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Root zone and crown temperature control in strawberry cultivation

딸기 재배에서의 근권 및 관부 온도 조절

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Root zone and crown temperature control in strawberry cultivation

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ABSTRACT

The meristems in plants are known to be sensitive to ambient temperatures, and the meristems in shoots and roots are suggested to perceive ambient temperatures in plants. This study focused on the temperature-sensitive organs and attempted to gain insights into the plant-organ temperature control methods, including the root zone and crown temperature controls on strawberry plants in a greenhouse and a closed transplant production system. Forcing cultivation of June-bearing strawberry cultivars in greenhouses has most commonly been applied worldwide. During winter, strawberry plants are in danger of exposure to low temperatures, but typical heating methods for a whole greenhouse volume may cost an excessive heating load. During the transplant production of June-bearing cultivars, uniform floral bud differentiation in strawberry transplants, initiated by low ambient temperatures, ensures early harvest. Year-round strawberry transplant production in a closed transplant system is also needed to meet the current demand for year-round strawberry production in plant factories. Under vegetative growth-promoting conditions with a high air temperature and an extended photoperiod in a closed transplant system, the promotion methods of floral bud differentiation should be developed without affecting the whole system environmental conditions.

In chapter one, root-zone pipe heating systems on strawberries were compared in a greenhouse during the winter. The strawberry plants were treated for two types of root-zone heating systems: crown-based heating (CBH) and root-based heating (RBH). The RBH system could maintain the optimum root-zone temperature conditions better than the CBH system, promoting the vegetative growth of strawberry plants, but the CBH system positively affected the strawberry yield. Two types of root-zone pipe heating systems could be utilized according to the desirable developmental phases of the strawberry plants.

In chapter two, the effects of crown cooling on the floral bud differentiation and the growth of strawberry transplants were investigated in a closed transplant production system. The transplants were treated for the crown-cooling temperature treatments with different coolant temperatures (10 (T10), 15 (T15), 20°C (T20), and no cooling (NC)), and the crown-cooling time treatments with different cooling application timings (daytime cooling (DC), nighttime cooling (NC), day- and nighttime cooling (DNC), as well as a no cooling (Control)) for six weeks. In the crown-cooling temperature treatments, floral bud differentiation was promoted more in the T10 and T15 treatments than in the TC treatment after four weeks. In the crown-cooling time treatments, the floral bud differentiation was promoted by the NC and DNC treatments after four weeks, and by the DNC treatment after six weeks. These results indicate that four weeks of crown cooling can promote floral bud differentiation in transplants under high air temperatures and extended photoperiod conditions. The results obtained in this study can improve efficiency in temperature control and productivity in strawberry cultivation. Further studies on the subtle temperature differences between the air and strawberry organs and their relationship with the physiological responses are needed.

Key words: crown cooling, crown temperature, floral bud differentiation, June-bearing strawberry, plant organ temperature, root zone heating

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GENERAL INTRODUCTION

Global strawberry production and consumption have increased dramatically in the twenty-first century, and the strawberry, *Fragaria* × *ananassa* Duch., is produced commercially in 76 countries worldwide (Simpson, 2018). Based on the latest data from the Rural Development Administration (RDA), strawberry production was 1.227 trillion won, accounting for 10.9% of the total amount of vegetable crop production in South Korea (Choi, 2022). The forcing cultivation has most commonly been applied in South Korea for June-bearing strawberry cultivars, such as ‘Seolhyang’ and ‘Kuemsil.’ They are transplanted into greenhouses for forcing cultivation in September and are harvested from December to May of the following year. During the winter, the air temperature fluctuates significantly over a wide range, putting the strawberry plants in danger of exposure to low temperatures at night. Extremely low temperatures can depress photosynthesis (Hidaka et al., 2013), affect floral development, pollination, and fertilization, and consequently induce fruit malformation in strawberry plants (Ariza et al., 2011). However, typical heating methods for a whole greenhouse volume may cost an excessive heating load, so the energy efficiency of heating methods should be improved to lower the management costs. To overcome such issues, heating methods such as root zone heating were investigated, focusing on the temperature-sensitive organs in strawberry plants in greenhouse winter cultivation.

Meanwhile, June-bearing strawberries are seasonal-flowering varieties in which floral bud differentiation is induced by short day length and low temperatures (Ito and Saito, 1962; Manakasem and Goodwin, 1998). Early and uniform floral bud differentiation in strawberry transplants ensures early harvest after transplanting, leading to high income (Jun et al., 2013), but recently there have been concerns in greenhouse transplant production that rising air temperatures in August and September will cause delayed flower bud differentiation in first inflorescences (Hidaka et al., 2017). Strawberry crown cooling methods in greenhouses for promoting floral bud differentiation during transplant production have been studied, but more sophisticated approaches are needed. Also, a closed transplant production system (CTPS) with artificial lighting has been introduced as a strawberry propagation system. CTPSs can be set up and maintain appropriate environmental conditions, including air temperature, relative humidity, CO_2 concentration, and photoperiod, allowing year-round strawberry transplant propagation with a significantly higher propagation rate (Chun et al., 2012; Kim et al., 2010; Kozai et al., 2000). The transplant production in the CTPS has the same problem as in the greenhouse because the floral bud differentiation is needed, but the environmental conditions are set to promote vegetative growth of transplants with high air temperatures and extended photoperiods. The investigation of the crown temperature control methods to promote floral bud differentiation without affecting the whole environmental conditions in CTPS can improve the efficiency of the systems, and transplants with differentiated floral buds can be supplied year-roundly to plant factories, leading to an early harvest. Knowledge gained from this study can be utilized to develop root zone and crown-temperature control methods to improve energy efficiency and productivity in strawberry cultivation.

LITERATURE REVIEW

Temperature perception of plants

Most plant species are considered as poikilotherms, so their organ temperatures fluctuate in response to the ambient thermal environment (Savvides et al., 2013). The meristems in plants are known to be sensitive to ambient temperatures (Metzger, 1988), and the meristems in shoots and roots are suggested to perceive ambient temperatures (Peacock, 1975; Fortin and Poff, 1990), which affect the development of leaves (Granier and Tardieu, 1998; Jamieson et al., 1995), primary roots (Fortin and Poff, 1990), floral buds (Lin et al., 2019; Song et al., 2013), and fruits (Kawasaki and Yoneda, 2019; Yoshioka et al., 1986). Plant root-zone temperature is known to affect growth and development as much as air temperature (Korner and Paulsen, 2004; Xu and Huang, 2000) and has significant effects on nutrient uptake by roots (Pregitzer and King, 2005). Root zone temperatures also affect the chemical composition of many horticultural crop families, such as Cucurbitaceae (Yan et al., 2013), Rosaceae (Sakamoto and Suzuki, 2015), and Solanaceae (Malik et al., 2013).

The strawberry plant has a crown, a short and thickened stem containing the shoot apical meristem (Dan et al., 2015; Poling, 2012), in which the floral bud develops. The flowering of most plant species is initiated by environmental signals, including temperatures, because the expressions of many flowering-time genes, called floral integrators, are controlled by the environmental signals (Samach and Wigge, 2005). Reproductive development can be initiated only when the shoots are exposed to thermoinductive temperatures (Metzger, 1988). Thus, the crown of a strawberry plant may be involved in temperature-induced physiological responses, including floral bud differentiation.

Plant organ-temperature control in greenhouses

Temperature conditions in greenhouses can be controlled easily compared to open fields, but the energy costs for heating and cooling are long-standing problems. Plant organ-temperature control methods to manipulate the plant organ and its local ambient temperature have been studied in greenhouses for fruit vegetable cultivation. The plant organ temperatures are reported to have vital feedback on the climate within the canopy, which interacts with the environment outside the canopy in greenhouses (Westreenen et al., 2020). Plant organ temperatures directly affect photosynthesis and plant development, and the activity of diseases and pests is strongly determined by organ temperatures and local humidity in greenhouses (Westreenen et al., 2020). For instance, doubling plant densities in tomatoes increased the difference between plant ambient and overall greenhouse air temperature at 1°C (Soni et al., 2005). Temperature-sensitive organs such as shoot tips (Grimstad and Frimanslund, 1993), roots (Gosselin and Trudel, 1983), flowers (Sato et al., 2002), and fruits (Bertin, 2005), for example, in tomato plants, are subjected to the plant organ-temperature control. Among the organ temperatures, the root zone temperature can be easily controlled and distinguished from above-ground temperatures, whereas temperature control of above-ground organs is difficult (Kawasaki and Yoneda, 2019). For the root-zone temperature control, increased mineral nutrient contents in shoots in tomato plants (Gent and Ma, 2000) and increased xylem exudation in cucumber plants were reported (Wang et al., 2016). For fruit temperature control, Fanwoua et al. (2012) suggested that heating the fruit can shorten the fruit growth period. For the shoot-tips, Kawasaki et al. (2011) investigated the shoot-tip and flower heating of tomatoes using an air heater and plastic ducts hung near the plant canopy and demonstrated that the organ temperature control reduced fuel consumption by 26% with a similar or higher yield. For strawberry shoot-tip temperature control, as they have shoot-tips in crowns located near the ground surface and their position does not move with growth, the crown temperature can be controlled easily by a similar system that used for root-zone temperature control (Kawasaki and Yoneda, 2019).

Floral bud differentiation in strawberries

Flowering plants have evolved a complex network of regulatory mechanisms to ensure the proper timing of reproductive transition (Lin et al., 2019). Flowering time, which is heavily influenced by environmental signals, is a critical step in the life cycle of plants, and its control mechanisms during vernalization are well studied (Sheldon et al., 2000). Strawberry flower bud differentiation in June-bearing cultivars is induced by low air temperatures and short day lengths (Ito and Saito, 1962; Manakasem and Goodwin, 1998). Among them, low air temperature is a primary factor, and short day length promotes floral bud differentiation (Jonkers, 1965). In contrast with Ever-bearing cultivars in which floral bud differentiation is hardly affected by day length, June-bearing cultivars are more environment-sensitive during the floral bud differentiation. Flower initiation in June-bearing strawberry cultivars begins in September under field conditions (Jahn and Dana, 1970), and floral bud differentiation during the transplant production for greenhouse forcing cultivation is important. Early and uniform floral bud differentiation in strawberry transplants ensures early harvest leading to high income (Jun et al., 2013). However, transplants are produced during summer for greenhouse cultivation, and early flowering is known to be feasible by exposing transplants to chilling temperatures or short-day conditions (Bish et al., 2004). Floral bud differentiation is first initiated by a broadening and flattening of apex (Guttridge, 1952, 1955), with the terminal flower appearing first (Ruef and Richey, 1926). The flower develops centripetally, the sepals appearing first, followed by the petals, stamens, and pistils (Guttridge, 1952; Taylor et al., 1997; Waldo, 1930). Secondary flowers appear in the axils of the bracts of the inflorescence (Guttridge, 1952) and are at a younger stage than terminal flowers (Ruef and Richey, 1926; Waldo, 1930). Since the inflorescence is determinate, vegetative growth continues from the meristems in upper axillary positions of crowns (Jahn and Dana, 1970). Many localized organ-temperature control systems have been designed to stabilize those strawberry flower bud differentiation processes under high-temperature conditions (Ikeda et al., 2007; Mukai and Ogura, 1988; Yamazaki et al., 2007).

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CHAPTER 1

Comparison of root-zone pipe heating systems on strawberries in a greenhouse during the winter season

ABSTRACT

To compare the root-zone pipe heating systems with the air source heat pump for strawberry (*Fragaria* × *ananassa*) cultivation in a greenhouse during the winter, the effects of two types of root-zone heating pipes on strawberries were investigated. 'Seolhyang' strawberry transplants were transplanted on coir slabs in a greenhouse and were treated with two types of root-zone heating systems such as crown-based heating (CBH) and root-based heating (RBH). The medium temperatures in the RBH treatment increased continuously from 6 am, resulting in the longest daily retention time for the optimum root-zone temperature in February, March, and April among the treatments. In the RBH treatment, the vegetative shoot and root growth were improved, resulting in the thickest crown diameter, heaviest fresh root weights, and greatest dry weight distribution in roots. The days from flower bud emergence to anthesis of the primary flower in the second flower cluster were retarded in the RBH treatment. The fruit yield in the middle stage of the harvest period was greater in the CBH treatment. Free amino acid contents in leaves, such as aspartic acid, decreased in the CBH and RBH treatments. The results indicate that the RBH system can maintain the optimum root-zone temperature conditions better than the CBH system, promoting the vegetative growth of strawberry plants. Even though the CBH system has lower efficiency for root-zone temperature manipulation, the strawberry yield can be positively affected. Two types of root-zone pipe heating systems could be utilized according to the desirable developmental phases of the strawberry plants.

Key words: crown heating, June-bearing strawberry, root zone heating, root zone temperature

INTRODUCTION

June-bearing strawberries are transplanted into a greenhouse for forcing cultivation in September and harvested from December to May in South Korea. Strawberry plants are often exposed to low air temperatures during the winter season in greenhouse-forcing cultivation, which depresses photosynthesis in strawberry plants (Hidaka et al., 2013). Strawberry plants are often subjected to extreme sporadic short-term chilling injury when heating methods are not strictly applied, leading to poor fruit set and fruit malformation by reducing pollen germination and decreasing yield (Cui et al., 2021). Cold temperature acclimation in strawberries also involves altering cellular osmotic properties correlated with the soluble carbohydrate and free amino acid contents in the leaf tissues (O'Neill, 1983). Thus, proper temperature control is needed to ensure overall strawberry fruit yield (Durner, 2016).

As the air temperatures in greenhouses are the lowest just before sunrise, greenhouse cultivation demands heating in the early morning (Elings et al., 2004), which can be one energy-saving strategy in greenhouses. However, typical heating methods for a whole greenhouse volume may cost an excessive heating load. To overcome such issues, greenhouse heating methods such as organ-based or plant-ambient local heating have been studied. Organ-based heating methods in greenhouses for fruit vegetable cultivation are aimed at modulating meristem temperatures as the meristems are known to be sensitive to ambient temperatures (Metzger, 1988), which affect the development of leaves (Granier and Tardieu, 1998; Jamieson et al., 1995), primary roots (Fortin and Poff, 1990), flower buds (Lin et al., 2019; Song et al., 2013), and fruits (Kawasaki and Yoneda, 2019; Yoshioka et al., 1986). Heat sources such as heat pumps are used for organ-based heating in greenhouses to balance accurate temperature control and low energy costs (Kawasaki and Yoneda, 2019).

The crown-based heating can be one of the strawberry organ-based heating methods because the crown is a short and thickened stem having meristems at the upper end (Poling, 2012). A few studies applied the water-heating pipes, and the initial strawberry yield from December to March increased by 43% when the crown temperature was increased by 3–5°C (Moon et al., 2016). Crown-based heating pipes also promoted the yield of second and third fruit clusters in strawberries (Lee et al., 2021). The root-based heating can also be applied, manipulating the root zone temperatures. Heated nutrient solution supply can be used as a simple root-based heating method in a soilless culture without an additional heat transfer system, but it has the limitation of increasing not only root zone temperatures but also the water contents of substrates. Thus, the root-based pipe heating can be a practical method, accelerating flower bud differentiation and flowering of axillary flower clusters, and increasing fruit yield (Kim et al., 2009). Jo and Shin (2022) also reported that root-based heating combined with a heated nutrient solution promoted the emergence of flower buds and increased the fruit productivity of strawberries.

However, crown- and root-based pipe heating systems in strawberry substrate cultures should be considered and interpreted as root-zone heating systems because the crown-based heating pipes are directly in contact with the substrates due to the shortened structure of crowns in strawberry plants, also manipulating the root zone temperatures. The crown- and root-based heating pipes have different diameters according to the installation positions, making differences in the effects and efficiencies of the root-zone heating systems. Plant root-zone temperature is known to affect growth and development as much as air temperature (Korner and Paulsen, 2004; Xu and Huang, 2000) and has significant effects on nutrient uptake by roots (Pregitzer and King, 2005). In strawberries, the rate of nutrient absorption in roots is known to be the fastest at approximately 18°C of root zone temperature (RDA, 2019; Udagawa et al., 1991), so the root zone temperature around 18ºC could be considered the optimum range. Root zone temperatures also affect the chemical composition of many horticultural crops in the Cucurbitaceae (Yan et al., 2013), Rosaceae (Sakamoto and Suzuki, 2015), and Solanaceae (Malik et al., 2013) families.

Extending the retention time for the optimum root-zone temperatures by root zone heating in the early morning and before sunset may affect positively on strawberry growth and development. Thus, the root zone temperature and the mitigated cold stress by the elevated root-zone temperature might affect the free amino acid contents in strawberry plants. Therefore, I compared the effects of the crown- and root-based pipe heating systems on the medium temperatures and growth, flowering, yield, and chemical contents of strawberry plants in a greenhouse winter cultivation, with the investigation of the coir substrates' thermal characteristics and suitability for pipe heating systems.

MATERIALS AND METHODS

Plant materials and environmental conditions

Strawberry (*Fragaria* × *ananassa* Duch. cv. Seolhyang) transplants provided by Nonsan Strawberry Experiment Station of Chungnam Agricultural Research and Extension Services (Nonsan, South Korea) were transplanted onto coir slabs (crushed chips: dust = 5: 5 (v/v), 1000 × 150 × 100 mm, length × width × height; Power, Daeyoung GS Co., Daegu, South Korea) in the greenhouse at Seoul National University in Suwon, South Korea (E 127.0°, N 37.3°) on 25 November 2021. The plants were fertigated with Yamazaki's strawberry nutrient solution (NO_3-N 5 me L^{-1}, NH_4-N 0.5 me L^{-1}, PO_4-P 1.5 me L^{-1}, K 3 me L^{-1}, Ca 2 me L^{-1}, Mg 1 me L^{-1}, at electrical conductivity (EC) 0.8 dS m^{-1}; Yamazaki, 1984). The concentration was gradually increased to an EC of 0.8 dS m^{-1}, and the pH was continuously adjusted within the 5.8–6.3 range during the experimental period. The flowers were pollinated by bees, and the number of flowers per cluster was limited to seven, with axillary buds removed. The number of leaves was maintained at a maximum of 10, with old leaves removed. When the root-zone heating system treatments were initiated, the minimum air temperature at night in the greenhouse was controlled and maintained at no lower than 7°C (Fig. 1-1), as the minimum growth temperature of strawberries is known to be around 5°C (Jung et al., 2012; Lee et al., 2021). The average air temperature in the daytime was controlled at 21°C, and the average relative humidity in the day was maintained at 60% during the treatments.

Root-zone heating system treatments

Strawberry plants were treated for two types of root-zone pipe heating systems such as crown-based heating (CBH) and root-based heating (RBH), with a control. An air source heat pump (ECO A-05, Innergie Technologies Co., Gwangju, South Korea) was installed in the greenhouse to maintain the water temperature in the heat storage tank at 31–33°C for the heating of the nutrient solution and root-zone heating water with a heat exchanger (Fig. 1-2). The heated nutrient solution of 24–26°C was supplied to all treatments two times a day for 5 min at 8 am and 3 min at 2 pm (300 mL d^{-1}/plant) to support the root-zone heating system and to supply the nutrient solution when the air temperature is high, respectively. Two circular corrugated copper pipes (Ø 15 mm) for the CBH and two square heat-conducting pipes (30 × 30 mm, width × height) for the RBH were arranged along both sides of the strawberry crowns and coir slabs, respectively, to fit the heating locations, and the root-zone

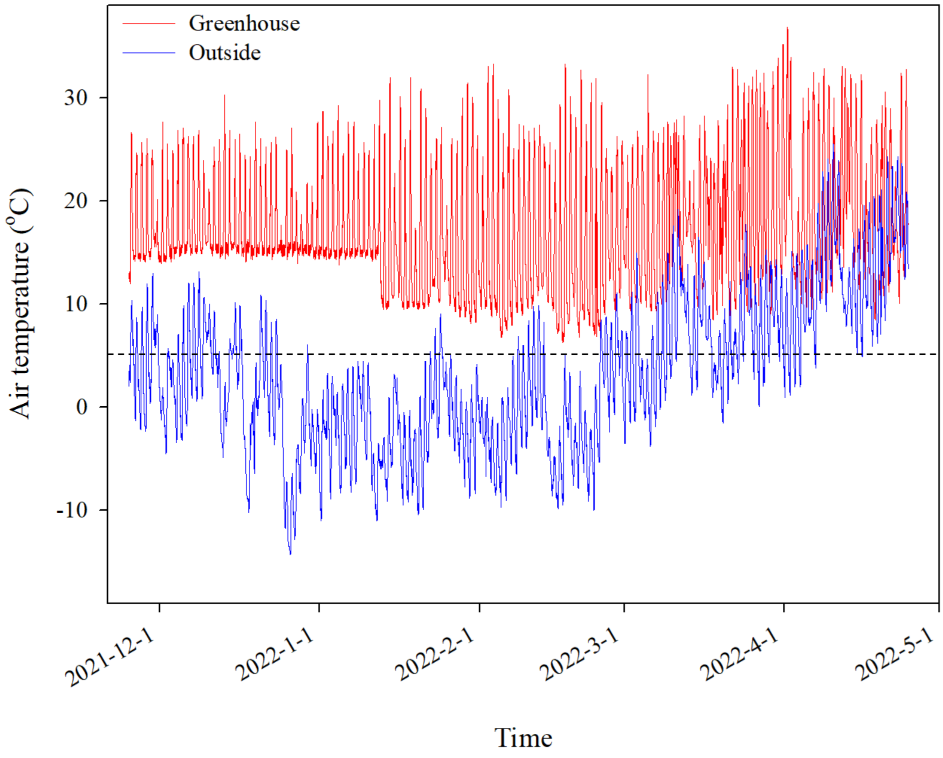

Fig. 1-1. Changes in the greenhouse (red line) and outside air temperatures (blue line) during the experimental period. The dotted line represents the minimum growth temperature (5°C) of strawberries.

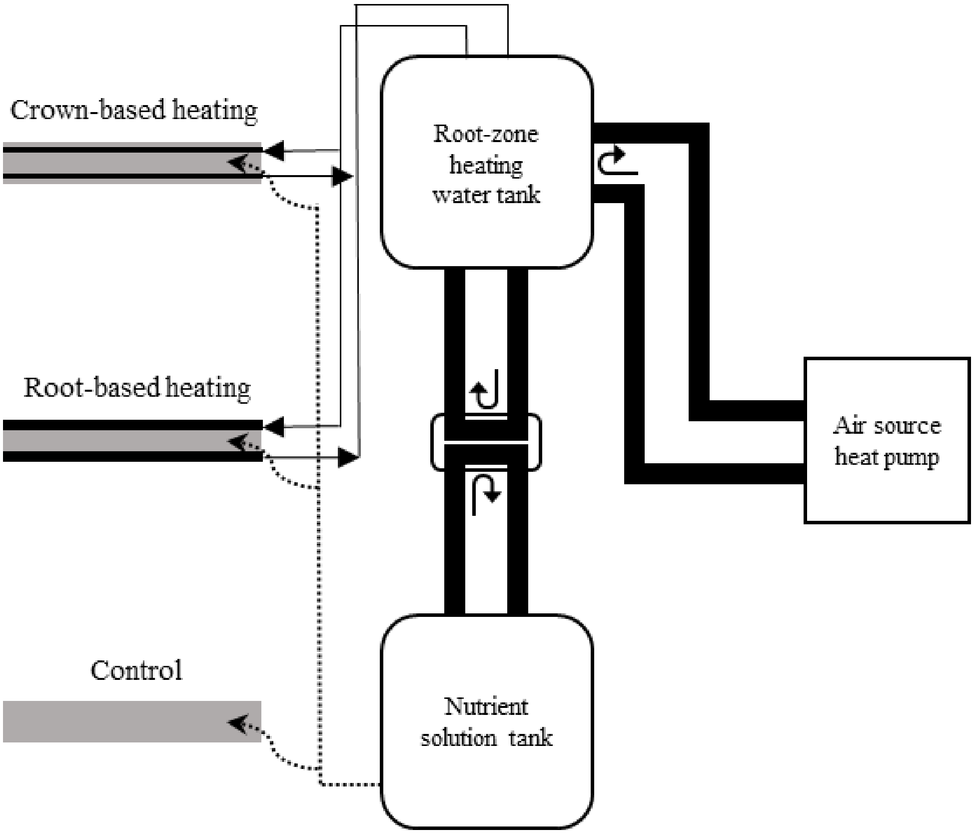

Fig. 1-2. Simplified diagram of the root-zone heating systems in the experiment.

heating water was circulated from the heat storage tank with a temperature of 26–28°C at 6–9 am and 4–5 pm. Except for the areas in contact with strawberry crowns and coir slabs, the pipes were insulated with reflective foams. The treatments started on 23 January 2022, when the strawberry plants had 5–6 unfolded leaves, and continued to the end of April as the minimum outside air temperatures still dropped to 5°C in April (Fig. 1-1).

Temperature data collection

The temperature of the coir slabs was measured by T-type thermocouples placed 30 and 70 mm below the surface (represented as upper and lower points, respectively) and recorded by a data logger (CR1000X, Campbell Scientific Co., Logan, UT, USA). The daily medium temperature changes and retention time for the optimum root-zone temperature (18±2°C) were calculated, and the greenhouse air temperature and relative humidity were recorded with a thermorecorder (TR-72wb, T&D Co., Nagano, Japan).

Plant growth and development

The crown diameter and the relative chlorophyll content (SPAD value) were nondestructively measured on six randomly selected strawberry plants per treatment every week from 4 March. For the destructive growth measurements, fresh and dry weights of leaf, crown, and root, and leaf area, in addition to the crown diameter and SPAD value, were measured on 15 randomly selected plants after 97 days of the treatments. The dry weights were measured after drying at 80ºC for a week, and the dry weight distributions in the leaf, crown, and root were calculated. The SPAD value was averaged with four leaves from the third newest unfolded leaf by chlorophyll meter (SPAD 502, Konica Minolta, Sakai, Japan). The total leaf area of each plant was measured with a leaf area meter (Li-3100, LI-COR, Lincoln, NE, USA).

To investigate the flowering and fruit characteristics, the dates of flower bud emergence and first flowering of 28 randomly selected plants per treatment were recorded, and the days from flower bud emergence to the anthesis of the primary flower in the first and second flower clusters were calculated. Flower bud emergence was recorded when the peduncle appeared over 5 mm, and primary flower anthesis was recorded when the pistils of the primary flower could be seen with the naked eye. The fruits in the first and second fruit clusters were harvested when the coloration was over 80%, and those heavier than 5 g were used for measuring diameter, length, and weight. The daily fruit yield in early, middle, and late harvest periods, 11 days each, was compared among the treatments.

Free amino acid contents

The free amino acid contents such as aspartic acid, glutamic acid, glycine, and proline in the strawberry leaves were analyzed with six plants per treatment. The fourth newest unfolded leaves were sampled from each plant on 28 April 2022 and were freeze-dried with a freeze-dryer (TFD8503, Ilshin Biobase, Dongducheon, South Korea). The leaf crude extracts were prepared by extracting the powdered leaves with 0.1 M perchloric acid containing 0.1% meta-phosphoric acid in a ratio of 1: 30 (w/v) (g/mL) in an ultrasonic bath (JAC Ultrasonic 4020, KODO Technical Research, Hwaseong, South Korea) for 1 h with an amplitude of 40 kHz. The samples were vortexed for 1 h at room temperature, and 1 mL of each extract was filtered through a 0.20-mm microbial filter (Sartorius Minisart, Hannover, Germany). Free amino acid contents were analyzed by Dionex Ultimate 3000 HPLC instrument (Dionex, Sunnyvale, CA, USA) following an established method (Min et al., 2020).

Thermal and physical characteristics of substrates

Thermal and physical characteristics of the coir (Power; Daeyoung GS Co.), soil (Plant World; Nong Woo Bio, Suwon, Korea), perlite (New PerlShine No. 1, Green Fire Chemicals Co., Hongseong, Korea), and rockwool (UR mat; Hankuk URmedia Co., Seoul, South Korea) were investigated. The thermal conductivity of each substrate was measured with a heat flow meter (HFM 436 Lambda; NETZSCH, Selb, Germany). The dry weights were measured after filling the plastic pot (Φ 150 mm, 1.4 L) with each substrate and drying at 105°C for a week, and the dry bulk density and maximum water holding capacity were calculated.

The thermal characteristics of the coir substrate used in this study were investigated under a simplified pipe heating system, mimicking the RBH pipes installed in the greenhouse. A silicone tube (8 mm in diameter) was coiled six times outside the same pot in the dry weight measurements. The pot was filled with coir and adjusted to the moisture content of 40 or 80% by weight, and was placed in the chamber with 14°C of air temperature and 65% of relative humidity until the temperature equilibrium. Then, the heated water of 40°C was circulated at a rate of 2.7 L min^{-1} in the silicone tube for 60 min. The temperature changes of coir were monitored and averaged at four positions (upper, middle, lower, and side points) in the pot (Fig. 1-3) with T-type thermocouples and data logger (UA11-K; Radionode Co., Yongin, South Korea) with Tapaculo Lite software.

Statistical analysis

Statistical Analysis System (SAS) for Windows version 9.4 (SAS Institute Inc., Cary, NC, USA) was used to determine the differences among means by analysis of variance (ANOVA). If a statistically significant effect was found, a comparison of means was performed using Duncan’s multiple range test. The differences among the treatments in all statistical tests were evaluated at $P < 0.05$.

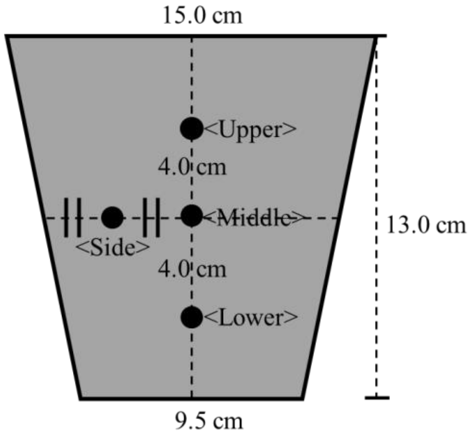

Fig. 1-3. Temperature measurement points of coir substrate in the measurements of the thermal characteristics under a simplified pipe heating system.

RESULTS AND DISCUSSION

Medium temperatures

From February to April, the daily minimum air temperature in the greenhouse gradually increased as the outside air temperature increased (Fig. 1-1). Because the heating pipes for the CBH and RBH were installed on the top and side of the medium, respectively, the medium temperatures of the upper and lower points in the RBH treatment and the upper point in the CBH treatment increased from 6 am. The temperature of the lower point in the CBH treatment and both points in the control continuously decreased until 8 am (Fig. 1-4). From 3 pm to 6 am the next day, the medium temperatures of the lower points were higher than those of the upper points in all treatments. Nevertheless, the temperature of the upper point in the CBH treatment was higher than that of the lower points between 6 am and 11 am (Fig. 1-4). Unlike the RBH treatment, the medium temperatures in both the CBH and control treatments temporally increased twice a day (8 am and 2 pm) due to irrigation and tended to temporally decrease and increase after irrigation at 8 am (Fig. 1-4). As the heating pipes with water circulation is known to be a suitable organ heating method in greenhouses due to the high thermal capacity of water (Ghosal and Tiwari, 2004), the RBH system provided more heat energy to the medium than the CBH system, even though two systems were supplied heated water at same temperature.

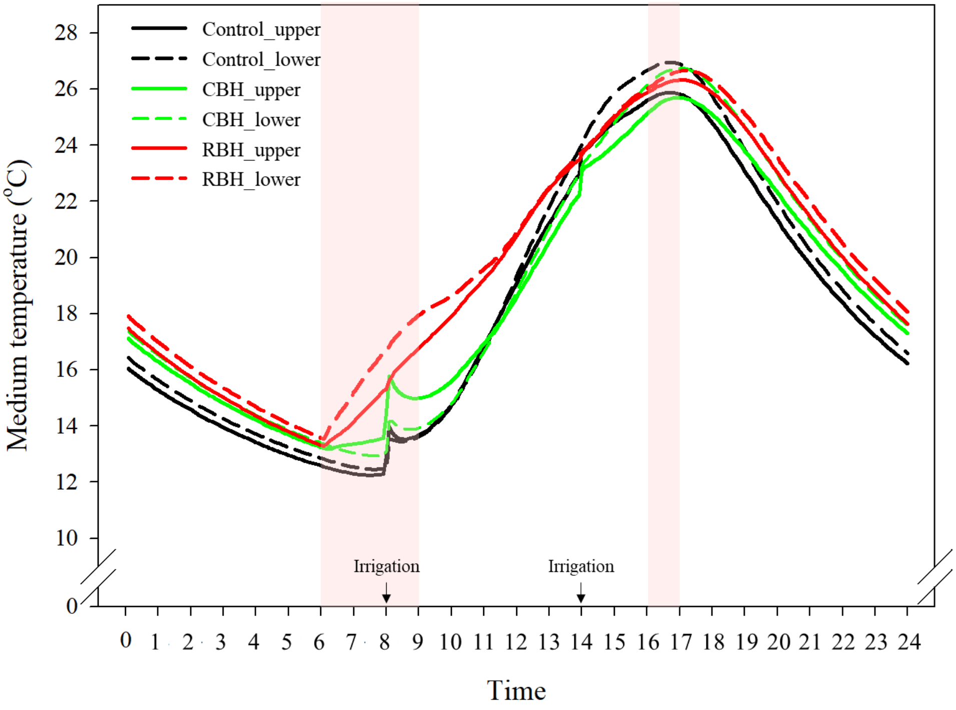

Fig. 1-4. Daily medium temperature changes under root-zone heating system treatments. The pink areas indicate heating periods, and the black arrows indicate the irrigation timings. Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating. Upper and lower, 30 and 70 mm below the surface of coir slab, respectively.

Temporal fluctuations in root growth could be induced by repetitively changing environmental factors, such as root zone temperature, to which root growth is highly susceptible (Walter et al., 2002). The daily medium temperature changing regime could have long-term effects on root growth, so the stable daily medium temperature regime in the RBH treatment may be one factor that affects the strawberry root growth and development. However, as Ghosal and Tiwari (2004) reported, heating pipes near plants can provide thermal energy simultaneously to both plants and ambient environments. It is thought that the CBH and RBH system applied in this experiment increased air temperature around the plants, unlike the control, affecting plant growth to some extent. This problem became a limitation in investigating the independent effects of root zone temperatures on strawberry plants in a greenhouse.

The daily retention time for optimum root-zone temperature in February and March was significantly longer in the RBH treatment, followed by the CBH and control treatments, and the medium temperatures stayed the longest in the optimum ranges in March among the months in all treatments (Table 1-1). The absorption of nutrients such as nitrogen, phosphoric acid, and potassium is suppressed, and the respiration of the root increases under low root-zone temperatures, thereby inhibiting root growth (RDA, 2019). As the daily retention time for the optimum root-zone temperature was extended, there is a possibility that the nutrient absorption of the strawberry plants would

Table 1-1. The daily retention time for optimum root-zone temperature (18±2°C) in February, March, and April as affected by the root-zone heating system treatments

Treatment[z]	Retention time ($h\ d^{-1}$)		
	February	March	April
Control	4.3 b[y]	6.2 b	5.2
CBH	4.8 b	7.2 ab	6.0
RBH	6.2 a	8.5 a	6.3
p-value[x]	***	*	ns

[z] Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

be promoted. The application timing of the root-zone heating systems can affect the retention time for optimum root-zone temperatures. Increasing the air temperature in the early morning promoted pepper growth against the freezing effects in the greenhouse (Ghosal and Tiwari, 2004). Abdel-Mawgoud et al. (2005) suggested that the positive physiological effects of elevated root-zone temperature on plants occur during the early morning when the water uptake from the roots increases very rapidly. Therefore, the root-zone heating system schedule must be designed to manipulate the root zone temperature in the early morning and just before sunset to increase the daily retention time for optimum root-zone temperature. Both CBH and RBH extended the daily retention time for optimum root-zone temperature consistently from February to March but not in April, indicating that the root-zone heating methods were effective in the winter season.

Growth characteristics

In the nondestructive growth measurement, the crown diameters in all treatments gradually increased during the experimental period, but a significant tendency was not found (Fig. 1-5A and B). The SPAD values were not significantly different among the treatments in all measured results, indicating that the root-zone heating system treatments might have little effect on leaf photosynthesis. In the destructive growth measurement, the crown diameter and fresh root weights were significantly higher in the RBH treatment

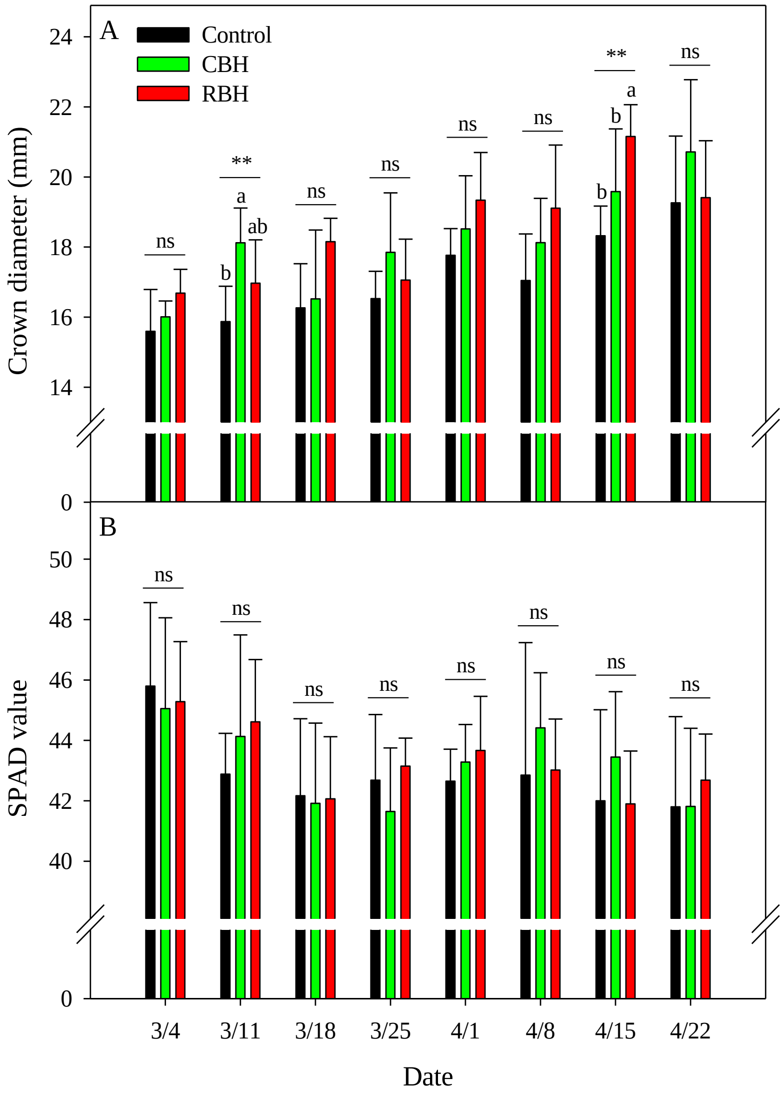

Fig. 1-5. Changes in the crown diameter (A) and SPAD value (B) of strawberry plants during the experimental period. The vertical error bars represent the standard deviations ($n = 6$). Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating. Different letters are considered significantly different according to Duncan's multiple range test at $P < 0.05$. Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

than those in the control (Table 1-2). The representative plants in the RBH treatment tended to have longer root lengths among the treatments (Fig. 1-6). Lee et al. (2021) reported that when strawberry plants were treated with crown-based pipe heating with the heated nutrient solution in the greenhouse, the crown diameter was significantly greater than that of nontreated plants, but there was a difference only in a specific period. In my results, the crown diameter in the CBH treatment tended to be greater than in control, but there was no significant difference, which indicates that the crown diameter might be affected by many factors, not only the crown-based pipe heating.

Even though the dry weight distribution in the crown in all treatments had no significant difference, the RBH treatment had the lowest and the highest dry weight distributions in the leaf (54.0%) and root (30.1%), respectively, among the treatments (Table 1-3). These results indicate that the RBH significantly affected the dry weight distribution of strawberry roots. Janes et al. (1981) reported that when tomatoes were grown under elevated root-zone temperature conditions under low air temperature at night, the growth and yield increased compared to plants grown in a conventionally heated greenhouse. The root-based pipe heating on tomatoes also enhanced the relative shoot growth rate and dry weights (Kawasaki et al., 2014). Therefore, the improvement of root growth in the RBH treatment might result from elevating the root zone temperatures before sunrise by RBH, which might also positively affect strawberry shoot growth, resulting in a thicker crown diameter. These results

Table 1-2. The crown diameter, fresh leaf, crown, and root weights, leaf area, and SPAD value of strawberry plants as affected by the root-zone heating system treatments

Treatment[z]	Crown diameter (mm)	Fresh weight (g/plant)			Leaf area (cm^2)	SPAD value
		Leaf	Crown	Root		
Control	19.9 b[y]	38.2	14.5	22.2 b	1073.7	41.4
CBH	20.6 ab	42.8	15.5	27.2 b	1141.6	41.8
RBH	22.0 a	44.8	16.9	34.4 a	1189.6	41.4
p-value[x]	*	ns	ns	**	ns	ns

[z] Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Fig. 1-6. Photograph of the strawberry plants as affected by the root-zone heating system treatments.

Table 1-3. The dry weight distributions in the leaf, crown and root of strawberry plants as affected by the root-zone heating system treatments

Treatment[z]	Dry weight distribution (% of whole plant dry weight)		
	Leaf	Crown	Root
Control	58.8 a[y]	16.8	24.4 b
CBH	58.0 a	16.4	25.6 b
RBH	54.0 b	15.9	30.1 a
p-value[x]	*	ns	*

[z] Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

indicate that the RBH system could further promote strawberry vegetative shoot and root growth than the CBH system, meaning that the greenhouse heating load could be further lowered through the application of the RBH system.

Flowering and fruit characteristics

The root-zone heating system treatments also affected the reproductive growth of strawberry plants. The days from flower bud emergence to the anthesis of the primary flower in the second flower cluster were significantly shorter in the control and CBH treatments than in the RBH treatment, while there was no significant difference in the first flower cluster (Table 1-4). The treatments did not affect the fruit diameter, length, and weight (Table 1-5). The fruit yield in the middle of the harvest period was significantly higher in the CBH treatment than in the RBH treatment, but there was no difference in the fruit yield in early and late harvest periods.

The CBH system can affect the micro-temperature environment near the crowns more than the RBH system because the heating pipes in the CBH system are in close contact with the strawberry crowns. Thus, the CBH system can affect the growth and development of the crowns. The previous study also suggested that CBH promoted the yield of strawberries in the second and third fruit clusters but not in the first cluster (Lee et al., 2021). Shortening flower development could reduce the time required to harvest fruits, which promotes

Table 1-4. The days from flower bud emergence to the anthesis of the primary flower in the first and second flower clusters of strawberry plants as affected by the root-zone heating system treatments

Treatment[z]	First flower cluster	Second flower cluster
Control	11.5	10.6 b[y]
CBH	11.9	10.8 b
RBH	11.5	11.9 a
p-value[x]	ns	*

[z] Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Table 1-5. The diameter, length, weight, and yield of fruits in the first and second fruit clusters of strawberries as affected by the root-zone heating system treatments

Treatment[z]	Fruit diameter (mm)	Fruit length (mm)	Fruit weight (g)	Yield ($g\ d^{-1}$)		
				Early	Middle	Late
Control	33.4	42.7	18.5	140.7	130.2 ab[y]	148.0
CBH	32.7	42.2	17.6	119.2	143.1 a	176.5
RBH	33.2	42.6	18.4	104.7	90.8 b	164.1
p-value[x]	ns	ns	ns	ns	*	ns

[z] Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

early harvest. In the RBH treatment, the time required for flowering increased even though root growth was improved. It suggests that the growth enhancement of the underground parts does not necessarily promote aboveground growth, especially in reproductive organ development. June-bearing strawberries are known to have dramatic shifts in biomass allocation to flowers when producing fruits and a surge in allocation to leaves, with a concomitant decline in root biomass in April (Fernandez et al., 2001). The RBH system promoted vegetative shoot and root growth in the experiments, but it seems better to apply the CBH systems for reproductive growth promotion. However, further studies are needed to prove the divided effects of the crown- and root-based heating systems on strawberry developments in long-term cultivation.

Free amino acid contents

The aspartic acid content in leaves in the CBH (68.3 mg 100 g^{-1} DW) and RBH (67.2 mg 100 g^{-1} DW) treatments was lower than those in control (91.7 mg 100 g^{-1} DW), and the lowest glycine content in the CBH treatment (1.7 mg 100 g^{-1} DW) was determined among the treatments (Table. 1-6). Glutamic acid and proline contents in all treatments had no significant differences. Accumulated amino acids in plants act as osmolytes, regulate ion transport, modulate stomatal opening, and detoxify heavy metals (Turhan and Eris, 2009), affecting the synthesis and activity of some enzymes (Rai, 2002). Strawberries

Table 1-6. The free amino acid content in strawberry leaves as affected by root-zone heating system treatments

Treatment[z]	Free amino acid content (mg 100 g^{-1} DW)			
	Aspartic acid	Glutamic acid	Glycine	Proline
Control	91.7 a[y]	213.8	2.2 a	3.3
CBH	68.3 b	175.1	1.7 b	3.5
RBH	67.2 b	188.7	2.2 a	3.1
p-value[x]	*	ns	*	ns

[z] Control, no root-zone heating; CBH, crown-based heating; RBH, root-based heating.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

accumulate soluble carbohydrates and free amino acids in the leaf tissues during cold acclimation (O'Neill, 1983). The proline accumulation in plants during cold stress is well established (Chu et al., 1978), but there was no significant difference in the proline content in this experiment. Farhangi-Abriz and Ghasemi-Golezani (2016) reported that aspartic and glutamic acid contents increased with enhanced salinity. Lee et al. (2021) suggested that exogenously applied glutamic acid improves yield through increased photosynthesis efficiency and antioxidant defense systems under chilling stress conditions in tomatoes and improve fruit quality and yield under stressed conditions with deficit fertigation in strawberries (Fard and Hassanpour, 2022). The significantly higher aspartic acid content and slightly higher glutamic acid content, even though there is no significant difference determined in control, might result in the stress response to the low-temperature condition. Glycine betaine, the amino acid betaine derived from glycine, is one of the major organic osmolytes that accumulates in various plant species in response to environmental stresses such as drought, salinity, and extreme temperature (Ashraf and Foolad, 2007). Glycine betaine is involved in inducing cold tolerance during cold acclimation of strawberry plants (Rajashekar et al., 1999), and the foliar application of glycine betaine on strawberry leaves contributes to the tolerance to low temperatures (Aras and Esitken, 2013). The lowest glycine content found in the CBH treatment might be the result of the elevated root zone and crown-ambient temperatures by the CBH system. The changes in free amino acid contents in strawberry leaves indicate that the root-zone heating systems can affect the chemical composition of leaves of strawberries by elevating the root zone temperatures and manipulating root activities.

Thermal and physical characteristics of substrates

The thermal conductivity of soil (0.169 W m^{-1} k^{-1}) was the highest among the substrates, followed by coir (0.156 W m^{-1} k^{-1}), perlite (0.108 W m^{-1} k^{-1}), and rockwool (0.044 W m^{-1} k^{-1}) (Table 1-7). The dry bulk density of perlite (171.4 g L^{-1}) was higher than other substrates, followed by soil (150.0 g L^{-1}) (Table 1-7). The dry bulk density of the coir substrate (67.1 g L^{-1}) was the lowest among the substrates (Table 1-7). However, the coir and rockwool had the greatest maximum water holding capacities, 7.38 and 7.47 g g DW^{-1}, respectively, and perlite's maximum water holding capacity was about one-sixth of that in coir. In the thermal characteristics measurements of coir substrate under a simplified pipe heating system, the temperature of coir substrate with 80% moisture content increased slower than those with 40% moisture content (Fig. 1-7). When the slope was approximated with the linear function, the slope value in the 40% moisture contents was about 1.84 times bigger than that in the 80% moisture contents (Fig. 1-7).

The substrate for the soilless culture has to be selected according to the type of crops and cultivation, so the thermal properties cannot solely determine the type of substrate. However, understanding the thermal and physical properties

Table 1-7. Thermal and physical characteristics of the coir, soil, perlite, and rockwool substrates

Substrate	Thermal conductivity[z] (W m^{-1} k^{-1})		Dry bulk density (g L^{-1})		Maximum water holding capacity (g g DW^{-1})	
Coir	0.156	b[y]	67.1	d	7.38	a
Soil	0.169	a	150.0	b	3.38	b
Perlite	0.108	c	171.4	a	1.23	c
Rockwool	0.044	d	100.0	c	7.47	a
p-value[x]	***		***		***	

[z] The thermal conductivity was measured at 25°C.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

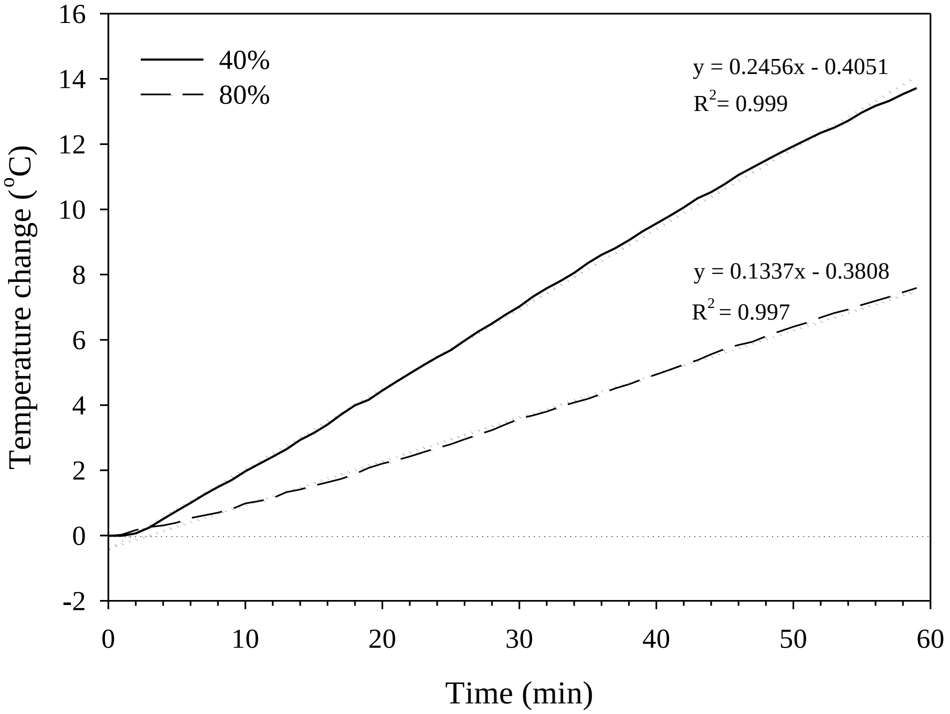

Fig. 1-7. Temperature changes in coir substrate with 40 (solid line) and 80% (dashed line) of moisture contents in the measurements of the thermal characteristics under the simplified pipe heating system. The dotted lines represent the linear regressions.

of the substrate is needed to develop precise root-zone pipe heating systems. In the case of the coir that was used in the experiment, it had relatively lower dry bulk density but higher water holding capacity, which means the thermal characteristics of the coir slab can change according to the moisture contents, as in the results obtained from a simplified pipe heating system. A significant portion of the temperature-changing rate of the coir is thought to be decided by its moisture contents. The highest thermal conductivity of coir among the substrates indicates that the temperature of coir can be manipulated relatively rapidly compared to the other substrates, uniformly minimizing the temperature differences inside the slabs. The thermal characteristics of substrates obtained from the study could help to design the optimal root-zone pipe heating systems for energy-efficient and effective plant organ-temperature control methods to produce horticultural crops in the greenhouse.

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CHAPTER 2

Strawberry crown temperature control to promote floral bud differentiation in a closed transplant production system

ABSTRACT

Year-round strawberry transplant production in a closed transplant production system (CTPS) is needed to meet the recent demand for year-round strawberry production in plant factories. The promotion methods of floral bud differentiation under high air temperature and extended photoperiod conditions should be developed to improve the efficiency of CTPSs. The effects of crown cooling on the floral bud differentiation and the growth of strawberry transplants were investigated in a CTPS. The plants with four unfolded leaves and crown diameters of 8 mm were treated for the crown-cooling temperature treatments with different coolant temperatures (10 (T10), 15 (T15), 20°C (T20), and no cooling (NC)), and the crown-cooling time treatments with different cooling application timings (daytime cooling (DC), nighttime cooling (NC), day- and nighttime cooling (DNC), as well as a no cooling (Control)) for six weeks. In the crown-cooling temperature treatments, floral bud differentiation was promoted in the T10 and T15 treatments more than in the TC treatment after four weeks, but crown cooling repressed floral bud differentiation after six weeks. In the crown-cooling time treatments, the floral bud differentiation was promoted by the NC and DNC treatments after four weeks and by the DNC treatment after six weeks. Significantly retarded growth parameters by the crown cooling were not observed, especially after four weeks. These results indicate that four weeks of crown cooling at nighttime can be applied to promote floral bud differentiation under high air temperature and extended photoperiod conditions, and further studies on how the temperature difference between the ambient and strawberry crown affects floral bud differentiation under high-air temperature conditions.

Key words: crown cooling, crown temperature, floral bud differentiation, June-bearing strawberry

INTRODUCTION

June-bearing cultivars of strawberries (*Fragaria* × *ananassa* Duch.) are seasonal-flowering varieties, and the floral bud differentiation is induced by short day length and low air temperatures (Darrow, 1936; Ito and Saito, 1962; Manakasem and Goodwin, 1998). Early floral bud differentiation in strawberry transplants is essential because it ensures early harvest (Jun et al., 2013). Among the various strawberry propagation methods, plug transplant production using unrooted runner tips has the advantages of a higher propagation rate, uniform transplant quality, and efficient utilization of space and resources (Durner et al., 2002). As year-round and large-scale strawberry transplant production is needed to meet recent demand for year-round strawberry production in plant factories, a closed transplant production system (CTPS), which enables the various environmental controls, can be utilized for transplants production and supply. The air temperature is kept high, and the photoperiod is extended for the vegetative growth promotion in the CTPS, so the methods for the promotion of uniform and accelerated floral bud differentiation without affecting whole system environments during transplant production need to be developed to improve the efficiency of the CTPS.

Even though the plant meristem temperature plays a significant role in plant development, it was hardly ever quantified, and the air temperature was usually used as its approximation (Savvides et al., 2013). Metzger (1988) maintained the separated temperatures for the shoot tip (containing apical meristem and immature leaves) and the rest of the plant of *Thlaspi arvens* L., and reported that the apparent site of perception of thermo-inductive temperatures for the reproductive development was the shoot tip. Most studies about the promotion of floral bud differentiation in strawberry transplants focused on air temperature control, so variation in crown temperature, which is very closely related to the meristem temperatures, and its difference with ambient temperatures was not sufficiently investigated. Previous studies suggested the promotion methods of the floral bud differentiation in strawberry transplants with the manipulation of the various temperature environments, such as decreasing air temperature (Jun et al., 2013; Li et al., 2021), cooling the nutrient solution at nighttime (Mukai and Ogura, 1988), and cooling the root zone with short day conditions (Mizuno et al., 2022). Few studies covered the crown-temperature control methods in strawberries. Hidaka et al. (2017) placed a polyvinyl chloride crown cooling tube beside the crown and controlled the temperature of the water circulating in the tube after transplanting the strawberry transplants in a greenhouse. They cooled strawberry crowns under high air temperature conditions (day/night temperatures of 30/27°C) and showed an acceleration of differentiation and flowering on the first inflorescence as the crown-cooling water temperatures were decreased.

The crown cooling might promote the rate of floral bud differentiation, and the shoot-zone temperature can be maintained in the suitable range even when the crown temperature is kept low. The relationship between crown temperatures, crown cooling times in a day, and the floral bud differentiation should be studied thoroughly. This chapter discussed the effects of crown cooling on the floral bud differentiation and growth of strawberry transplants in a CTPS.

MATERIALS AND METHODS

Plant materials and cultivation conditions

Strawberry plants (*Fragaria* × *ananassa* Duch. cv. Seolhyang) were propagated in the CTPS under cool-white light emitting diodes (LEDs) (TTCC20365E01E9, Namyung Co., Seoul, South Korea) with a photosynthetic photon flux density of 160 μmol m^{-2} s^{-1}, with a photoperiod of 16 h d^{-1}. When runner tips with unfolded bracts were produced, they were fixed on 32-cell plug trays (150 mL $cell^{-1}$) filled with commercial growing media (Baroker; NongwooBio Co. Ltd., Suwon, Korea) for rooting and developing into runner plants. The runner plants were subirrigated for 45 min d^{-1} with the modified Yamazaki's strawberry solution (NO_3-N, 5.0 me L^{-1}; NH_4-N, 0.5 me L^{-1}; PO_4-P, 1.5 me L^{-1}; K, 3.0 me L^{-1}; Ca, 2.0 me L^{-1}; Mg, 1.0 me L^{-1}; S, 1.0 me L^{-1}; Yamazaki, 1984) at electrical conductivity (EC) 1.2 dS m^{-1} and pH 6.0–6.5.

Crown cooling treatments

Crown-cooling temperature treatments

Uniformly rooted runner plants with four unfolded leaves and a crown diameter of 8 mm were treated. The silicone tubes (⌀ 5 mm) were coiled 2.5 rounds around each strawberry crown (Fig. 2-1A and B), and the crown cooling water was cooled down with a water chilling machine (DA-500B; Daeil Co.,

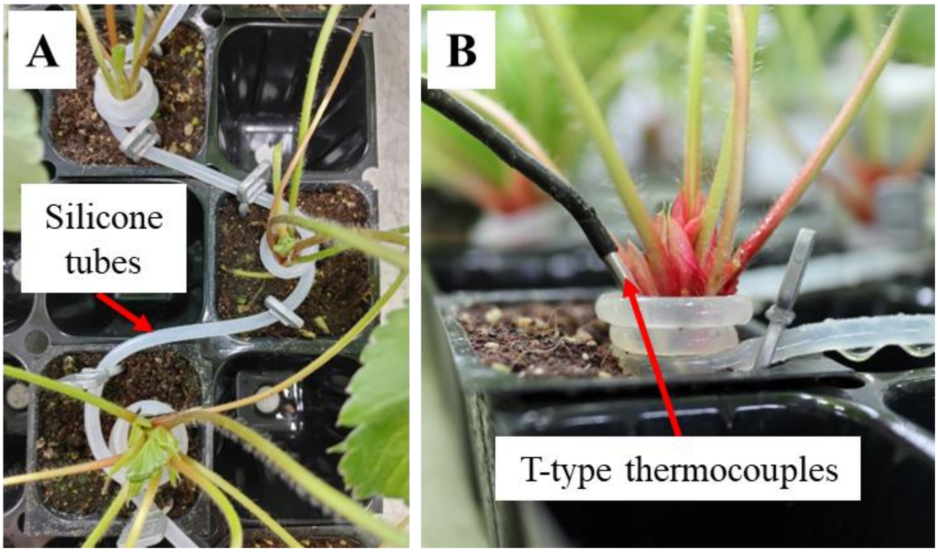

Fig. 2-1. Crown-cooling silicone tubes (A) and T-type thermocouple positions (B) for the crown cooling treatments.

Busan, Korea). The crown-cooling temperature treatments were set with four coolant temperatures (10 (T10), 15 (T15), and 20°C (T20)), as well as a no-cooling (TC). The crown cooling water was circulated in the tubes at predetermined temperatures at nighttime for six weeks. The photoperiod was set at 10 h d^{-1}, and the air temperature and relative humidity in photo-/dark periods were set at 20.5/25.5°C and 65/95%, respectively, during the experimental period (Fig. 2-2).

Crown-cooling time treatments

Crown-cooling time treatments were set and conducted independently of the crown-cooling temperature treatments to investigate the effectiveness of the crown cooling methods under extended photoperiod and higher air temperature conditions, but the plant materials were prepared, and the same methods in the crown-cooling temperature treatments cooled the crown. Four treatments were daytime cooling (DC), nighttime cooling (NC), day- and nighttime cooling (DNC), as well as a no cooling (Control) (Fig. 2-3). The crown cooling water at the temperature of 4°C was circulated in the tubes during the daytime, nighttime, and whole day (day and nighttime) in the DC, NC, and DNC treatments, respectively. The photoperiod was extended to 14 h d^{-1}, as the previous study reported that June-bearing strawberry cultivars require a day length no longer than 14 h for floral initiation (Darrow, 1936), and the air temperature and relative humidity in photo-/dark periods were set

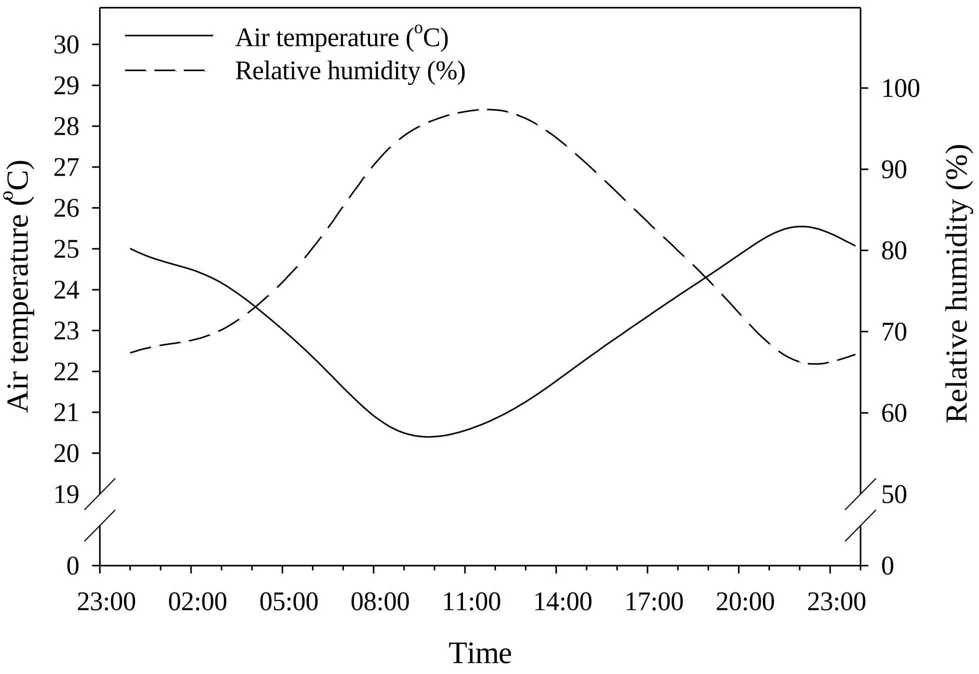

Fig. 2-2. Daily changes in air temperature (solid line) and relative humidity (dashed line) in the closed transplant production system during the crown-cooling temperature treatments.

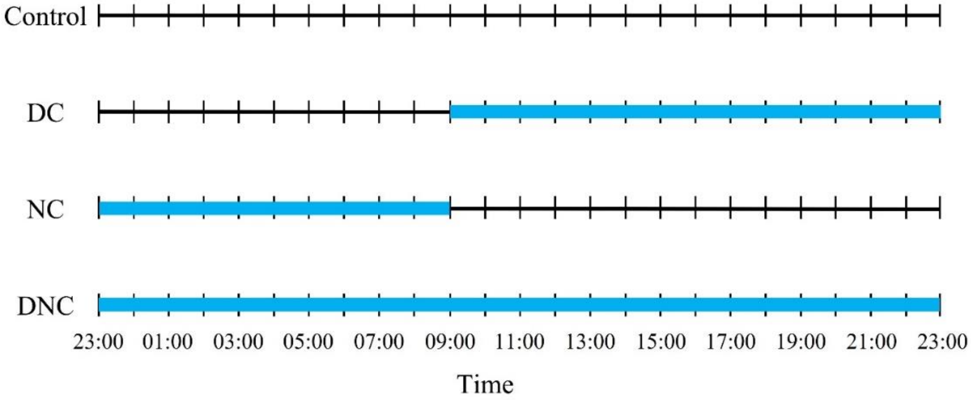

Fig. 2-3. Schedule of the crown-cooling time treatments in a day. Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling. Blue bars represent the cooling application times.

at 21.0/28.0°C and 60/95%, respectively, during the experimental period (Fig. 2-4).

Measurements

Crown temperatures

The crown temperatures were measured with T-type thermocouples and a data logger (UA11-K, Radionode Co., Yongin, South Korea) with Tapaculo Lite software. The thermocouples were set between each crown cooling tube and strawberry crown (Fig. 2-1B). The crown temperature data were collected for 40 days and averaged in each treatment.

Floral development

Six strawberry transplants in each treatment were randomly selected after four and six weeks of treatments. All unfolded leaves were removed from the transplants, and folded leaves enclosing the meristem were removed by a sharp knife. Apical meristems in crowns were observed under a light microscope to examine the floral bud differentiation stages. According to a reference report by Jahn and Dana (1970), floral bud differentiation was classified into 10 stages (1 to 10). These stages were: 1, the vegetative apex stage; 2, the apex enlargement stage; 3, the bract initiation stage; 4, the primary flower primordium initiation stage; 5, the sepal development stage; 6, the petal initiation stage; 7, the sepal and petal development stage; 8, the stamen

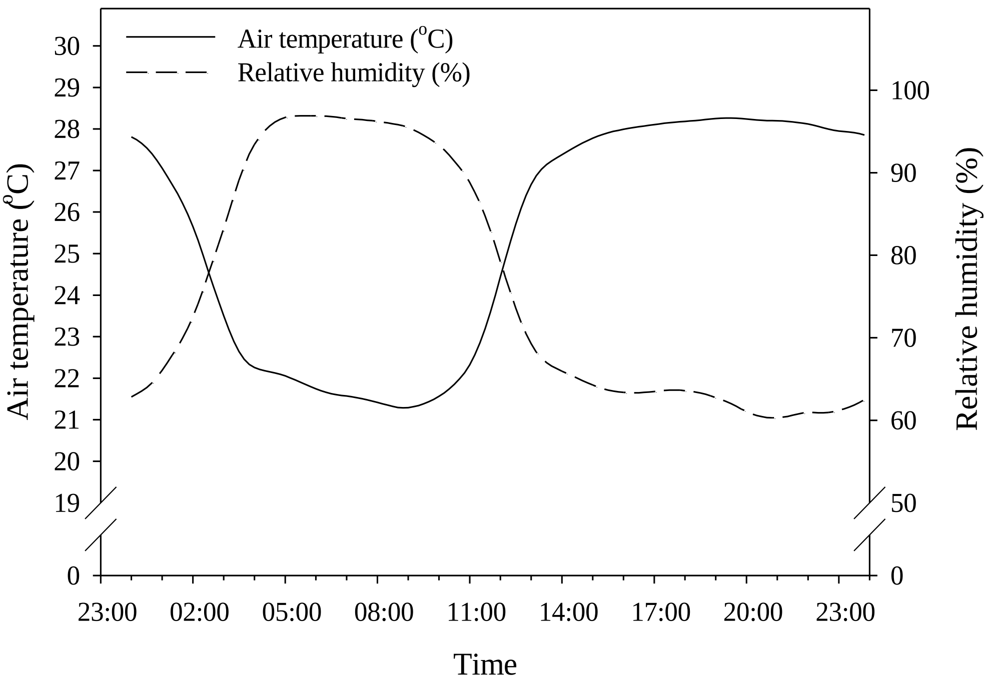

Fig. 2-4. Daily changes in air temperature (solid line) and relative humidity (dots) in the closed transplant production system during the crown-cooling time treatments.

development stage; 9, the epidermal hair development stage; 10, the enclosed primary primordium stage (Fig. 2-5).

Growth characteristics

Crown diameter, fresh and dry weights of leaf, crown, and root, leaf area, and the relative chlorophyll content (SPAD value) were measured on randomly selected six plants per treatment after four and six weeks in both crown cooling treatments. For the crown-cooling time treatments, growth parameters of runner plants, including the number and fresh and dry weights, were additionally measured. The crown diameter was measured just above the root using digital calipers (Mitutoyo Corp., Kawasaki, Japan). The dry weights were measured after drying at 80°C for a week, and the dry weight distributions in the leaf, crown, root, and runner plant were calculated. The total leaf area of each plant was measured with a leaf area meter (Li-3100, LI-COR, Lincoln, NE, USA). The average relative chlorophyll content (SPAD value) of three leaves from the second unfolded leaf was measured by chlorophyll meter (SPAD 502, Konica Minolta, Sakai, Japan).

Environmental conditions

The air temperature and relative humidity were recorded with a thermorecorder (TR-72wb, T&D Co., Nagano, Japan).

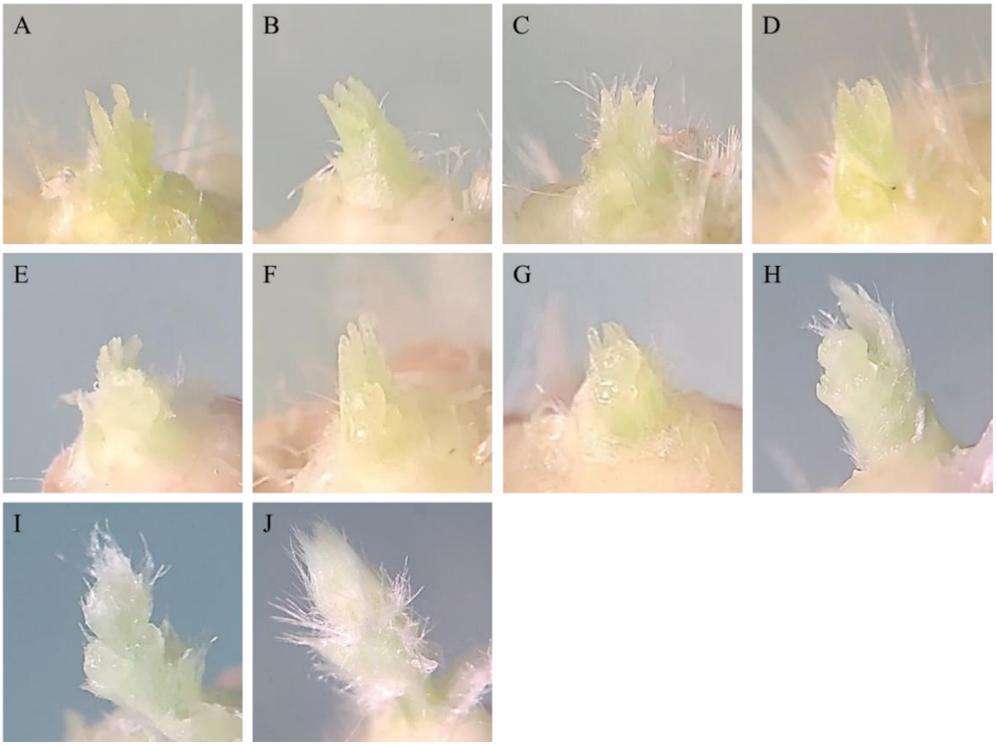

Fig. 2-5. Microphotograph of the flower bud differentiation stages based on the apical meristems in the crowns. From the microscopic examination, floral bud differentiation was classified into 10 stages (1 to 10). 1, the vegetative apex stage (A); 2, the apex enlargement stage (B); 3, the bract initiation stage (C); 4, the primary flower primordium initiation stage (D); 5, the sepal development stage (E); 6, the petal initiation stage (F); 7, the sepal and petal development stage (G); 8, the stamen development stage (H); 9, the epidermal hair development stage (I); 10, the enclosed primary primordium stage (J).

Statistical analysis

Statistical Analysis System (SAS) for Windows version 9.4 (SAS Institute Inc., Cary, NC, USA) was used to determine the differences among means by analysis of variance (ANOVA). If a statistically significant effect was found, a comparison of means was performed using Duncan's multiple range test. The differences among the treatments in all statistical tests were evaluated at $P < 0.05$.

RESULTS AND DISCUSSION

Crown temperatures

Crown temperatures at nighttime under the crown-cooling temperature treatments were the lowest in the T10 treatment (16.4–17.3°C), followed by the T15 (18.2–18.9°C), TC (18.9–20.0°C), and T20 (19.3–20.2°C) treatments (Fig. 2-6). The crown temperatures at nighttime in the T20 treatment were higher than those in the TC treatment because the crowns in the TC treatment were directly exposed to the nighttime air temperatures without silicone pipes, which dropped to a minimum of 20.5°C (Fig. 2-2). The nighttime air temperature was sufficiently low, so crown cooling with the water temperature of 20°C (T20) did not significantly decrease the crown temperature. The crown temperatures at daytime in all treatments range from 20.5 to 22.0°C (Fig. 2-6), which are 3.5–5°C lower than the maximum air temperature in the daytime (25.5°C) (Fig. 2-2).

The crown-cooling time treatments significantly affected the crown temperatures throughout the day. The crown temperature in the Control treatment changed from 20.7°C to 24.2°C in a day (Fig. 2-7), following the air temperature changing regime (Fig. 2-4). In the DC treatment, the crown temperature during daytime was lower than at nighttime, and crown temperature ranged from 18.3 to 22.8°C in a day (Fig. 2-7). In the NC treatment, the crown temperature at nighttime decreased by crown cooling and dropped

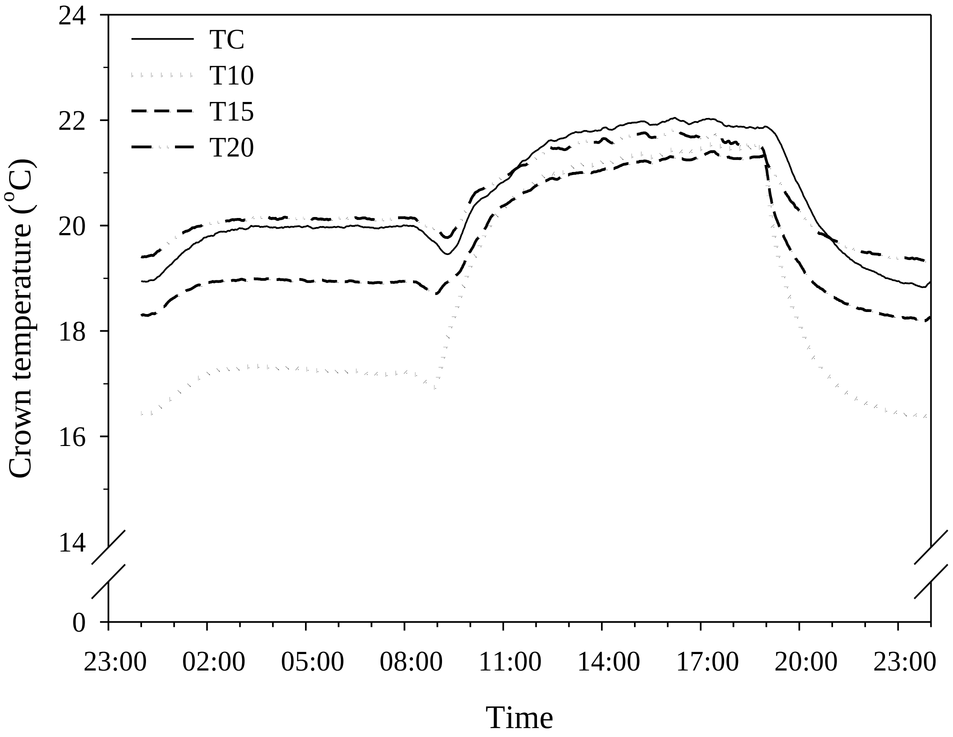

Fig. 2-6. Daily crown temperature changes of the strawberry transplants in the crown-cooling temperature treatments. TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation.

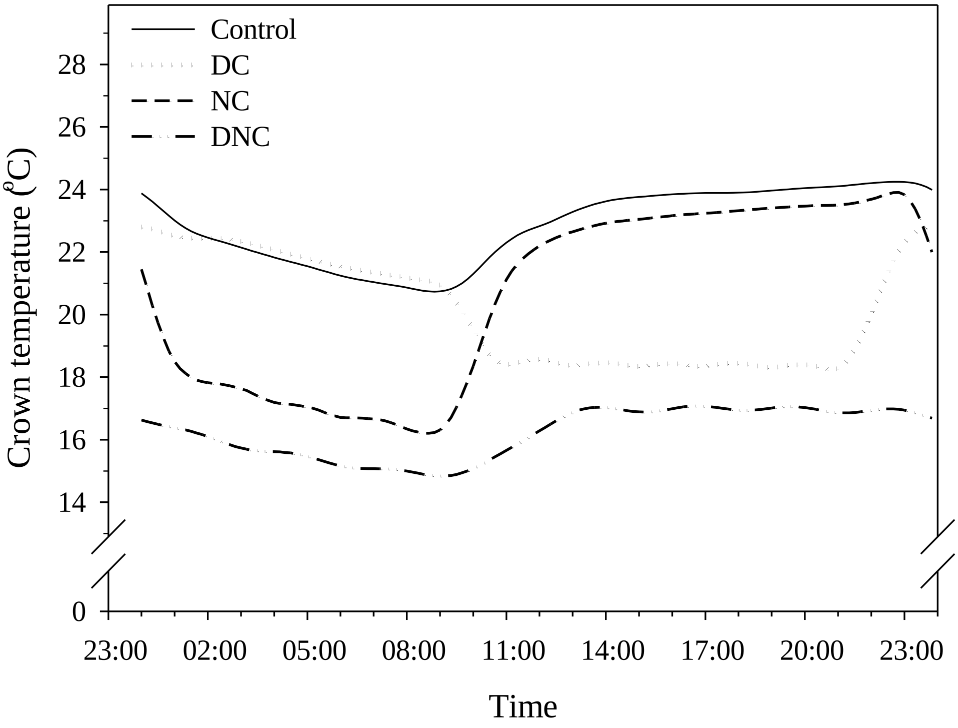

Fig. 2-7. Daily crown temperature changes of the strawberry transplants in the crown-cooling time treatments. Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling.

to the minimum of 16.2°C (Fig. 2-7). The DNC treatment significantly decreased the crown temperature all day between 14.8 and 17.1°C during the day, even though there was a slight increase and decrease in temperature following the air temperature changing regime (Fig. 2-7).

The plant organ temperatures, including strawberry crown temperatures, are affected by air temperature and other environmental variables like radiation, wind speed, and vapor pressure deficit (VPD) (Novel, 2009). Savvides et al. (2013) suggested that the enclosure of the meristem within the bud consists of the microenvironment around the meristem, and therefore the meristem temperatures are strongly related to the bud structure and function. Strawberry crown has complex structures such as folded developing leaves and epidermal hairs, which can affect the heat exchange between the crown and ambient environments.

In the crown-cooling temperature treatments, the temperatures of the crown exposed to air (TC treatment) and the crown in contact with the cooling pipe (T20 treatment) were different at nighttime, although the temperatures of the air and the cooling pipe were similar. The previous study can interpret this result which reported that the apical meristem temperatures of tomato and cucumber plants at nighttime were lower than the air temperature (Savvides et al., 2013). The crown temperature in the TC treatment was also lower than the nighttime air temperature, but that in the T20 treatment might be affected by the cooling tube with the 20°C water circulation.

In the crown-cooling time treatments, even though the water temperatures in all treatments were the same, cooling application timings in a day affected how much the crown temperature decreased during the cooling period of each treatment. These results indicate that when the crown cooling methods are developed, precise coolant temperature control reflecting the application timing is needed to maintain the desired crown temperatures.

Floral development

In the crown-cooling temperature treatments, floral bud differentiation was promoted in the T10 and T15 treatments than in the TC treatment after four weeks, showing the floral bud differentiation stages of 6.2, 5.8, and 3.0 in the T10, T15, and TC treatments, respectively (Fig. 2-8A). However, the floral bud differentiation stages were lower in the T10, T15, and T20 treatments than in the TC treatment after six weeks, with the TC treatment having 9.3 of the floral bud differentiation stage (Fig. 2-8B).

In the crown-cooling time treatments, the floral bud differentiation stages after four weeks in the NC and DNC treatments, 4.5 and 4.2, respectively, were higher than those in the DC and Control treatments, 2.4 and 2.8, respectively (Fig. 2-9A). The stage after six weeks in the DNC treatment was 9.2, the highest among the treatments, followed by that in the NC treatment after six weeks (Fig. 2-9B).

The results of floral bud differentiation stages in the crown-cooling

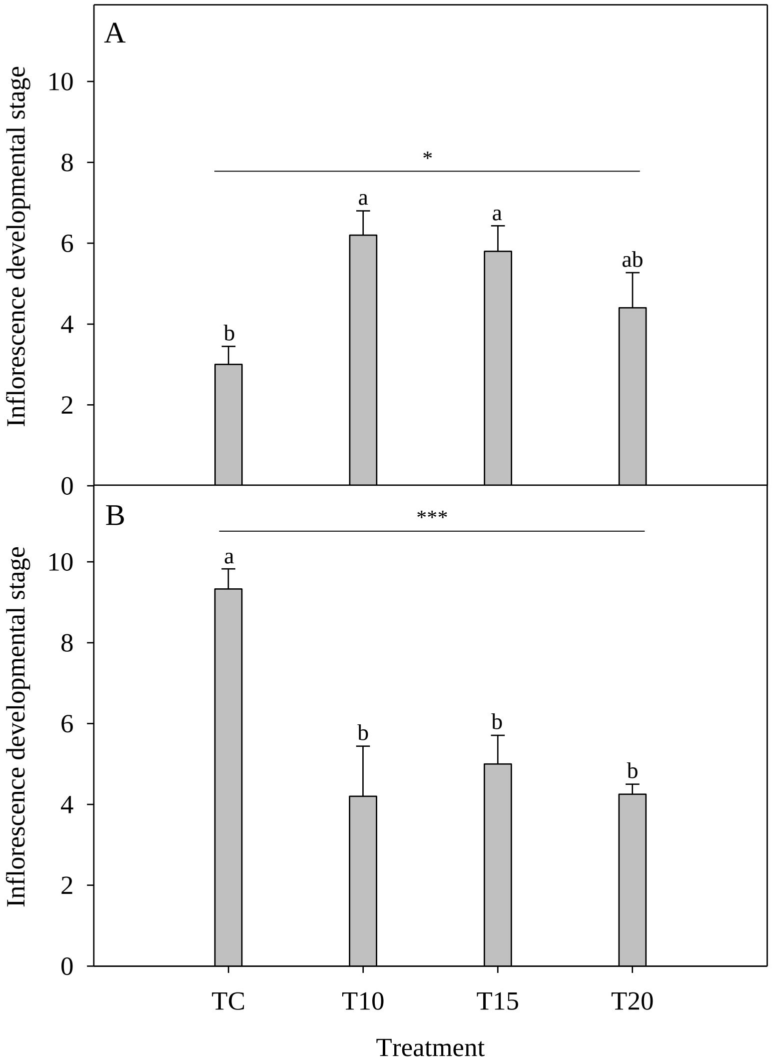

Fig. 2-8. Floral bud differentiation stages of the strawberry transplants after four (A) and six weeks (B) of the crown-cooling temperature treatments. TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation. Different letters are considered significantly different according to Duncan's multiple range test at $P < 0.05$. Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant. The vertical error bars represent the standard error of the means (n = 6).

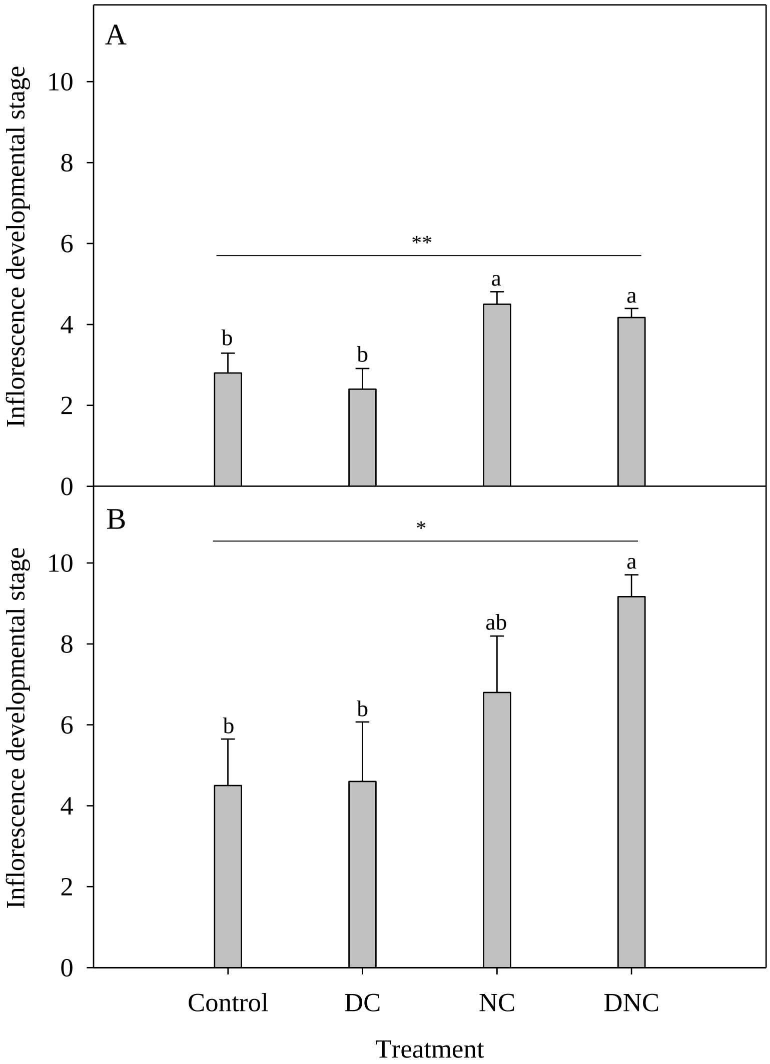

Fig. 2-9. Floral bud differentiation stages of the strawberry transplants after four (A) and six weeks (B) of the crown-cooling time treatments. Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling. Different letters are considered significantly different according to Duncan's multiple range test at $P < 0.05$. Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant. The vertical error bars represent the standard error of the means (n = 6).

temperature treatments indicated four weeks of crown cooling at nighttime with 10 and 15°C of water temperatures, maintaining crown temperatures lower than 19°C (Fig. 2-6), which can promote floral bud differentiation in strawberry transplants. However, the floral bud differentiation was inhibited after six weeks in all crown cooling treatments compared to the TC treatment. According to Fujime and Yamazaki (1988), dormancy, which causes dwarfing and suspension of growth, was induced in ‘Hoko-wase’ strawberries grown under a low air temperature of 15°C. Also, the ‘Seolhyang’ cultivar is known to have small to medium chilling requirements for floral initiation (An et al., 2018; Kim et al., 2006; Lee et al., 2014). In the T10 and T15 treatments, six weeks of continuous crown cooling may have induced dormancy beyond the floral initiation. The results indicated that the floral buds could be sufficiently initiated within the four weeks of crown cooling, and continuous cooling after four weeks could negatively affect the development of the floral bud.

The results of the floral bud differentiation stage in the crown-cooling time treatments indicated that the cooling application time in a day, including the nighttime, is needed to promote the floral bud differentiation. The NC and DNC treatments promoted floral bud differentiation, but the DC treatment, which is the only treatment that had a lower daytime crown temperature than nighttime crown temperature, did not promote floral bud differentiation (Fig. 2-9). It was proved that the inversed crown temperature conditions from the natural environment, which means the lower daytime crown temperature than that in the nighttime, do not have the promotion effects on the floral bud differentiation. These results might also be because the average crown temperature during the cooling application time in the DC treatment was higher than in the NC and DNC treatments. However, the promotion of floral bud differentiation in the four weeks of the NC and DNC treatments in the crown-cooling time treatments, under more extended photoperiod and higher air temperature conditions than those in the crown-cooling temperature treatments, proved the effectiveness of the crown cooling methods in the crown-cooling time treatments. In conclusion, four weeks of crown cooling at nighttime or all-day could promote floral bud differentiation in strawberry transplants under high air temperature (28°C during daytime) and extended photoperiod (14 h day^{-1}) conditions. Still, more research is required on how the temperature difference between the ambient and strawberry crown affects floral bud differentiation under high-air temperature conditions to develop practical techniques.

Growth characteristics

After four weeks of the crown-cooling temperature treatments, the fresh root weight was the greatest in the T10 and T15 treatments, followed by the T20 and TC treatments (Table 2-1). The dry weight distributions in the leaf, crown, and root had no significant difference (Table 2-2). After six weeks, the fresh leaf weight was the greatest in the T20 treatment, and the fresh root

Table 2-1. The crown diameter, fresh leaf, crown, and root weights, leaf area, and SPAD value of strawberry plants as affected by four weeks of the crown-cooling temperature treatments

Treatment[z]	Crown diameter (mm)	Fresh weight (g/plant)			Leaf area (cm^2)	SPAD value
		Leaf	Crown	Root		
TC	19.6	11.4	1.5	1.7 c[y]	462.9	36.8
T10	10.8	13.7	2.2	3.3 a	527.2	35.1
T15	11.0	10.7	1.9	2.7 ab	397.7	34.5
T20	10.8	12.5	1.6	2.3 bc	408.3	36.5
p-value[x]	ns	ns	ns	**	ns	ns

[z] TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Table 2-2. The dry weight distributions in the leaf, crown, and root of strawberry plants as affected by four weeks of the crown-cooling temperature treatments

Treatment[z]	Dry weight distribution (% of whole plant dry weight)		
	Leaf	Crown	Root
TC	77.9	8.9	13.2
T10	77.8	9.7	12.4
T15	74.0	10.4	15.6
T20	77.8	8.0	14.3
p-value[y]	ns	ns	ns

[z] TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation.

[y] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

weight was the greatest in the T10 and T20 treatments, followed by the T15 and TC treatments (Table 2-3). The T20 treatment also had greater leaf area than the other treatments. In the dry weight distributions, the TC and T20 treatments had higher dry weight distributions in leaves but had lower distributions in crowns and roots than the T10 and T15 treatments (Table 2-4). Compared to the representative plant in the T20 treatment after four weeks, the plant after six weeks had significant shoot growth (Fig. 2-10).

After four weeks of the crown-cooling time treatments, the number of runner plants was greater in the Control and DC treatments, and fresh root weights were heavier in the NC and DNC treatments (Table 2-5). In the dry weight distributions, there were similar results of greater distributions in roots in the DNC and NC treatments and the greatest distribution in runner plants in the Control treatment (Table 2-6). After six weeks, the number of runner plants and the fresh weight of runner plants were greater in the Control and DC treatments than in the NC and DNC treatments (Table 2-7). The fresh root weight was the greatest in the NC treatment, and the leaf area was the greatest in the DNC treatment. The NC and DNC treatments had greater dry weight distributions in leaves and crowns than in the Control and DC treatments, and the DNC treatment had the greatest dry weight distribution in roots. (Table 2-8). The Control and DC treatments had greater distributions in runner plants than in the NC and DNC treatments. In the DNC treatment, severe leaf discoloration was observed in the transplants after six weeks (Fig. 2-11), which

Table 2-3. The crown diameter, fresh leaf, crown, and root weights, leaf area, and SPAD value of strawberry plants as affected by six weeks of the crown-cooling temperature treatments

Treatment[z]	Crown diameter (mm)	Fresh weight (g/plant)			Leaf area (cm^2)	SPAD value
		Leaf	Crown	Root		
TC	11.8	15.4 b[y]	2.1	2.3 c	621.2 ab	37.7
T10	12.2	11.9 b	2.7	4.2 a	501.1 bc	38.2
T15	12.1	13.7 b	2.6	3.2 b	475.3 c	37.7
T20	12.4	22.2 a	2.6	4.1 a	694.7 a	37.3
p-value[x]	ns	**	ns	***	**	ns

[z] TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Table 2-4. The dry weight distributions in the leaf, crown, and root of strawberry plants as affected by six weeks of the crown-cooling temperature treatments

Treatment[z]	Dry weight distribution (% of whole plant dry weight)		
	Leaf	Crown	Root
TC	79.1 a[y]	8.4 b	12.5 bc
T10	71.4 b	11.8 a	16.8 a
T15	73.9 b	11.5 a	14.5 ab
T20	80.4 a	8.1 b	11.5 c
p-value[x]	***	***	**

[z] TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Fig. 2-10. Photographs of the strawberry transplants as affected by four (A) and six weeks (B) of the crown-cooling temperature treatments. TC, no crown cooling; T10, T15, and T20, crown cooling with 10°C, 15°C, and 20°C of water circulation.

Table 2-5. The crown diameter, number of runner plants, fresh leaf, crown, root and runner plant weights, leaf area, and SPAD value of strawberry plants as affected by four weeks of the crown-cooling time treatments

Treatment[z]	Crown diameter (mm)	No. of runner plants	Fresh weight (g/plant)				Leaf area (cm^2)	SPAD value
			Leaf	Crown	Root	Runner plant		
Control	10.8	2.5 a[y]	10.2	1.7	1.4 b	4.5	400.0	39.6
DC	9.6	2.5 a	9.4	1.5	1.4 b	2.9	373.6	39.5
NC	10.5	1.5 ab	10.8	1.8	2.1 a	1.6	422.7	37.5
DNC	10.7	0.7 b	10.5	1.5	2.2 a	0.9	420.2	40.8
p-value[x]	ns	*	ns	ns	**	ns	ns	ns

[z] Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Table 2-6. The dry weight distributions in the leaf, crown, root, and runner of strawberry plants as affected by four weeks of the crown-cooling time treatments

Treatment[z]	Dry weight distribution (% of whole plant dry weight)			
	Leaf	Crown	Root	Runner
Control	65.5	7.9	7.6 c[y]	19.1 a
DC	69.9	7.6	9.5 bc	13.1 ab
NC	72.2	9.0	12.6 ab	6.2 b
DNC	75.0	6.3	15.2 a	3.5 b
p-value[x]	ns	ns	**	*

[z] Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Table 2-7. The crown diameter, number of runner plants, fresh leaf, crown, root and runner plant weights, leaf area, and SPAD value of strawberry plants as affected by six weeks of the crown-cooling time treatments

Treatment[z]	Crown diameter (mm)	No. of runner plants	Fresh weight (g/plant)				Leaf area (cm^2)	SPAD value
			Leaf	Crown	Root	Runner plant		
Control	9.7	3.3 a[y]	11.5	1.5	2.6 ab	10.3 a	481.4 ab	38.5
DC	10.2	2.5 ab	8.9	1.6	2.1 b	7.6 a	353.8 bc	37.6
NC	10.7	0.2 c	8.8	1.9	3.8 a	2.7 b	316.6 c	36.8
DNC	11.1	1.7 b	12.9	2.4	2.3 b	0.1 b	495.4 a	39.3
p-value[x]	ns	***	ns	ns	*	***	*	ns

[z] Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

Table 2-8. The dry weight distributions in the leaf, crown, root, and runner of strawberry plants as affected by six weeks of the crown-cooling time treatments

Treatment[z]	Dry weight distribution (% of whole plant dry weight)			
	Leaf	Crown	Root	Runner
Control	49.8 b[y]	5.8 c	8.7 b	35.8 a
DC	52.3 b	6.4 c	10.8 b	30.5 a
NC	67.6 a	9.2 b	9.5 b	13.7 b
DNC	71.1 a	11.4 a	16.8 a	0.8 c
p-value[x]	***	***	**	***

[z] Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling.

[y] Means within columns followed by different letters are significantly different by Duncan's multiple range test at $P < 0.05$.

[x] Subscripts indicate: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – not significant.

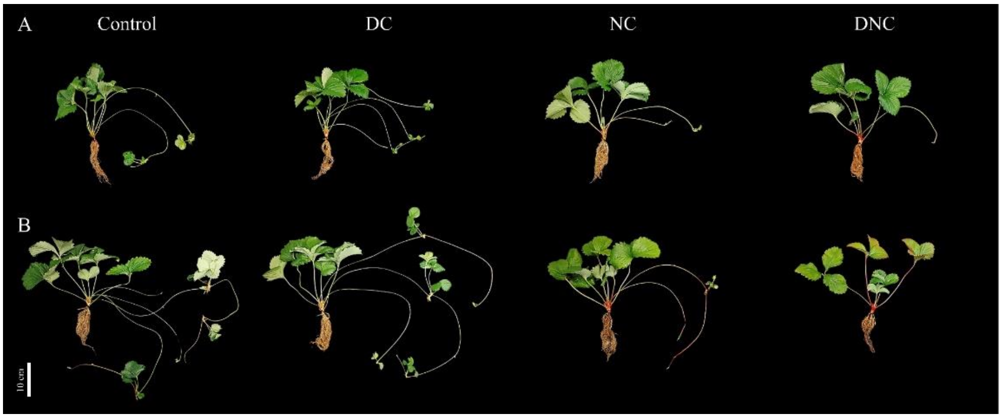

Fig. 2-11. Photographs of the strawberry transplants as affected by four (A) and six weeks (B) of the crown-cooling time treatments. Control, no crown cooling; DC, daytime cooling; NC, nighttime cooling; DNC, day- and nighttime cooling.

might result from stressed conditions by continuous crown cooling in a day.

Even though the starting number of leaves and crown diameter were the same in each plant, the increasing pattern in crown diameter in strawberry plants was different according to the treatments. According to Jahn and Dana (1970), there is an increase in crown diameter as more leaves are produced because the base of each leaf contributes to the diameter of the crown early in the development of strawberry transplants. Arney (1953) noted that the initiation of an inflorescence delayed the appearance of the next leaf primordium which is in an axillary position. However, the correlation between the number of leaves and crown diameters was unclear in this experiment. Instead, the tendency of improved root growth was found in the plants in the crown cooling treatments than in control, and the significantly retarded shoot growth parameters by the crown cooling were not observed, especially after four weeks of the treatments, which indicated the crown cooling with the silicone pipe did not have significant physical stresses.

In the life cycle of a strawberry plant, two different developmental stages: the vegetative and reproductive stages, typically respond in opposite manners to many environmental factors, including day length and temperature (Battey et al., 1998; Konsin et al., 2001). The significantly deceased runner plant development in the NC and DNC treatments in the crown-cooling time treatments (Table 2-7 and 2-8) indicates the developmental stage transition of strawberry transplants because the runner production belongs to the vegetative stages (Serce and Hancock, 2005). In conclusion, crown cooling affected the growth of transplants, but significantly retarded growth parameters were not observed, especially after four weeks. Therefore, four weeks of crown cooling can be applied in a closed transplant production system during the strawberry transplant production.

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CONCLUSIONS

This study attempted to gain insights into the temperature control methods such as the plant organ-temperature control, including root zone and crown temperature controls on strawberry plants in a greenhouse and a closed transplant production system.

In chapter one, the root-based heating methods could provide the most stable root-zone temperature environments among the root-zone pipe heating systems, resulting in the longest daily retention time for the optimum root-zone temperature in February and March. The root-based heating can also improve root growth represented by fresh root weights and higher dry weight distributions in roots. The anthesis in the second flower clusters could be retarded by the root-based heating method, and the fruit yield in the middle harvest period might increase by the crown-based heating method. The vegetative shoot and root growth promotions on strawberries do not directly enhance the total yield, which indicates that the root-based and crown-based pipe heating systems for root-zone temperature control can be utilized according to the desirable developmental phases of strawberries during the cultivation, thoroughly considering the heat source and thermal characteristics of substrates in the system for the energy-efficiency.

In chapter two, floral bud differentiation can be further promoted as the crown-cooling temperature decreases, and the crown cooling time must include the nighttime to promote floral bud differentiation under high air temperatures and extended photoperiod conditions. The effective crown temperature range on the floral bud initiation is thought to be from 14.8 to 18.9°C, according to this study. But the continuous crown cooling for more than four weeks can repress the floral bud differentiation. Significantly retarded growth parameters by crown cooling were not observed, especially after four weeks, and even crown cooling is thought to improve root growth of the transplants. Further studies on how the temperature difference between the ambient and strawberry crown affects floral bud differentiation under high-air temperature conditions to keep the air temperature high in the transplant production system to maintain the vegetative growth of the transplants.

The results obtained in this study can improve energy efficiency and productivity in strawberry cultivation and simplify plant organ-temperature control systems that need to be developed for practical application.

ABSTRACT IN KOREAN

식물의 생장점은 주변 온도에 민감하며, 지상부와 지하부의 생장점이 주위 온도를 감지하는 것으로 알려져 있다. 본 연구는 온도에 민감한 식물 기관을 중심으로, 온실과 폐쇄형 육묘 시스템에서 재배되는 딸기의 근권 및 관부를 대상으로 하는 식물체 기관 온도 조절 방법을 연구하였다. 온실에서의 일계성 딸기 촉성 재배는 세계적으로 널리 적용되고 있다. 촉성 재배에서 딸기는 겨울 동안 저온에 노출될 위험이 있으나, 온실 전체 공간을 대상으로 하는 기존의 난방 방법은 난방 부하가 과도한 경우가 있다. 한편, 일계성 딸기의 육묘에서 저온에 의해 유도되는 균일하고 빠른 화아 분화는 정식 후 조기 수확을 가능하게 한다. 최근 식물공장에서의 딸기 주년 생산을 뒷받침하기 위해 폐쇄형 육묘 시스템에서의 안정적인 주년 육묘가 필요하다. 고온 장일 조건으로 영양생장을 촉진하는 폐쇄형 육묘 시스템에서 전체 환경을 바꾸지 않고 딸기 묘의 화아 분화를 촉진하는 기술이 개발될 필요가 있다.

1장에서는 딸기의 온실 겨울 재배에서 근권부 파이프 난방 시스템을 시험하기 위해 두 종류의 근권부 난방 시스템인 관부 기반 난방과 뿌리 기반 난방을 실시하였다. 뿌리 기반 난방이 관부 기반 난방보다 안정적인 근권 온도 환경을 조성하였고 영양생장을 촉진하였으며 관부 기반 난방은 딸기 생산량을 증진하였다. 두 종류의 근권부 파이프 난방 시스템은 딸기 재배에서 원하는 발달 단계에 따라 활용될 수 있음을 시사한다.

2장에서는 폐쇄형 육묘 시스템에서 딸기 묘의 화아 분화와 생육에 미치는 관부 냉각의 효과를 조사하였다. 딸기 묘에 6주 간 네 개의 냉각수 온도(10, 15, 20°C 및 대조구)로 이루어진 관부 냉각 온도 처리구와, 네 개의 일중 냉각 시간(주간, 야간, 종일 및 대조구)으로 이루어진 관부 냉각 시간 처리를 실시하였다. 관부 냉각 온도

처리구에서는 처리 4주 후에 10도 및 15도 처리에서 대조구보다 화아 분화가 촉진되었다. 관부 냉각 시간 처리구에서는 처리 4주 후 야간 및 종일 처리에서, 처리 6주 후 종일 처리에서 화아 분화가 촉진되었다. 이러한 결과는 고온 장일 조건에서 딸기 묘의 화아 분화 촉진을 위해 4주 간의 관부 냉각이 적용될 수 있음을 시사한다. 본 연구 결과가 딸기 재배에서 온도 조절의 에너지 효율 및 생산성 향상에 기여할 것으로 기대한다. 식물체 주변 국부 난방 시스템의 열적 특성과, 딸기 기관과 주변 기온의 미세한 차이와 생리적 반응의 관계에 대한 추가적 연구가 요구된다.

주요어: 관부 냉각, 관부 온도, 근권부 난방, 식물 기관 온도, 일계성 딸기, 화아 분화

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