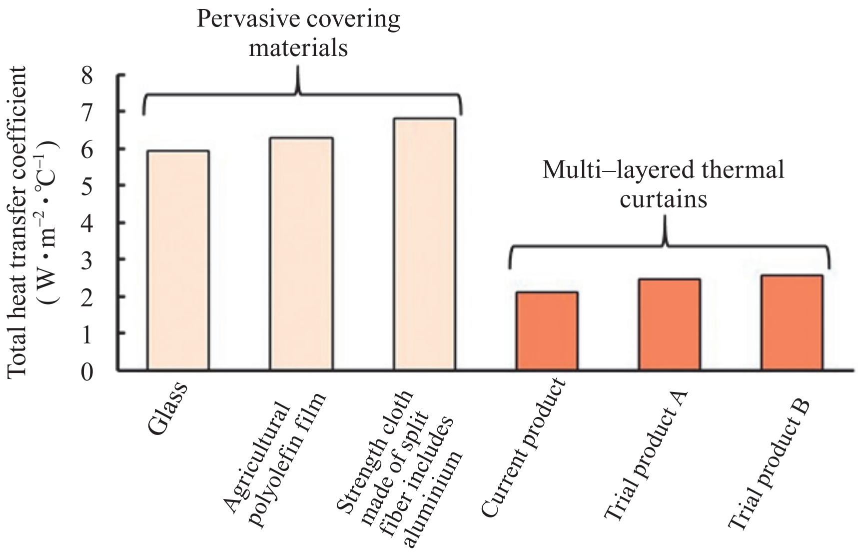

Fig. 1. Thermal transmission coefficients of selected thermal curtains
Trial products A and B are fabricated using nanofibers. This figure is derived from a study by Kawashima et al. (2017).

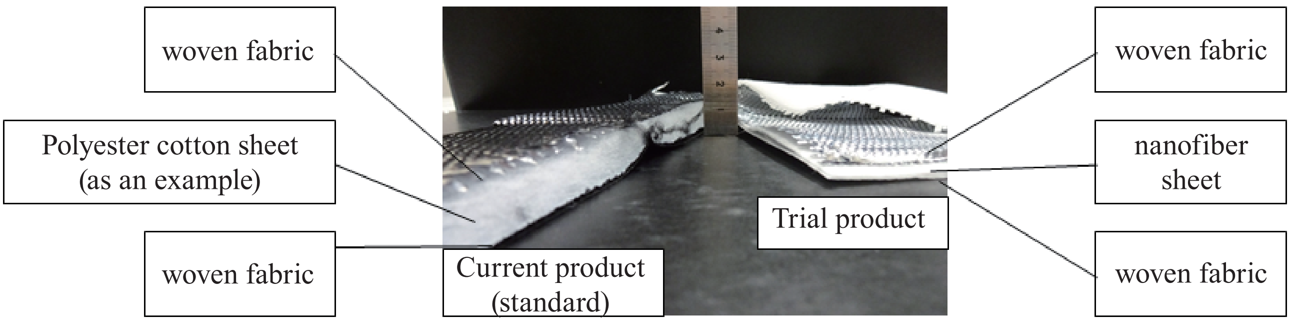

Fig. 2. Current (left) and trial products of multilayered thermal curtains
The trial product, which is thinner than the current product, incorporates a nanofiber sheet that replaces the middle polyester cotton layer of the conventional thermal curtains.

Fig. 3. Rolled down and rolled up positions of the multilayered nanofiber thermal curtain used in conjunction with a movable shaft system

were used as the internal thermal curtains in a greenhouse covered with a 0.150-mm-thick agricultural polyolefin film and the heating systems were operated so that the difference between the air temperature inside the greenhouse and outside air temperature were 15°C, 10°C, and 5°C, respectively (*Noshoku-jigyo 27013C* Consortium 2018). It was also demonstrated that this 10% reduction of solar radiation inside the greenhouse did not reduce the marketable fruit yield of tomato during winter and spring (*Noshoku-jigyo 27013C* Consortium 2018). The trial product can significantly reduce fuel consumption without reducing the fruit yield of tomato during winter and spring compared with a 0.0750-mm-thick agricultural polyolefin film.

Local heating techniques

Another approach to saving energy entails the use of local heating techniques, wherein heat is provided to the specific parts of a plant, such as the shoot apex or rhizosphere, contrary to the standard techniques wherein the entire greenhouse is heated. Compared with the standard techniques, the local heating technique can substantially reduce energy consumption while still providing sufficient heat to promote plant growth.

For instance, the crown heating technique has been applied for strawberry production using high bench culture during winter (Okimura 2009). In high bench culture, the temperature of the culture medium can easily decrease, which increases heating costs. In this context, direct crown heating using a heating wire, warm water, or a tape heater promotes plant growth and saves heating costs. The suitable temperature for crown heating is approximately 20°C depending on the cultivar and minimum ambient temperature in the greenhouse (Okimura 2009, Sato & Kitajima 2010a, Ando et al. 2018). Sato & Kitajima (2010b) reported that crown heating reduced heating costs by 27% in a greenhouse heated to at least 7°C and by 62% in a greenhouse heated to at least 4°C compared with a greenhouse heated to at least 10°C without crown heating. Furthermore, the efficacy of the crown heating technique has been demonstrated in regions with diverse climatic conditions, such as Fukuoka (Sato & Kitajima 2010a), Aichi (Ando et al. 2018), and Miyagi (Dan et al. 2015, 2018). Additionally, crown heating conducted from early November to early March increased fruit yield by 7%-19% throughout the culture period (Sato & Kitajima 2010a, Ando et al. 2018, Dan et al. 2015, 2018). According to Ando et al. (2018), the best time to start crown heating is after the formation of secondary flowers. In soil culture, crown heating in a greenhouse heated to at least 5°C reduced heating costs by 31%-35% compared with no crown heating in a greenhouse heated to at least 8°C (Takayama et al. 2015).

The local heating technique has also been applied in cherry tomato and tomato cultivation (Kawasaki et al. 2010). In this technique, a warm air duct is hung in the vicinity of the plants to selectively heat the areas surrounding the tomato shoot apices and flower clusters (Fig. 4). However, this approach does not involve active heating of the lower parts of the plants, which are

Fig. 4. Localized heating in the vicinity of tomato shoot apices and flower clusters using a hanging duct

resistant to low temperatures. Compared with the standard heating technique with ground-fixed warm air ducts, this technique reduced energy consumption by minimizing the soil heat flux (Kawasaki et al. 2020) and reduced fossil fuel consumption by 10% (Kawasaki et al. 2011, 2019). Moreover, at the same accumulated temperature, crown heating maintained plant growth, such as the number of flower clusters, compared with the standard heating technique (Kawasaki et al. 2011, 2019).

Multivariable environmental control

In recent years, advances in various low-cost sensors and information and communication technology have promoted the use of growth environment monitoring and multivariable environmental control systems by Japanese farmers. Monitoring systems can improve the labor productivity of farmers by facilitating remote monitoring and can enable the storage of environmental data, such as ambient temperature, humidity, solar radiation, CO_2 concentration, ground temperature, and soil moisture, which can be further utilized to enhance production. Moreover, such monitoring systems can be applied to boost regional vegetable production by analyzing cultivation data.

Multivariable environmental control systems save energy by facilitating the efficient use of energy and resources. Unfortunately, however, these systems are often rather expensive for widespread use by Japanese farmers. Indeed, multivariable environmental control systems have been introduced in only 3% of the total protected horticultural area in Japan (42,164 ha) (MAFF 2018). Nonetheless, the development of low-cost sensors has contributed to a reduction in the price of some control systems. For instance, "YoshiMax" (Sanki-keiso Co., Ltd.) is a low-cost system for automatically controlling the growth environment within greenhouses for strawberry production (Yasuba 2018). This system uses fossil fuel and liquefied petroleum gas as energy sources to reduce CO_2 concentrations according to ambient temperature (degree of greenhouse ventilation) (Yamanaka et al. 2019) (Fig. 5). Moreover, it reduces fertilizer waste by decreasing the frequency of fertigation according to the amount of solar radiation. Furthermore, a user manual describing the procedures of operating "YoshiMax" for stable strawberry production has been published (Yoshida & Yasuba 2020).

High-density planting techniques

High-density planting is an energy-saving technique. It involves planting numerous plants within a relatively confined space, which is an effective means of reducing energy consumption per unit yield while enabling the growers to obtain high yields from a limited

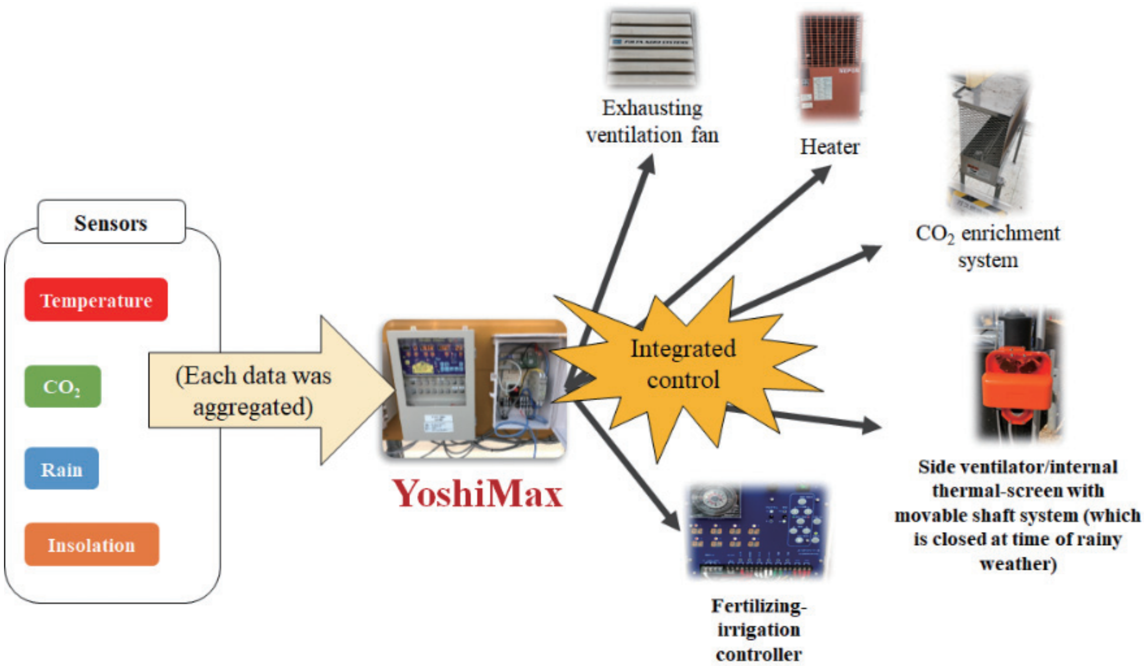

Fig. 5. Schematic diagram of the operation of "YoshiMax"

space. For instance, a movable bench cultivation system has been developed for high-density planting of leafy vegetables and strawberries (Yoshida et al. 2008, Nagasaki 2010) (Fig. 6). Indeed, a system integrating environmental control and movable beds with a 1.5-fold increase in planting density (8-12 plants·m^{-2}) achieved a twofold increase in strawberry production (Hidaka et al. 2016). Consequently, high-density planting can increase productivity per unit energy input and enhance energy efficiency. However, despite these clear advantages, caution should be exercised when using this approach, as high plant densities are conducive to a rapid spread of diseases and pests.

Conclusion

To prevent global warming, energy-saving techniques for protected horticulture have been developed in Japan. To reduce the consumption of fossil fuels, thermal insulation of greenhouses has been improved using water curtain and multilayered thermal curtain, such as a novel multilayered thermal curtain fabricated with nanofibers. In strawberry, cherry tomato, and tomato production, local heating techniques and multivariable environmental control are used to efficiently control the plant growth with a small amount of energy input. To increase the efficiency of energy use, it is also effective to increase yield per energy input by high-density planting. Energy-saving techniques for protected horticulture are also effective in saving running costs, and it is expected that the energy-saving techniques will be further developed and popularized.

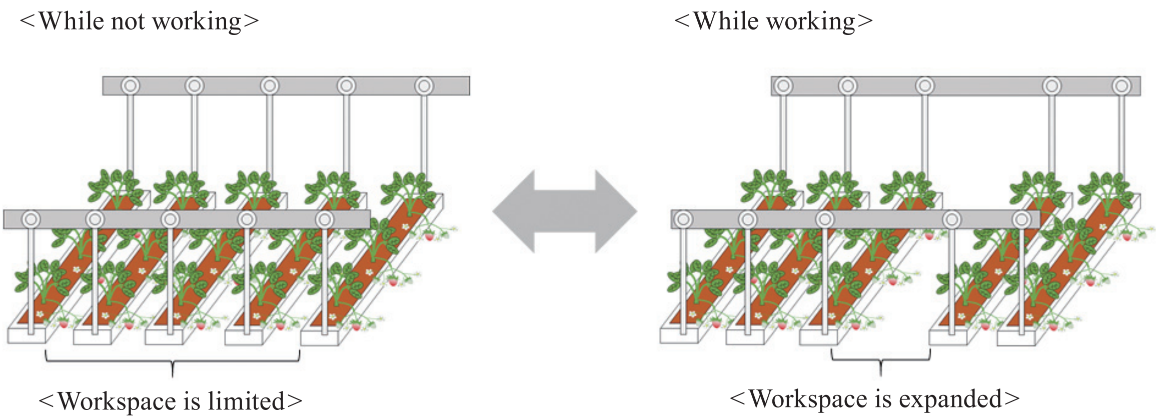

Fig. 6. Schematic diagram of a movable bench cultivation system

In the absence of workers, there are similar spaces between benches (left). When necessary, the benches can be moved laterally to the right and left to widen the workspace (right).

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