Research Reports

Root-zone Cooling Evaluation Using Heat Pump for Greenhouse Strawberry Production

Shigeoki Moritani^{1,5}, Hirotada Nanjo^{2,4}, Atsushi Itou³, and Teruki Imai³

ADDITIONAL INDEX WORDS. chilled-water temperature, ellipse, *Fragaria × ananassa*, media container, temperature

SUMMARY. Ground-source heat pumps (GSHPs) have been used to chill water to facilitate cooling of ‘Natsuakari’ strawberry (*Fragaria × ananassa*) grown within containers during the summer. Two types of soil containers and cooling systems have been considered. In one system, cold-water tubes were placed under as well as over the top of the soil, whereas the other cooling system used cold water passing through tubes placed under the soil and within the irrigation channel to facilitate bottom irrigation. The cooling efficiency of each system was evaluated by observing temperature relationships between greenhouse air and soil. The relationship was represented by means of an elliptic curve, the geometric center and tilt angle of which indicated representative daily soil temperatures and degree of temperature stability, respectively. Both values were observed to be lower for the bottom irrigation system during the two plant growth periods considered in this study, thereby indicating that colder and relatively constant soil temperatures can be maintained via greater heat convection. This greater cooling method was facilitated by rapid transfer of cold water through the bottom irrigation channel into the root zone, resulting from reduction in soil moisture content induced by plant transpiration in addition to heat conduction from the soil to the cooling tube. Measured soil temperatures for the buried-tube system were observed to be coldest when the tube was chilled considerably (9.4 °C). Although the setup of the considered bottom watering system was rather sensitive in that the system required maintenance of a constant water level throughout the container, both systems effectively produced cooler soil temperatures compared with the case in which no GSHP was used.

During the hot summer, greenhouse cooling is essential for the production of high-quality crops, which require cooler ambient temperatures. Although many cooling options exist, they all depend on the availability of affordable resources, such as electricity and groundwater (Kumar et al., 2009; Sethi and Sharma, 2007). Conventional greenhouse cooling techniques typically use fog or pad and fans in conjunction with natural or mechanical ventilation and shade screens

(Ahemd et al., 2016). Although individual components of used systems, such as fogging nozzles, fans, and

shade screens, are affordable, high-quality water supply is required to generate the fog, and electricity is necessary to power high-pressure pumps or ventilation fans. To ensure occurrence of the adiabatic evaporation, the air temperature cannot be allowed to decrease below the wet bulb temperature (Alkhedhair et al., 2016). Consequently, evaporative cooling systems are incapable of significantly decreasing high temperatures that prevail during the hot and humid summer season. However, some crops, such as strawberry, require cooler temperatures (Hidaka et al., 2017; Ledesma et al., 2008; Tanino and Wang, 2008; Wang and Camp, 2000) compared with those that can be achieved by the previously mentioned cooling systems.

Heat pumps can also be used in greenhouse cooling systems. Although they offer a wide range of temperature control, their efficiency is largely dependent on the pump’s power consumption and type of refrigerant used (Sagia and Rakopoulos, 2016). In addition, high costs associated with the installation and operation of heat pumps have caused them to become less popular, despite their versatility in terms of performing sustained heating and cooling operations during cold and hot seasons, respectively. In this study, a GSHP system was developed using a heat pump converted from an air source (a commercial air conditioner) to a ground-water source by means of a simple heat exchanger (Moritani et al., 2017b). One important factor necessary for efficient cooling of a greenhouse is minimization of the volume that must be cooled. Spot cooling, which is used primarily in bench cultivation practices, has recently become popular in Japan as a means of increasing energy efficiency (Ikeda et al., 2007; Yamasaki, 2013). This method involves installation of a cooling tube in the soil, because root-zone

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
18.6000	inch ³ /ft	dm ³ ·m ⁻¹	0.0538
0.0254	mil	mm	39.3701
1.6093	mile(s)	km	0.6214
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

temperature affects the quality and yield of strawberry fruit. Geater et al. (1997) reported that a constant, high root-zone temperature on the order of 35 °C in a hydroponic system reduces the root dry weight whereas the greatest fresh weight is yielded under conditions corresponding to a constant temperature of 23 °C. Biela et al. (1999) concluded that optimal temperatures of the root zone are 17, 23, and 29 °C, which correspond to attainment of the greatest transpiration rate, leaf area, and fruit dry weight, versus 11 and 35 °C, with the poorest results obtained at 35 °C. Sakamoto et al. (2016) demonstrated that roots exposed to cooler temperatures of the order of 10 to 20 °C had greater fruit weight, but roots maintained at a temperature of 30 °C resulted in the development of irregularly shaped fruit. Utagawa et al. (1989) observed that relatively cooler temperatures, in the range of 13 to 23 °C in terms of root media, not only increased the root weight but also reduced sugar content in the berries. Although experimental conditions, such as the strawberry cultivar, type of substrate, and ambient temperature, differed among studies just cited, soil temperatures on the order of ≈ 20 °C invariably resulted in better strawberry growth and quality. Moritani et al. (2017b) previously reported methods for cooling soil and strawberry crowns using GSHPs during the summer. They observed that the temperature distribution along the soil bed over a length of 20 m remained unaffected by the direction of water flow within two parallel tubes installed

Fig. 1. Overall layout of greenhouse for growing ‘Natsuakari’ strawberries, including heat pump and ground-source heat-exchanger (GSHE) setups. Sites A and B were located 1 km (0.62 mile) apart, both at latitude 40°38’N and longitude 140°34’E. Two heat pumps were used in conjunction with a GSHE to cool the soil and vegetation separately at site A, whereas one heat pump and GSHE were used to cool both the soil and irrigation water at site B. Cooling treatment was conducted through a pipe in which cooling water flowed (site A) and through cooling water irrigation from the bottom of the media (site B). A control was selected at site A without a cooling pipe. 1 m = 3.2808 ft.

on the soil bed, be it in the same or opposite directions.

The soil bed for bench cultivation is usually placed within a container made of polystyrene foam to facilitate easy maintenance of cooler soil temperatures. However, heat flux at the soil surface and that through drainage of excess irrigation water tends to reduce the cooling effect. As a result of the greater cooling demand during the middle hours of the day, it is essential that the soil cooling system be able to reduce the temperature rapidly in response to heat inflow into the soil. In this study, two types of soil containers using two different cooling methods were compared to determine the optimum container design for maintaining cooler soil temperatures through use of the proposed GSHP.

Materials and methods

GSHP SETUP. Two greenhouses comprising steel-pipe frames covered

with a single layer of 0.15-mm-thick polyolefin were used during experiments for this study, which was performed in Kuroishi City, Aomori, Japan (Fig. 1). The greenhouses were located 1.0 km apart, with location coordinates given by latitude 40°38’N and longitude 140°34’E, but at different altitudes of 27 m (site A) and 37 m (site B), respectively (Google, Mountain View, CA; Zenrin Co., Fukuoka, Japan). The two greenhouses measured 46 × 7.2 m and 27 × 7.2 m, respectively, in terms of areas occupied. Furthermore, they possessed the same ridge height of ≈ 3.9 m and were oriented along south-southwest to north-northeast and southwest to northeast directions, respectively. One or two ground-source heat exchangers (GSHEs) were installed outside each greenhouse (Fig. 2A). Each GSHE comprised a solid-bottom steel cylinder measuring 10 m in height and 19 cm o.d. (Hamada et al., 2007). All GSHEs were filled with groundwater after installation.

This work was partially funded by JSPS KAKENHI (grant no. 26850150). We are thankful to Kiyomitsu Muramoto for his technical assistance during greenhouse experiments. Mention of trade names implies no endorsement of the products mentioned nor criticism of similar products not mentioned.

¹Faculty of Agriculture and Life Science, Hirosaki University, 3 Bunkyo, Hirosaki, Aomori 0368561, Japan

²Hirosaki University, Hirosaki, Aomori, Japan

³Agriculture Research Institute, Aomori Prefectural Industrial Technology Research Center, 82-9 Tanaka, Kuroishi, Aomori 0360522, Japan

⁴Professor Emeritus.

⁵Corresponding author. E-mail: moritani@hirosaki-u.ac.jp.

<https://doi.org/10.21273/HORTTECH04007-18>

Fig. 2. Installation of (A) the ground source heat exchanger (GSHE), (B) the converted heat pump, and (C) the cultivation bench of 'Natsuakari' strawberry with the heat pump at site A, with latitude 40°38'N and longitude 140°34'. The pictures of the GSHE and heat pump were actually taken at different sites and at different times, although the same installation methods were used in our study. The GSHE was set up with a solid-bottom steel cylinder by drilling via rotation with a downward pressure loaded with a hydraulic excavator (A). Outdoor and indoor units of 1-kW commercial air conditioners were converted to water source units in both the condenser and the evaporator unit, respectively (B). The heat pump supplies cooling water from the evaporative unit to the media container in which the strawberries grow (C), whereas the heating coil in the condenser unit is cooled by circulating water through the GSHE (A).

A majority of the GSHP cost is attributable to actual heat pump and GSHE installation. To make the system affordable to farmers, a relatively cheap, commercial 1-kW air conditioner was converted from an air-source unit to a water-source unit for heating and cooling (Fig. 2B). The outer packaging and the indoor and outdoor fans were first removed from the air conditioner. The refrigerant gas was then collected from the unit, after which the condenser and evaporator were separated from the heat pump unit. The two heat exchangers were subsequently reinstalled at their original positions after the two tanks had been added to enclose each exchanger completely. Next, inlets and outlets for water circulation were attached to the two tanks.

The heat pumps were operated using their original remote controllers. The cooling mode was set to 16 °C, which was the minimum possible temperature. The heat pumps operated continuously across all experiments. The chiller temperature was regulated using an originally integrated thermistor submerged inside the chiller water rather than being placed in the soil. This was done primarily because the thermistor cord length was insufficient, which led to difficulties associated with extending the cord to the growing benches.

COOLING TREATMENT. 'Natsuakari' strawberries were grown on benches at a density of 10 plants/m length of the soil container in both greenhouses. A 0.025-mm-thick

opaque plastic film was placed over the soil surface. Two different types of containers and soils were used in the two greenhouses. An expanded polystyrene foam soil container with a triangular (TA) cross-section (Mitsubishi Chemical Agri Dream Co., Tokyo, Japan) was used in the greenhouse located at site A, as depicted in Fig. 3A. The growing media were packed at a rate of $\approx 30 \text{ dm}^3 \cdot \text{m}^{-1}$ length of the container. An organic coconut-fiber substrate with a greater rewetting capacity compared with peat was used (Michel, 2010). Eight benches, each measuring 20 m long, were arranged in four columns and two rows for cultivation (Fig. 1). The TA container enabled immediate drainage of excess water from growing media to the bottom of the container, thereby preventing occurrence of plant diseases induced by root decay. A polyvinyl chloride (PVC) pipe measuring 20 mm o.d. was buried in the soil near the bottom of the container and was used to convey cooling water produced by the GSHP. In addition, two polyethylene pipes were laid on the soil surface to control the soil and plant temperatures (including the strawberry crown). Two separate heat pumps were used to cool the soil and crown. This cooling treatment was referred to as TA-HP, whereas the control treatment exclusively using the TA container without cooling tubes was referred to as TA-control. The supply of irrigation water containing essential nutrients to TA containers was

facilitated via drip irrigation tubes laid on the soil surface.

Cultivation at site B was performed within a square (SQ) polystyrene foam container (Kaneko Seeds Co., Gunma, Japan) equipped with a bottom irrigation channel filled with water containing nutrients (Fig. 3B). To achieve direct cooling of both soil and irrigation water, two PVC supply pipes (20 mm o.d.) were placed on each side at the bottom of the container, and a return pipe was placed in the drainage channel (Fig. 3B). This system was referred to as SQ-HP. To maintain a consistent water level in all media containers, benches were carefully positioned horizontally. Because organic rooting media is prone to decompose under anaerobic, waterlogged conditions (Barrett et al., 2016), which are likely to prevail at the bottom of containers, an inorganic substrate comprising pumice sand (container length, $\approx 40 \text{ dm}^3 \cdot \text{m}^{-1}$) was used.

DATA MEASUREMENT AND ANALYSIS. K-type thermocouples were installed at shaded, nonaspirated locations inside both greenhouses, 1.7 m from the center of the benches. Others were inserted into the media midway along the depth and into chiller tanks located in the vicinity of the outlet. Data measured by thermocouples were collected using a data logger (GL820; Graphtec, Yokohama, Japan), with an internal reference junction used for compensation. Data were collected at 10-min intervals and averaged every

Fig. 3. Cross-sectional evaluation of the two media-container types used in this study: (A) triangular and (B) square. The growing media was packed at a rate of ≈ 30 and $40 \text{ dm}^3 \cdot \text{m}^{-1}$ (558.0 and $744.0 \text{ inch}^3/\text{ft}$) in triangular and square treatments, respectively. The main materials constituting the media were coconut fiber and pumice sand in the triangular and square treatments, respectively. ‘Natsuakari’ strawberries were grown in the container with a density of 10 plants/m length (3.0 plants/ft). 1 mm = 0.0394 inch.

hour. The experimental investigation was divided into three periods lasting 10 d each. Specifically, these periods were 12–21 Aug., 6–15 Sept., and 18–27 Sept. 2011, respectively. The three investigation periods considered in this study corresponded to different average ambient temperatures (24.2 , 20.9 , and 15.7°C corresponding to periods 1, 2, and 3, respectively). These temperature values were obtained from the nearest weather station, at which temperature measurements were performed using a device set at a height of 2 m (in accordance with guidelines prescribed by the Japan Meteorological Agency). Because both greenhouses were located only 1 km apart, their geographic locations were nearly identical (lat. $40^\circ 40' \text{N}$, long. $140^\circ 35.1' \text{E}$). As such, the measured average temperature values were considered representative of conditions prevailing at both greenhouses. Days toward the end of August and beginning of September were omitted because of significant fluctuations in daily temperatures caused by transitioning of seasons.

Song et al. (2017) observed the hysteresis effect when evaluating diurnal temperature cycles in urban areas, including those observed in grass and air. Such hysteresis is likely

to be caused by differing amplitudes and phase lags of temperature diurnal cycles resulting from varying heat capacities (Gao et al., 2010). The hysteresis effect was more evident in temperature relationships between water and air, which could be described in the form of an ellipsoidal relationship (Cho and Lee, 2012). Experimental results obtained in this study reveal an increase in greenhouse temperature after sunrise, followed by a more gradual increase in media temperature (Fig. 4). The soil temperature subsequently decreased more slowly compared with the decreasing air temperature after solar noon. However, no clear point of maximum soil temperature was determined corresponding to any of the treatments. The only observable variations were seen to occur between 1:00 PM and 4:00 PM. The slow increase and decrease in soil temperatures after sunrise and solar noon, respectively, led to creation of an ellipsoidal diurnal relationship between greenhouse air and media temperatures. This was the case for all treatments. The standard equation of an ellipse, as expressed by Eq. [1], can be defined using slope θ , with x and y being hourly temperatures of greenhouse air and growing media, respectively (Xu et al., 2014):

Fig. 4. Elliptical relationship between greenhouse air and soil temperatures under which ‘Natsuakari’ strawberry cultivation was investigated in this study. The geometric center of the ellipse is denoted by (x_0, y_0) , θ is the tilt angle, and a and b are the semimajor and semiminor axes, respectively. The average times for periods 1 (12–21 Aug.), 2 (6–15 Sept.), and 3 (18–27 Sept.) of the investigations are 4:47 AM, 5:12 AM, and 5:24 AM for sunrise, and 11:41 AM, 11:34 AM, and 11:29 AM for solar noon, respectively. The geometric center of the ellipse can indicate the representative daily temperature of air (x_0) and media (y_0). Tilt angle can be considered an indication of the temperature stability of the media; for instance, a lower θ value means high stability against ambient temperature.

$$\left[\frac{(x - x_0) \cos \theta + (y - y_0) \sin \theta}{a} \right]^2 + \left[\frac{(y - y_0) \cos \theta - (x - x_0) \sin \theta}{b} \right]^2 = 1 \quad [1]$$

Here, (x_0, y_0) refers to the geometric center of an ellipse that comprises semimajor axis (a), semiminor axis (b), and tilt angle θ , as illustrated in Fig. 4. Microsoft Excel 2016 (Microsoft, Redmond, WA) was used to calculate average hourly temperatures over diurnal cycles. Consequently, 24 data units were obtained for both of x and y . By replacing the left-hand side of Eq. [1] with $f(x, y)$, determination of each variable was performed using the least square method until the square error, defined by Eq. [2], approached zero.

$$\sum_{i=1}^n \{f_i(x, y) - 1\}^2 \quad [2]$$

Here, n is the number of hours in a day. Considering the difficulty of drawing an elliptical curve with five variables (x_0, y_0, a, b , and θ) using Eq. [1], recalculated coordinates (x^*, y^*) with angle α are depicted in Fig. 4. These coordinates were obtained using following equations:

$$x^* = a \cos \theta \cos \alpha - b \sin \theta \sin \alpha + x_0 \quad [3]$$

$$y^* = a \sin \theta \cos \alpha + b \cos \theta \sin \alpha + y_0 \quad [4]$$

where α is a parameter with its value ranging between 0 and 2π radians.

Results

Average daily temperatures, including those that prevail during nighttime, of the two greenhouses at

sites A and B were observed to be similar. Throughout the three investigation periods, values of these temperatures equaled 25.1, 22.2, and 17.9 °C, respectively (Table 1). The similarity in temperatures observed at the two sites was because they were located only 1 km apart, with temperatures at site B being 0.1 to 1.2 °C cooler compared with those at site A (Table 1). Colder temperatures at site B could be attributed to the smoother ventilation afforded by the presence of fewer obstructions, as depicted in Fig. 1, and a cross breeze produced by shorter total lengths of benches when compared with the case at site A (Bartzanas et al., 2002).

Temperatures of the chiller water tank resulted in different temperatures of the media and strawberry crown. Chiller-water temperatures tend to decrease from period 1 through period 3 (Table 1) as a result of the low cooling requirements caused by cooler ambient temperatures outside the greenhouse, although chiller-water temperatures at site B remained mostly constant during periods 2 and 3. Considering the SD in chiller-water temperature to be colder compared with that of the greenhouse temperature, the proposed use of the heat pump system helped successful maintenance of a stable temperature. The chiller-water temperature used to cool the media during TA-HP treatment was observed to the coldest among the three treatment methods, with the average temperature over the three investigation periods being 12.4 °C [i.e., 9.4 °C colder compared with that of the air inside the two greenhouses (21.8 °C)]. Chiller-water temperatures corresponding to the other two treatment methods were observed to be nearly identical, with

the maximum difference between them being 1.7 °C during period 1, and the average temperature maintained across all periods equaled 18.0 °C (i.e., 3.8 °C colder compared with temperatures of the air in the two greenhouses).

The chiller-water temperature was used to cool the strawberry crown during the TA-HP treatment. During the SQ-HP treatment, observed chiller-water temperatures exceeded 16 °C (Table 1), which refers to the minimum temperature set by the remote controller. The chiller-water temperature for cooling the bench soil during the TA-HP treatment (≈ 10.2 °C) measured less than the previously stated minimum value during periods 2 and 3. This result could be attributed to the thermistor not being inserted properly into the chiller water, with some part of it being exposed to nearby air. Such an incorrect placement may result in the heat pump continuing to cool the chiller water even after it had attained the limiting temperature of 16 °C, under the consideration that the sensor still measures the warmer ambient-air temperature. This, however, demonstrates that a converted air conditioner can be used intentionally to control temperature below the preset minimum value by placing the thermistor in a warmer environment. This additional cooling operation can be used to decrease the temperature until ice is created around the evaporator (Moritani et al., 2017a).

The elliptical trend of the temperature relationship between greenhouse air and growing media with a positive slope for all treatment methods and investigation periods (Fig. 5A–C) can be explained as follows. Initially, the soil temperature increases slowly as the greenhouse

Table 1. Daily average temperatures of air within the two greenhouses and water inside the heat-pump chiller tank evaluated for growing ‘Natsuakari’ strawberries during each experimental period.

Time period	Greenhouse temp		Chiller water temp		
	[mean $\pm$ SD (°C)] ^a		[mean $\pm$ SD (°C)]		
	Site A ^b	Site B ^b	Site A (TA-HP) ^c		Site B ^c (SQ-HP)
			Media cooling	Crown cooling	
Period 1 (12–21 Aug.)	25.2 $\pm$ 0.66	25.1 $\pm$ 0.66	16.9 $\pm$ 0.15	19.0 $\pm$ 0.2	20.7 $\pm$ 0.3
Period 2 (6–15 Sept.)	22.8 $\pm$ 0.73	21.6 $\pm$ 0.53	11.0 $\pm$ 0.13	17.7 $\pm$ 0.08	17.0 $\pm$ 0.04
Period 3 (18–27 Sept.)	18.1 $\pm$ 0.79	17.7 $\pm$ 0.46	9.4 $\pm$ 0.13	16.7 $\pm$ 0.2	17.1 $\pm$ 0.06

^a(1.8 $\times$ °C) + 32 = °F.

^bSites A and B = greenhouses at latitude 40°38'N and longitude 140°34'E located 1 km (0.62 mile) apart from each other. Two heat pumps were respectively used to cool the media and crown at site A, while only one heat pump was used at site B.

^cTA = triangle form of media container; HP = heat pump cooling treatment; SQ = square form of media container.

Fig. 5. Elliptical relationships between greenhouse air and growing media temperatures during (A) period 1 (12–21 Aug.), (B) period 2 (6–15 Sept.), and (C) period 3 (18–27 Sept.) investigated in this study of ‘Natsuakari’ strawberry cultivation. The geometric centers are denoted by x_0 and y_0 , which indicate the representative daily values of air and media temperatures, respectively. Tilt angles are expressed by θ , which indicates the temperature stability of the media. For instance, the small θ value can be explained by the high soil heat capacity and the constant cooling produced by the heat pump system. Other factors of the ellipsoidal curves are a , and b , and their values are included. Cnt, control treatment; HP, heat-pump cooling; SQ, square media container (Fig. 3); TA, triangular media container (Fig. 3). $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

warms up within an hour after sunrise, the timing of which varied between 4:43 AM and 5:29 AM during the investigation periods considered in this study. As a result of the greater heat capacity of wet soil relative to air, the observed increase in soil temperature is slower compared with greenhouse air temperature. This leads to the generation of the downward convex portion of the curve depicting the relationship between air and media temperatures. This trend continues until the greenhouse air temperature attains its maximum value within 2 h after solar noon—which, during the current study, occurred between 11:28 AM and 11:42 AM because of the eastern location (long. 135°E) of the Japanese standard time meridian. Subsequently, with a decrease in air temperature, the observed soil temperature decreased at a lower rate—which is also partly a result of the greater heat capacity of soil—until the greenhouse air temperature attains its minimum value around sunrise. This trend generates the upward convex portion of the curve.

The best fitting curves, obtained using Eqs. [3] and [4], were observed to match well with experimental measurements. The square errors were calculated using Eq. [2] and demonstrated values in the range of 0.35 to 1.11. Values of y_0 and the daily average soil temperature demonstrated only slight variation, between 0.01 and 0.51 °C, for all treatments. The value of y_0 was, therefore, regarded as the representative daily media temperature. The value of x_0 was also observed to be greater compared with daily greenhouse air temperatures, with differences varying between 0.67 and 1.27 °C. The relatively small tilt angle, θ , of the ellipse can be explained in terms of the high soil heat capacity and constant cooling produced by the system. The large volume of wet soil demonstrates a proportionally large heat capacity, and considering the rapid response of supplemental cooling systems, the media temperature is unlikely to increase significantly as a result of fluctuations in the warmer ambient air temperature.

Values of y_0 and θ were observed to be greatest for control treatments during all investigation periods; values of y_0 ranged between 18.1 and 25.8 °C whereas those of θ

ranged between 26.0 and 28.1 °C (Fig. 5). Observed y_0 values closely approximated the greenhouse air temperature (Table 1), thereby indicating that media containers surrounded by air, in the case of benchtop systems without supplemental cooling, maintained a thermal state in accordance with ambient air.

With regard to heat pump cooling, during period 1 (Fig. 5A) of the TA-HP and SQ-HP treatments, the value of y_0 was observed to decrease by 2.9 and 6.4 °C, respectively, relative to the control treatment. The lowest values of θ and y_0 were observed during SQ-HP. This is attributable to the greater heat capacity of SQ, which is more resilient to ambient temperature changes because 1) the soil volume within SQ per unit bench length equals 1.3 times that within the TA container and 2) the cooling irrigation water was supplied from the bottom of the SQ, thereby resulting in greater soil-moisture content. In addition, soil-moisture content in the root zone was reduced by plant transpiration, thereby promoting the transfer of cooling irrigation water in the SQ into growing media and resulting in greater heat removal. In contrast, cooling during the TA-HP treatment was achieved exclusively via heat conduction through the water tube, the conduction rate of which was low as a result of lower soil-moisture content relative to the SQ case (Abu-hamdeh and Reeder, 2000). The soil-moisture content, however, was not actually measured. Moreover, the cooling irrigation water could be released from the TA container via drainage rather than being retained within the media. On the other hand, drainage loss from SQ might be small as a result of small amounts of water being absorbed into growing media.

With regard to media temperature, the value of y_0 corresponding to the control treatment equaled 23.2 °C, which is 4.3 °C warmer compared with the average value for both TA-HP and SQ-HP, the specific values of which differed only slightly during period 2. This equal cooling effect when using heat pumps was observed despite the chiller-water temperature within TA (11.0 °C) being considerably colder compared with that within SQ (17.0 °C) (Table 1). Moreover, a stable media

temperature was observed during SQ-HP, presumably resulting from a lower value of θ (4.4°) compared with the TA-HP case (16.5°). This demonstrates the difficulty involved in achieving effective cooling exclusively via heat conduction across PVC water pipes.

However, a superior cooling effect during TA-HP was observed during period 3 at 15.9 °C, when the soil temperature was observed to be 1.5 °C colder compared with that during the SQ-HP case. This effect was a result of the colder chiller-water temperature, which caused the media and strawberry-crown temperatures to be colder compared with greenhouse air temperatures by 8.7 and 1.4 °C, respectively. Correspondingly, a temperature difference of only 0.62 °C was observed during SQ-HP. However, tilt angle θ was low during the SQ-HP treatment, thereby indicating more rapid cooling of growing media.

Conclusions

In this study, the effects of media container shape on media cooling inside a greenhouse were examined. Triangular and square media containers equipped with a heat pump cooling system were considered, and the cooling efficiency was evaluated based on the elliptic relationship between greenhouse air and growing media temperatures. Because the media temperature y_0 at the geometric center of the ellipse was comparable to the average daily media temperature, it was considered representative of the average daily media temperature. The slope angle of the ellipse was considered an indication of temperature stability. As observed, application of the heat pump cooling technique demonstrated a reduction in the average value of y_0 by 3 °C relative to the corresponding control treatment temperature (25.8 °C) for the two types of containers (TA and SQ) during the first investigation period (12–21 Aug. 2011). The lowest values of y_0 (19.4 °C) and θ were observed for the SQ-HP treatment. The increased cooling effect of SQ-HP can be explained on the basis of enhanced temperature stability of media in view of its greater heat capacity, as well as rapid transfer of cooling irrigation water to soil in response to the reduction in

soil-moisture content induced by transpiration. The cooling process in SQ-HP was realized via heat conduction as well as convection, whereas during TA-HP, only conductive heat transfer from cooling water to soil mainly occurred. The maximum cooling effect in TA-HP was observed during the third period of investigation (18–27 Sept. 2011) at 15.9 °C. This result was attributed to the colder chiller-water temperature (9.4 °C), which occurred despite the cooling temperature being preset to its minimum value of 16.0 °C for the system. Faulty positioning of the temperature in a warm environment caused the heat pump to continue to operate because the temperature recorded by the sensor remained above 16.0 °C, thereby resulting in the very low chiller-water temperature. This implies that a converted air conditioner can be used to realize temperatures below the minimum allowable by a system by simply placing the temperature sensor in an ambient air environment. The feasibility of using this method to achieve very cold chiller-water temperatures was again verified by placing the sensor in ambient air and allowing the heat pump to perform unrestricted cooling until the chiller-water temperature dropped to the freezing point (Moritani et al., 2017a). These observations indicate that a greater cooling effect can be expected from the SQ-HP system if its chiller-water temperature can be maintained close to that of the TA-HP system. However, the SQ system setup is more sensitive, considering the need to maintain a consistent water level within the channel.

Major components of the TA-HP and SQ-HP systems include the external borehole, heat pump, and media-filled container. A borehole measuring 10 m deep and a 1-kW heat pump were used for both systems in this study. However, different types of polystyrene foam containers as well as media placed inside these containers resulted in operating costs of the two systems to differ significantly. In addition, because of the need for continuous irrigation of growing media from the bottom of the SQ container, the overall size of the SQ-HP system was larger compared with that of the TA-HP system, which used regular drip irrigation

from the top of the growing media. Because of the expected prevalence of anaerobic conditions in the SQ-HP system, it was filled with inorganic pumice sand instead of the coconut fiber used in the TA-HP system. Optimization of the cooling system, including media-container configuration and irrigation method, was found to be largely dependent on the temperature levels required for strawberry cultivation as well as the greenhouse temperature. However, similar design characteristics with respect to soil volume, amount of irrigation water, soil temperature, and so on, are required for scientific comparisons. Moreover, the proposed examination of the cooling effect was based exclusively on soil-temperature measurements, and plant responses in terms of yield, quality, and economic factors must also be investigated to evaluate their performance. In addition, a cost analysis should be performed of cultivation systems involving cooled growing media.

Literature cited

- Abu-hamdeh, N.H. and R.C. Reeder. 2000. Soil thermal conductivity: Effects of density, moisture, salt concentration, and organic matter. *Soil Sci. Soc. Amer. J.* 64:1285–1290.
- Ahemd, H.A., A.A. Al-Faraj, and A.M. Abdel-Ghany. 2016. Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. *Scientia Hort.* 20:36–45.
- Alkhedhair, A., I. Jahn, H. Gurgenci, Z. Guan, and S. He. 2016. Parametric study on spray cooling system for optimising nozzle design with pre-cooling application in natural draft dry cooling towers. *Intl. J. Therm. Sci.* 104:448–460.
- Barrett, G.E., P.D. Alexander, J.S. Robinson, and N.C. Bragg. 2016. Achieving environmentally sustainable growing media for soilless plant cultivation systems: A review. *Scientia Hort.* 212:220–234.
- Bartzanas, T., T. Boulard, and C. Kittas. 2002. Numerical simulation of the airflow and temperature distribution in a tunnel greenhouse equipped with insect-proof screen in the openings. *Comput. Electron. Agr.* 34:207–221.
- Biela, M.M., G.R. Nonnecke, W.R. Graves, and H.T. Horner. 1999. 326 High root-zone temperature inhibits strawberry reproductive and vegetative growth development. *HortScience* 34:499 (abstr.).
- Cho, H.-Y. and K.-H. Lee. 2012. Development of an air–water temperature relationship model to predict climate-induced future water temperature in estuaries. *J. Environ. Eng.* 138:570–577.
- Gao, Z., R. Horton, and H.P. Liu. 2010. Impact of wave phase difference between soil surface heat flux and soil surface temperature on soil surface energy balance closure. *J. Geophys. Res. Atmos.* 115(D16):D16112.
- Geater, C.A., G.R. Nonnecke, W.R. Graves, A.S. Aiello, and C.A. Dilley. 1997. High root-zone temperatures inhibit growth and development of *Fragaria* species. *Fruit Var. J.* 51:94–101.
- Hamada, Y., H. Saitoh, and M. Nakamura. 2007. Field performance of an energy pile system for space heating. *Energy Build.* 39:517–524.
- Hidaka, K., K. Dan, H. Imamura, and T. Takayama. 2017. Crown-cooling treatment induces earlier flower bud differentiation of strawberry under high air temperatures. *Environ. Control Biol.* 55:21–27.
- Ikeda, T., K. Yamazaki, H. Kumakura, and H. Hamamoto. 2007. Effect of cooling of medium on fruit set in high-bench strawberry culture. *HortScience* 42:88–90.
- Kumar, K.S., K.N. Tiwari, and K. Madan. 2009. Design and technology for greenhouse cooling in tropical and subtropical regions: A review. *Energy Build.* 41:1269–1275.
- Ledesma, N.A., M. Nakata, and N. Sugiyama. 2008. Effect of high temperature stress on the reproductive growth of strawberry cvs. “Nyoho” and “Toyonoka.” *Scientia Hort.* 116:186–193.
- Michel, J.C. 2010. The physical properties of peat: A key factor for modern growing media. 1 May 2018. <<https://hal-agrocampus-ouest.archives-ouvertes.fr/hal-00729716/document>>.
- Moritani, S., S. Araki, and H. Nanjo. 2017a. Estimation of heating performance of heat pump in greenhouse. *Proc. Annu. Mtg. Irr. Drainage Rural Eng.* 140–141 (in Japanese).
- Moritani, S., H. Nanjo, and A. Itou. 2017b. Partial cooling of strawberry plant by water tube utilizing geo-thermal heat pump. *J. Appl. Hort.* 19:186–190.
- Sagia, Z. and C. Rakopoulos. 2016. Alternative refrigerants for the heat pump of a ground source heat pump system. *Appl. Therm. Eng.* 100:768–774.
- Sakamoto, M., M. Uenishi, K. Miyamoto, and T. Suzuki. 2016. Effect of root-zone temperature on the growth and fruit quality of hydroponically grown strawberry plants. *J. Agr. Sci.* 8:122–131.
- Sethi, V.P. and S.K. Sharma. 2007. Experimental and economic study of a greenhouse thermal control system using aquifer water. *Energy Convers. Mgt.* 48:306–319.
- Song, J., Z.H. Wang, S.W. Myint, and C. Wang. 2017. The hysteresis effect on surface–air temperature relationship and its implications to urban planning: An examination in Phoenix, Arizona, USA. *Landsc. Urban Plan.* 167:198–211.
- Tanino, K.K. and R. Wang. 2008. Modeling chilling requirement and diurnal temperature differences on flowering and yield performance in strawberry crown production. *HortScience* 43:2060–2065.
- Utagawa, Y., T. Ito, and K. Gomi. 1989. Effects of root temperature on some physiological and ecological characteristics of strawberry plants Reiko grown in nutrient solution. *J. Jpn. Soc. Hort. Sci.* 58:627–633 (in Japanese).
- Wang, S.Y. and M.J. Camp. 2000. Temperatures after bloom affect plant growth and fruit quality of strawberry. *Scientia Hort.* 85:183–199.
- Xu, X., Z. Wu, Y. Chen, G. Huang, and T. Zhu. 2014. Plant root spatial distribution measurements based on the Hough transformation. *Neurocomputing* 145:209–220.
- Yamasaki, A. 2013. Recent progress of strawberry year-round production technology in Japan. *Jpn. Agr. Res. Qrtly.* 47:37–42.