Journal of Applied Horticulture, 19(3): 186-190, 2017

Partial cooling of strawberry plants by water tube utilizing geo-thermal heat pump

Moritani Shigeoki[1]*, Nanjo Hirotada[2] and Itou Atsushi[3]

*[1]Faculty of Agriculture and Life Science, Hirosaki University, 3 Bunkyo, Hirosaki, Aomori, 036-8561, Japan. [2]Professor Emeritus, Hirosaki University, Hirosaki, Aomori, Japan. [3]Agriculture Research Institute, Aomori Prefectural Industrial Technology Research Center, 82-9 Tanaka, Kuroishi, Aomori, 036-0522, Japan. *E-mail: moritani@ hirosaki-u.ac.jp*

Abstract

A commercial heat pump was utilized to cool strawberry plants using a heat exchanger well at 10 m of soil depth. Two lines of strawberry were planted to grow fully on a high bench of 20 m length. The cooling treatment was conducted through a water tube connected to the chiller tank of the heat pump. A single water tube was buried under the soil surface. Two kinds of set-up for the water tube on the soil surface were designed to cool the strawberry crown. Compared with that of the control, the temperature of crown and soil was effectively lowered by the two treatments. Regardless of the setup of the water tube, the temperature of soil and crown did not differ between the two treatments. Considering the high water temperature of the heat exchanger tank of the heat pump system, the length of the heat exchange well was insufficient for the extraction of sufficient geothermal energy in this experiment. However, the converted heat pump and facile establishment of wells achieved cooling of the 4 benches effectively and at a reasonable cost.

Key words: strawberry, cooling, geo-thermal energy, heat pump, temperature, greenhouse

Introduction

As strawberry plants are highly susceptible to high temperatures, farmers harvest crops during the winter and spring seasons, and not in the summer (Yamasaki, 2013). Therefore, the domestic supply of strawberries declines considerably in Japan in the summer. In order to meet demand from consumers all year round, strawberries are imported from other countries, resulting in high prices.

Greenhouse cultivation may be utilized throughout the year as this technique provides protection from the rain, as well as ensures warmth. However, during summer, cooling methods are needed as the thin plastic film of the outer cover of greenhouses allows the penetration of sunlight, which raises the temperature inside the greenhouse. Although the high latitude of the Tohoku region of Japan provides suitable planting conditions owing to the relatively cold weather, greenhouses in this region remain difficult to cool during the daytime as up to 1 kW m^{-2} of solar energy is produced by penetration of sunlight into the greenhouse; this is as high as in southern regions (Enteria *et al.*, 2013).

The mist cooling system with natural ventilation and shading of sunlight is widely used owing to its low cost of operation if sufficient groundwater may be successfully obtained (Kumar *et al.*, 2009). However, thermal reduction by mist is restricted by the ambient air temperature, humidity, and ventilation rate (Abdel-wahab, 1994). However, heat pumps are capable of controlling the air temperature over a wide range through the consumption of electric energy.

As the crown part of the strawberry acts as a site of growth for flower bud differentiation and vegetative vigor, spot cooling of ambient air around the crown promotes fruit growth (Hidaka *et al.*, 2017). Spot cooling methods, including soil cooling, have been utilized for strawberry cultivation during the hot summer season, with localized cooling along the soil and strawberry crown (Ikeda *et al.*, 2007; Iwasaki, 2008). Heat pump systems are capable of controlling the water temperature, enabling the lowering of the temperature via the use of water flowing in the tube, making the water effectively cooler than groundwater. When considering the reduction of energy consumption, geothermal energy may be coupled with the heat pump; the resulting system is known as the geo-thermal heat pump (GHP). Numerous studies of GHPs and their application in greenhouses for controlling the ambient temperature (Boughanmi *et al.*, 2017; Mongkon *et al.*, 2013; Noorollahi *et al.*, 2016) have been reported; however, to our knowledge, this system has not been applied to the partial cooling of greenhouses to date. In this study, we investigated the utility of GHPs for achieving low temperatures of soil and ambient air around the crown during the cultivation of strawberry crops in northern Japan, Aomori prefecture. Cooling down of soil and crown was attempted in high-bench strawberry culture in a greenhouse during the summer season.

Materials and methods

GHP setup: In this study, experiments were performed in a greenhouse (6.5 m wide and 50 m long) during the summer (August and September) at Kuroishi City, Aomori-ken in Japan (latitude 40° 38’ N, longitude 140° 34’ E). Two heat-exchanger wells, of 10 m depth each, were installed immediately outside the greenhouse before starting the experiment (Fig. 1). Each well was made of steel, with 125 mm of the outer diameter open on the upper side, and closed on the lower side. The well was set up by drilling via rotation, loading the downward pressure by connecting to tip of the arm of power shovel itself. This methodology, which has previously been shown to be cost effective, enables quick installation of the well (Nanjo

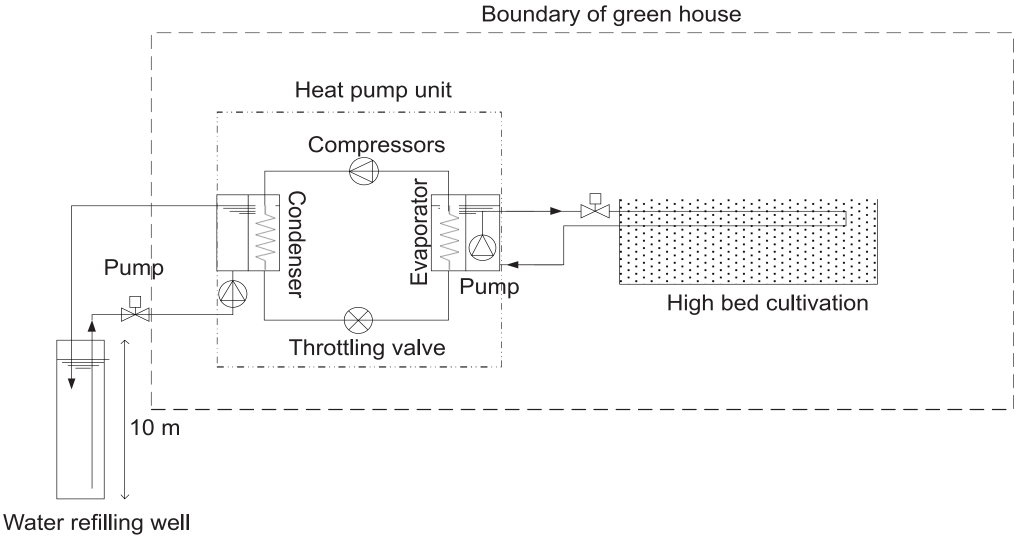

Fig. 1. Schematic diagram of geothermal heat pump system for cooling strawberry vegetation

and Moritani, 2014). Water was refilled in two wells: one well was used for cooling soil, while the other was used to cool the strawberry crown. Two 1-kW commercial air-conditioners were converted to GHP system. Generally, an air conditioner consists of a fan in each outdoor and indoor unit with a condensing and evaporator coil that enables exchange of heat with ambient air. The converted heat pump was designed to enable heat exchange between these two coils and water; two steel water tanks fully covering the condenser and evaporator coil were installed after the removal of two fans. An inlet and outlet for flowing water were set on each tank surface. This conversion was made with two heat pump units for soil and crown cooling; only one set of heat pump units and bed cultivation is shown in Fig. 1. These GHP systems were aimed at cooling strawberry plants grown under high-bed cultivation through the use of a cooling water tube established in the bed; heating water was discharged from the heat exchanger tank into the well, allowing heat exchange with the ground, which was of suitable temperature.

Cooling treatment: In the greenhouse, four horizontally lined benches, each 20 m long, were established in two rows, with 8 benches in total. Two modified outdoor units were placed inside the greenhouse near the entrance. The everbearing strawberry cultivar 'Natsuakari' was chosen in this experiment, as this cultivar is well adapted to growth in relatively high temperatures and is popular for its taste (Okimura *et al.*, 2011). Strawberries were grown along two rows in all benches, and four benches were subjected to the cooling treatment. To cool the soil in which the strawberry cultivar was grown, a polyethylene tube for the flow of chilled water was buried under the soil surface in all four benches. In addition, a polyethylene tube containing chilled water for crown cooling was laid on the soil surface in four benches to maintain maximum possible proximity to the strawberry crown from tube surface. The present cooling methods for crown involved two sets of treatments: first, 2 lines of tubes on the soil surface with same flow direction (2L) were established in 3 benches. The other treatment involved the establishment of 2 lines consisting of a single tube with round-trip (RT) in one bench. The RT setup was aimed at minimizing the distribution of heat along the bench. A cultivation bench without any water tubes was set up as a control (NT).

Temperature measurement: Soil temperature was measured using thermocouples buried in the subsurface of the crown, with the couple inserted into the crown hole. Soil temperature was measured at two points, the interval between these being the trisection bench length. One of the crowns was measured at three points, with an interval of a quarter of the bench length. Direct measurement of the temperature of the tube water was not conducted. Instead, the thermocouples were attached to the tube via a steel connector to determine reference values for the temperature of the flowing water. Thermocouples were set along the tube for both crown and soil in each of the two positions shortly before the entrance into the bench, as well as shortly after the bench. The temperature of the tank water of the chiller and heat exchanger was measured at two positions, upper and lower, in each tank. The air temperature was measured at a height of 1.7 m. All temperature data were monitored using datalogger (GL820, Graphtec Corporation, Kanagawa, Japan) at 10-min intervals. The electric power consumption of the heat pump used for soil cooling was monitored using a wattmeter, from 11 August onward, at 10-min intervals. Nine raw data values for the power consumption of the heat pump used for crown cooling were obtained after 7 September; measurements were performed by checking the display of the wattmeter at 9 AM on 9 days at random during stages 2 and 3.

Statistical analysis: The experimental period was divided into three terms of 10 days each. These were categorized according to the greenhouse temperature as hot, mild, and cool conditions (Table 1). The data gathered at intervals of 10 min were averaged into values for each hour and day. Averaged daily data during each stage were analyzed for homogeneity of variance by Levene's test. If variances were homogeneous, the variables were analyzed by one- or two-factor analysis of variance (ANOVA) with Tukey's test. If normality was not achieved, non-parametric tests were conducted for multiple comparison (Steel-Dwass) following tests for significance (Kruskal-Wallis). All statistical analyses were performed using Ekuseru-Toukei 2012 (Social Survey Research Information).

Table 1. Greenhouse temperature and heat pump performance as indicated by power consumption, and water temperature in chiller and heat exchanger tank

Stage	Greenhouse temperature (°C)	Power consumption (W)		Water temperature in chiller (°C)		Water temperature in heat exchanger (°C)	
		Soil	Crown	Soil	Crown	Soil	Crown
Stage 1 (8/8-8/17)	26.6 ± 0.5^{a}	845.5 ± 10.1^{a}	n.d.	19.2± 0.7^{a}	20.4± 0.3^{a}	55.9 ± 0.1^{a}	53.3±2.4^{a}
Stage 2 (9/7-9/16)	21.3 ± 0.6^{b}	653.4± 36.6^{b}	560.4± 18.1^{a}	11.2± 0.3^{b}	17.9± 0.3^{b}	44.3 ± 1.6^{b}	45.4± 1.2^{b}
Stage 3 (9/18- 9/27)	15.7± 0.5^{C}	458.0± 15.7^{C}	421.8 ± 4.9^{b}	9.4 ± 0.2^{C}	16.7± 0.2^{C}	28.2 ± 1.3^{C}	38.7± 0.7^{C}

Note: The values represent means ($n = 10$). Different letters within a column indicate significant differences at $P < 0.05$; n.d., no data.

Results and discussion

Greenhouse environment: The experiment was performed from the first of August until the end of September 2011. The three stages, of 10 days each, were carefully selected based on low variation of greenhouse temperature with significant difference (Table 1). For instance, relatively large fluctuations of daily temperature were found between 18 August and 6 September. Therefore, we avoided using data collected during these periods as the GHP performance would have been affected by the ambient temperature. The greenhouse temperature decreased significantly ($P < 0.05$) with time towards the end of the summer season, from an average of 26.6 °C to 15.7 °C at stage 1 and stage 3, respectively, while a steep decline of temperature of 5.6 °C, from stage 2 to stage 3, was found to occur within 10 days (Fig. 2).

GHP technical performance: The power consumption of the heat pump used for soil treatment decreased significantly ($P < 0.05$), by approximately 26%, from stages 1 to 2 and stages 2 to 3. This decrease in power consumption was attributed to the lower cooling requirement, which resulted from the cooler temperature in the greenhouse. The power consumption for the crown treatment decreased significantly, by 24.7%, from stage 2 to stage 3; however, the data were scarce, as only 9 raw data were available.

In most cases, the water temperature of the chiller was lower than that of the greenhouse, by at least 6.2 °C, for both treatments of the soil and crown. However, the water temperature for soil cooling was lower than that for crown cooling; further, this difference increased at each stage. This lower value of temperature for soil was attributed to the lower demand for cooling resulting from a shorter total length of the soil water tube relative to the crown tube length. The water temperature of the heat exchanger at stage 1 was far above 50 °C, for both soil and crown. Those temperatures decreased to 45 °C at stage 2. A sudden decrease by 16.1 °C was seen for the crown from stages 2 to 3, while a decrease of 6.7 °C was observed for the soil from stages 2 to 3. As indicated by the higher water temperature of up to 59.9 °C, geothermal energy in the range of 10 m depth in this experiment was not sufficient to meet the demands for cooling under hot conditions. Therefore, additional wells would be needed for appropriate operation of GHP in order to reduce the energy cost.

Cooling effect on soil: Fig. 2 shows the average daily temperature, of soil and tube water for cooling soil, at each stage. The soil temperature in 2L and RT were significantly lower than that in the control, except for at stage 3. There were no significant differences ($P < 0.05$) between water and soil temperature for each treatment; however, the results of statistical analysis are not shown in Fig. 2. These findings indicate that the thermal conductivity of the tube was high enough to deliver a cooling effect into the soil. However, the temperature of tube water was higher than that of the chiller water by 5.5 °C to 7.7 °C. This may be attributed to the insufficient thermal insulation of the part of the water tube connecting the heat pump to the soil bed.

Cooling effect on the crown: The crown temperature significantly decreased at stage 1 and 2 owing to the cooling treatment (Fig. 3); however, there was no difference in temperature value between 2L and RT at any stage. However, no significant difference between control and treatment was observed at stage 3; the temperature of the chiller water, greenhouse, and soil differed by only 2 °C. This resulted in a temperature equilibrium in the entire system, including tube water for the crown. Despite the differing methodology for the water tube set-up in the cooling treatment of 2L and RT, no significant temperature difference between the positions in each bench was observed for both crown and soil.

Control environment: A significant difference was observed in the soil temperature of the cooling treatment between 2L and RT

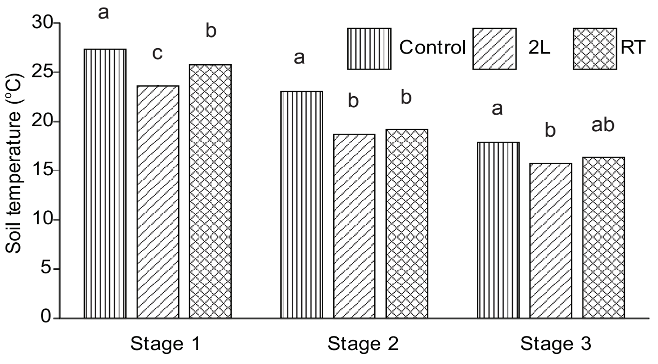

Fig. 2. Soil temperatures for periods 1, 2, and 3. The different letters indicate significant differences between the soil temperatures for different treatment methods for each period ($P < 0.05$).

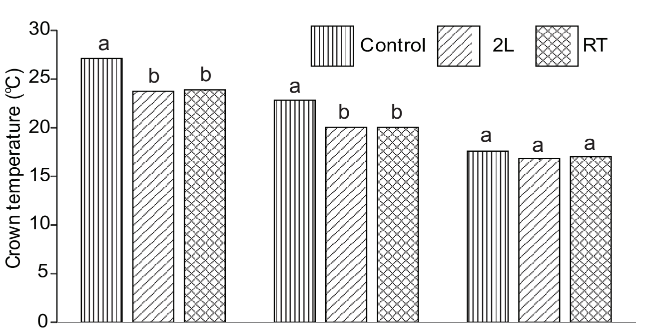

Fig. 3. Temperatures of the strawberry crown during periods 1, 2, and 3. The different letters indicate significant differences between the crown temperatures for different treatment methods for each period ($P < 0.05$).

at stage 1 (Fig. 2). However, assuming no significant temperature difference for soil and crown between 2L and RT, the hourly temperatures under these values in 2L and RT were averaged against those for the soil and crown, respectively. Fig. 4 shows the hourly temperature, averaged at each stage, of soil and crown in the control and the treated group, and in the greenhouse. At all stages, the temperature of the soil and crown in the control showed similar values, with a maximum difference of 1.4 °C. The amplitude of the hourly variation of temperature in the control was lower than that of greenhouse owing to the higher heat capacity of vegetation, including wet substrate of vegetation. As shown in Fig. 4, the soil and crown temperature in the control was higher than the greenhouse temperature. These values were below the greenhouse temperature only from 8 am to 3 pm at stage 1; this was attributed to shade from direct sunlight resulting from the presence of covered vegetation, and latent heat loss by evapotranspiration.

Comparison of the results: The temperature of the soil and crown in the treated group were successfully lower than that of the control at stages 1 and 2 (Fig. 4). At stage 1, the temperature of the crown in the control was maintained at 30 °C from 1 pm to 5 pm; however, this peak decreased up to 26.4 °C owing to the cooling treatment. The peak temperature of the crown at stage 2 also decreased from 25.3 °C to 22.6 °C. However, at stage 3, the temperature in the treated group, from 8 am to 2 pm, was higher than that of the control. This was attributed to the higher temperature of the chiller water for the crown at stage 3 compared with greenhouse temperature (Table 1); the higher temperature of the greenhouse resulted in ineffective cooling of the crown. The peak temperature values of soil in the treated group were 26.3 °C, 20.6 °C, and 18.1 °C at stage 1, 2, and 3, respectively; these values were lower than that for the control by 3.8 °C, 5.4 °C, and 3.2 °C, respectively. The peak values for the crown were lower than those for the control by 3.6 °C, 2.7 °C, and 0.4 °C at the corresponding stages. Therefore, these peak reductions in soil temperature were more effective than those of the crown temperature by approximately 2.7 °C at stages 2 and 3, owing to the lower water temperature of the chiller tank for the soil compared with that for the crown (Table 1). The degree of peak reduction for the soil at stage 1 was higher by only 0.2 °C; this was attributed to the similar water temperature of the chiller tank for the soil and crown (19.8 °C).

In this study, the methodology for partial cooling of both soil and crown was applied to strawberry vegetation using a heat pump coupled with the geo-thermal energy. For the cooling treatment, two different directions of flow of water in two line tubes laid on the soil surface, named 2L and RT, were established, and a single water tube was buried in both treatment methods. The effects of the cooling treatments were observed during three stages, in which the greenhouse temperature was with 26.5 °C, 21.3 °C, and 15.7 °C. At stage 1, the power consumption of the heat pump was almost at the maximum limit of 845.5 W owing to the high heat demand. However, the amount of thermal energy extracted from the heat exchange well was too high to follow the energy supplement from the ground along with 10 m of depth, which resulted in a considerably high temperature of approximately 54.6 °C. This power consumption was reduced to almost half of the maximum consumption (439.9 W) as the greenhouse temperature decreased owing to the lower cooling demands of the vegetation. The peak temperatures of soil and crown were successfully reduced, in comparison with those of the control, by approximately 4.1 °C and 2.3 °C, respectively; further, the soil temperature was lower than that of the crown. The greater reduction of temperature of the soil was attributed to the lower temperature of the chiller tank water for soil cooling, which in turn resulted from the shorter length of the water tube used for cooling the soil. In this experiment, a total of 2 kW of energy was utilized by the commercial heat pump to successfully reduce the temperature of both crown and soil, in 4 benches of 20 m length each, with facile set-up of heat exchange wells. There was no significant difference in temperature between the 2 kinds of

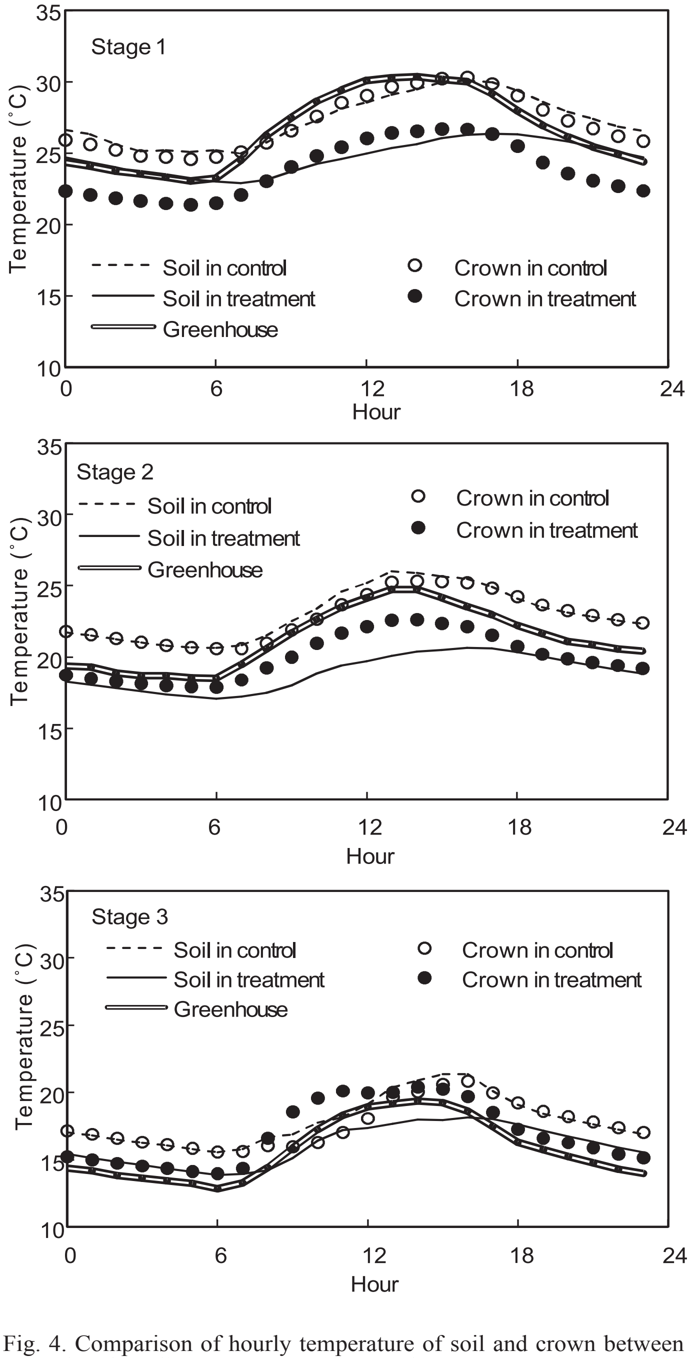

Fig. 4. Comparison of hourly temperature of soil and crown between control and cooling treatment with greenhouse temperature at stages 1, 2 and 3

cooling treatments employed. However, the reduction of energy-related costs and increased effectiveness of GHP systems in greenhouses require the establishment of a heat exchange well as well as sufficient thermal insulation of water tubes. GHP systems with improved heat pumps and wells should enable the facile and effective cooling down of benches at a reasonable cost.

Acknowledgements

The authors are thankful to Mr. Muramoto for kindly permitting the use of the greenhouse in this study. We would like to thank Editage (www.editage.jp) for English language editing.

References

Abdel-wahab, S. 1994. Energy and water management in evaporative cooling systems in Saudi Arabia. *Resources Conservation and Recycling*, 12: 135-146.

Boughanmi, H., M. Lazaar, A. Farhat, and A. Guizani, 2017. Evaluation of soil thermal potential under Tunisian climate using a new conic basket geothermal heat exchanger: Energy and exergy analysis. *Appl. Therm. Eng*., 113: 912–925.

Enteria N., H. Yoshino, R. Takaki, H. Yonekura, A. Satake and A. Mochida, 2013. First and second law analyses of the developed solar-desiccant air-conditioning system (SDACS) operation during the summer day. *Energy and Buildings*, 60: 239-251.

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.

Iwasaki, Y. 2008. Root zone aeration improves growth and yields of coir-cultured strawberry (*Fragaria ananassa* Duch.) during summer. *ISHS Acta Hort.*, 779: 251–254.

Kumar, K.S., K.N. Tiwari and K. Madan, 2009. Design and technology for greenhouse cooling in tropical and subtropical regions: A review. *Energy and Buildings*, 41:1269–1275.

Mongkon, S., S. Thepa, P. Namprakai and N. Pratinthong, 2013. Cooling performance and condensation evaluation of horizontal earth tube system for the tropical greenhouse. *Energy and Buildings*, 66: 104-111.

Nanjo H. and S. Moritani, 2014. Snow melting system and rotary penetration pipe. Japanese patent application of 2014–83089: In Japanese

Noorollahi, Y, P. Bigdelou, G. Pourfayaz and H. Yousefi, 2016. Numerical modeling and economic analysis of a ground source heat pump for supplying energy for a greenhouse in Alborz province, Iran. *J. Cleaner Production*, 131: 145–154.

Okimura, M., K. Okamoto, M. Honjo, S. Yui, H. Matsunaga, T. Ishii, I. Igarashi, M. Fujino, S. Kataoka and Y. Kawazu, 2011. Breeding of new everbearing strawberry cultivars, ‘Natsuakari’ and ‘Dekoruju’. *Hort. Res. (Japan)*, 10: 121-126. Japanese with English abstract.

Yamasaki, A. 2013. Recent progress of strawberry year-round production technology in Japan. *Jpn. Agr. Res. Qrtly.*, 47: 37-42.

Received: January, 2017; Revised: May, 2017; Accepted: May, 2017