

Development of Environmental Control System for High-Quality Shiitake Mushroom (*Lentinus edodes* (Berk.) Sing.) Production

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Received: November 7th, 2018; Revised: November 19th, 2018; Accepted: November 20th, 2018

Abstract

Purpose: Recently, an increasing number of farms have been cultivating shiitake mushrooms using a sawdust substrate and a cooler/heater. In this study, an attempt was made to develop an environmental control system using a heat pump for cultivating high-quality shiitake mushrooms. **Methods:** An environmental control system, consisting of an air-to-water type heat pump, a thermal storage tank, and a radiator in a variable opening chamber, was designed and fabricated. The system was also installed in the cultivation facility of a farm cultivating shiitake mushrooms so as to compare the proposed control system with a conventional environmental control system using a cooler-condensing unit and an electric hot water boiler. **Results:** The uniformity of the environment was analyzed through environment measurements taken at several positions inside the cultivation facility. It was determined that the developed environmental control system is able to control the variations in temperature and relative humidity to within 1% and 3%, respectively. In addition, a maximum temperature difference of 30°C (maximum of 35°C, minimum of 5°C) and a maximum relative humidity difference of 30% (maximum of 90%, minimum of 60%) can be attained within 30 min inside the cultivation facility through the cooling of the heat pump and heating of the radiator in a variable opening chamber. Thus, the developed control system can be used to cultivate high-quality shiitake mushrooms more effectively than a conventional cooler and heater. **Conclusions:** In comparison with a conventional environmental control system, the developed system decreased the yield of ordinary mushrooms by 65%, and increased that of high-quality mushrooms by 217%. This corresponds to a 16% increase in gross farm income. Consequently, the developed system is expected to improve the income of shiitake mushroom cultivating farms.

Keywords: Environmental control, Heat pump, Heating and cooling, Shiitake mushroom, Yield

Introduction

The cultivation and import of shiitake mushrooms (*Lentinus edodes* (Berk.) Sing.) have recently increased owing to their value as pharmacological and food sources. In the Republic of Korea, the types of cultivation used for growing shiitake mushrooms have developed from log cultivation to sawdust substrate cultivation, from field

cultivation to facility cultivation, and from wild cultivation to annual occurrence cultivation. The facility-based sawdust substrate cultivation of shiitake mushrooms has many advantages, such as a high cultivation density, decreased labor, and a shortening of the cultivating period. Accordingly, an increasing number of farms are cultivating shiitake mushrooms throughout the year using environmental control facilities with heaters, coolers, ventilators, and humidifiers.

Because the growth and quality of shiitake mushrooms are significantly affected by the environment, many

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studies have attempted to identify adequate cultivation conditions (Park et al., 2001; Seo and Koo, 2009; Jhune et al., 2014). For facilities cultivating shiitake mushrooms in the Republic of Korea, the structure, temperature, and relative humidity of the facility, the environmental control systems used, and mushroom quality according to the environment were analyzed (Lee et al., 1998). To develop a facility for sawdust substrate cultivation of shiitake mushrooms that is suitable for the weather conditions in the Republic of Korea, five model facilities were proposed by analyzing the existing cultivation facilities there and in Japan and Taiwan (Son et al., 2000). In addition, the relationships among the shading level, ventilation rate, and environment in the facilities were analyzed for the development of a shiitake mushroom facility with improved ventilation (Son, 2000). The adequate temperature, relative humidity, and light conditions for the cultivation of ordinary shiitake mushrooms have been identified in previous studies. However, the cultivation conditions of *hwago* and *donggo*, which have been evaluated as high-quality shiitake mushrooms, are slightly different from those of ordinary shiitake mushrooms. Son and Choi (2005) analyzed the impact of environmental conditions on the growth and quality of log-cultured shiitake mushrooms under protected cultivation, and proposed an adequate night air temperature, relative daytime humidity, and wind velocity to improve the harvesting of *hwago* and *donggo*.

Precise environmental control for heating, cooling, and humidity control is required to produce high-quality shiitake mushrooms. As an air conditioning unit capable of heating, cooling, and dehumidification, a heat pump is suitable for the cultivation of high-quality shiitake mushrooms. Some studies have assessed the agricultural application of heat pumps to horticultural facilities (Gracia et al., 1988; Willits and Gurjer, 2004). In the Republic of Korea, the application of a vertical closed-loop ground source heat pump for a horticultural greenhouse was examined (Kang et al., 2007), and the development of a high-performance air source heat pump selectively using surplus solar heat inside the greenhouse and air heat outside the greenhouse was also conducted (Kwon et al., 2013). In Japan, a hybrid heat pump system in combination with an air source heat pump and a hot air heater using heavy fuel was developed to reduce the installation costs and prevent degradation in the performance owing to a low air temperature (Kawashima et al.,

2008; Tong et al., 2011). The Ministry of Agricultural Food and Rural Affairs in the Republic of Korea supports the installation costs for heat pumps used in agricultural facilities through its "Agricultural energy use efficiency project." However, unlike ground source heat pumps, the support items of air source heat pumps enabling hybrid environmental control do not include mushroom cultivation facilities (MAFRA, 2017).

In this study, an environmental control system composed of an air source heat pump, thermal storage tank, and radiator in a variable opening chamber was developed, which precisely controls the environmental conditions such as the temperature and relative humidity, enabling the cultivation of high-quality shiitake mushrooms. The developed environmental control system was installed in a greenhouse-type cultivation facility of a shiitake mushroom farm. The indoor environmental factors, such as the temperature, relative humidity, and yield of high-quality mushrooms, were compared between the facility where the developed system was installed and a control cultivation facility with an ordinary cooler with a cooler-condensing unit.

Materials and Methods

Environmental control system design

Because cooling is more important than heating for the annual environmental control of each shiitake mushroom cultivation facility, the capacity of the heat pump was set based on the maximum cooling load of the cultivation facility. Daegu, which is located at a similar latitude to that of Jinan, Jeollabuk-do, where the environmental control system will be installed, was selected from seven cities for which typical meteorological data have been provided. The data on Daegu were used to determine the cooling loads, and the maximum cooling load was calculated using Equation (1). Because a cooling load is greatly affected by solar radiation rather than the outside air temperature, the horizontal solar radiation of 1% TAC was first determined from the typical meteorological data from Daegu. The corresponding outside temperature was then used, and the inside temperature was set to 5°C in consideration of the dehumidification required for high-quality shiitake mushrooms. The width and heights of the eaves and the ridges of the greenhouse to be designed were 8, 2.0, and 5.0 m, respectively. The solar radiation transmittance was set to 0.3 by considering the

installation of a shading screen. The overall heat transfer coefficient of the covering material was $3.6 \text{ W/m}^2\cdot^\circ\text{C}$ for double-layer polyethylene film. In addition, the ventilation heat-transfer coefficient was set to 0.35 W/m^2 for a vinyl house.

$$H_T = [A_s(r_Q Q_w + r_q q_w)] + [A_w U(T_o - T_i)] + [A_w h_{ven}(T_o - T_i)] + A_s h_s \quad (1)$$

where r_Q is direct solar radiation transmittance, Q_w is direct solar radiation (kcal/hr), r_q is diffuse solar radiation transmittance, q_w is diffuse solar radiation (kcal/hr), A_w is the covering material area (m^2), U is the overall heat transfer coefficient of the covering material ($\text{kcal/m}^2\cdot\text{h}\cdot^\circ\text{C}$), T_o is the outside air temperature for the design ($^\circ\text{C}$), T_i is the inside air temperature ($^\circ\text{C}$), h_{ven} is the ventilation heat transfer coefficient ($\text{kcal/m}^2\cdot\text{h}\cdot^\circ\text{C}$), A_s is the facility soil area (m^2), and h_s is the soil heat flux ($\text{kcal/m}^2\cdot\text{h}$).

The maximum cooling load for the target greenhouse, the area of which was 165 m^2 , was calculated to be 72.1 kW . It turned out that two heat pumps with a capacity of 35 W each needed to be installed. Figure 1 shows a schematic diagram of the environmental control system

used for the shiitake mushroom cultivation facility. Along with the heat pumps, a humidifier and a dehumidifier for adjusting the humidity, a ventilation fan for controlling the CO_2 concentration, and a fan coil unit, which was connected to a thermal storage tank for heating during winter, were installed inside the facility. The heat pumps were air-to-water type devices, installed inside the facility and connected to the thermal storage tank. The heat pumps were operated using a heating cycle during both the summer and winter. The cultivation facility was cooled when the heat pumps applied air as a heat source to produce hot water inside the thermal storage tank. The thermal storage tank was connected to a radiator in a variable opening chamber, which was installed adjacent to the cultivation facility. Two sides of the chamber had doors leading to the outside and into the cultivation facility, respectively. Hot water in the thermal storage tank, which was produced through the use of the heat pumps, was cooled by the outside air during the summer, as shown in Figure 2(a), or used to increase the temperature drastically and decrease the relative humidity of the cultivation facility in the production of high-quality

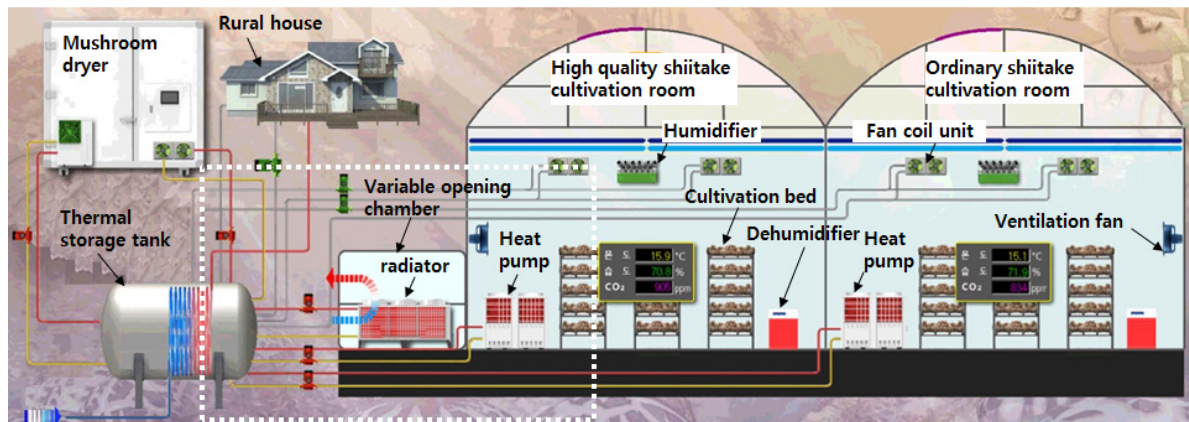
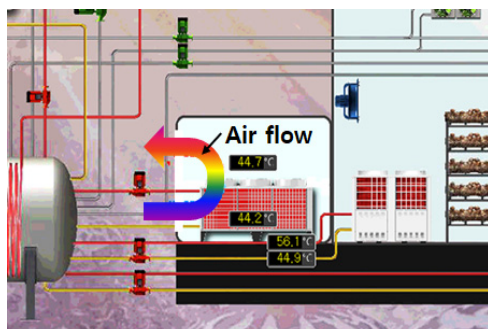
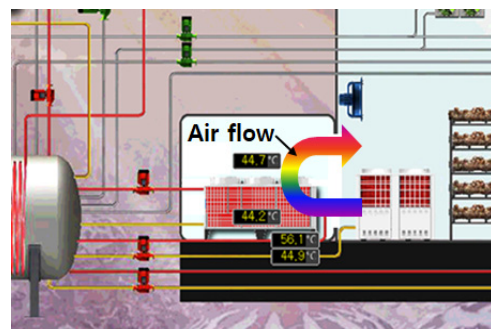


Figure 1. Schematic of environmental control system used for shiitake mushroom cultivation facility.



(a) Cooling of thermal storage tank



(b) Heating of cultivation facility

Figure 2. Selective operation of radiator in variable opening chamber.

Table 1. Configuration of environmental control system for shiitake mushroom facility

Element	Specification	Number	Manufacturer
Heat pump	35 kW	2	Daesung Heatpump, Seoul, Korea
Fan coil unit	11.6 kW	6	Iroom, Siheung, Korea
Radiator	40 kW	1	Busung, Incheon, Korea
Ventilation fan	4,000 m ³ /h	4	Dae Ryun, Wanju, Korea
Humidifier	3 L/h	2	Mtechwin, Gimhae, Korea
Dehumidifier	2 L/h	2	Winix, Siheung, Korea

shiitake mushrooms, as illustrated in Figure 2(b). Table 1 lists the elements of the environmental control system.

Environmental setup

The environmental control system developed in this study was installed on a shiitake mushroom farm located in Jinan-gun, Jeollabuk-do, as shown in Figure 3. The cultivation facility was a 3-span plastic greenhouse, whose width and heights of the eaves and the ridge of the greenhouse were 8, 2.0, and 5.0 m, respectively. The greenhouse was covered by double-layer polyethylene film, and shading screens and multi-layer thermal curtains were installed in the upper part. The sidewall of the cultivation facility was constructed using polyurethane of 100 mm in thickness to improve the thermal insulation and allowing the installation of ventilation fans and a variable open chamber. As shown in Figure 3(c), control groups 1 and 2 were installed in two spans on the eastern side, and the proposed environmental control system was installed in a span on the western side. To produce high-quality shiitake mushrooms, the span on the western side was separated by a partially opened wall. Thus, the high-quality shiitake mushroom area was separated from the ordinary shiitake mushroom area. Based on the quality during the early stage of cultivation, sawdust

substrates, which were expected to produce high-quality shiitake mushrooms, were moved to the high-quality shiitake mushroom area, and the remaining substrates were placed in the ordinary shiitake mushroom area. Both areas had a heat pump. The variable opening chamber was installed at the end of the exterior wall of the high-quality shiitake mushroom area such that hot air discharged from the radiator could be first supplied to the high-quality shiitake mushroom area rather than to the ordinary shiitake mushroom area. For environmental control of the control groups, a conventional unit cooler-condensing unit (30 kW, BCAV-100, Busung, Incheon, Korea) and an electric hot water boiler (116 kW, KDB-2003RE, KD Navien, Seoul, Korea) were used.

Mushroom cultivation

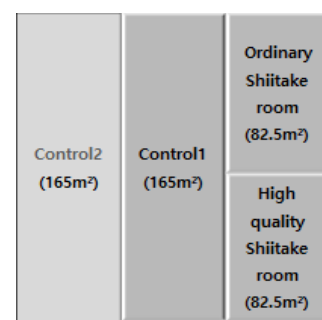
The cultivation experiment was conducted after the proposed environmental control system was installed in the cultivation facility of a farm cultivating shiitake mushrooms. Sanjo 701, a medium- to high-temperature variety oak mushroom, bred in the Republic of Korea, was cultivated. Cylindrical vinyl bag-type sawdust substrates with a weight of 4 kg were purchased, and the starters were inoculated and completely cultured. They were then loaded onto five-stage cultivation beds on July 1,



(a) Installation location



(b) Greenhouse



(c) Test setup

Figure 3. Farm with environmental control system and experimental treatment setup.

2017. Cultivation began on July 11, 2017 and continued for three cycles. The third cycle terminated on September 30, 2017. The purchased sawdust substrates were defrosted at room temperature for 1 day. A daytime temperature of approximately 20°C, a nighttime temperature of approximately 10°C, and a relative humidity of 80% or above were maintained for a 3–5 week period to allow the buds to break. As the next step, thinning was applied for 2 to 3 days to remove the poor-quality mushrooms. The daytime temperature, nighttime temperature, and relative humidity were set to 20°C, 10°C, and 50–60%, respectively. To produce high-quality shiitake mushrooms, namely, hwago and donggo, the inside temperature of the cultivation facility was drastically increased to 25–30°C, and the relative humidity was lowered to approximately 60% between two and four times for a 3–5 day period during the early cultivation stage. This control was applied to generate cracks in the mushroom surfaces and achieve a higher density.

Data acquisition

Because a sawdust substrate is typically loaded onto a multi-stage cultivation bed in a mushroom cultivation facility, the temperature and humidity inside the cultivation facility are likely to be non-uniform according to the location and capacity of the air-conditioning system. Such nonuniformity of the cultivation environment may not only cause a nonuniformity of the mushroom culture but also degrade the culture owing to the occurrence of disease caused by excessive moisture or dryness. Accordingly,

as shown in Figure 4, the performance of the proposed environmental control system was evaluated at 15 positions by measuring the air temperature, the relative humidity inside and outside the cultivation facility, the temperature in the sawdust substrate, and the illuminance in the cultivation bed, and by analyzing the environmental uniformity. In Figure 4, the “lower” position is 30 cm above the ground, and the “upper” position is 150 cm above the ground. The temperature and relative humidity were measured using a temperature and relative humidity recorder (TR-72wf, T&D, Nagano, Japan). The inside temperature of the sawdust substrate was measured using a temperature recorder (TR-71Ui, T&D, Nagano, Japan). The illuminance was measured using an ultraviolet recorder (TR-74Ui, Nagano, Japan). The yield of the shiitake mushrooms was surveyed in each cultivation room shown in Figure 3(c). The survey distinguished high-quality shiitake mushrooms (*whago* and *dongo*) from ordinary shiitake mushrooms (*hyanggo* and *hyangsin*). The quality of the mushrooms was identified according to the sorting criterion, which is applied when the farmers sell their products to a rural agricultural wholesale marketing center.

Results and Discussion

Environmental control system

Figure 5 shows the hardware of the environmental control system, which was developed in this study and

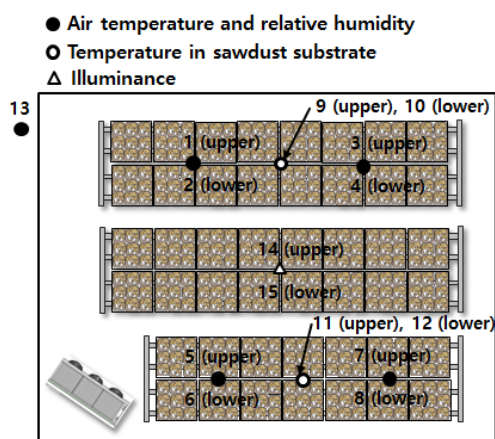


Figure 4. Data measurement positions of cultivation facility.



Figure 5. Hardware components of the environmental control system.

installed in a cultivation facility. Two 35 kW air-to-water type heat pumps were installed in the high-quality and ordinary shiitake mushroom areas, respectively. The heat pumps were connected to a closed-type thermal storage tank with a capacity of 10 tons. During both summer and winter, the heat pumps of the cultivation facility operated by heating cycles to cool the facility and store hot water with a temperature of 40~60°C in the thermal storage tank. The variable opening chamber had a door that could be opened and closed on the wall of either side, and included a radiator connected to the thermal storage tank. When the thermal storage tank reached the upper temperature limit, the radiator discharged hot air through the door opening to the outside of the variable opening chamber. In this manner, the temperature of the thermal storage tank was adjusted. When the temperatures and relative humidity in the high-quality and ordinary shiitake mushroom areas were drastically increased and decreased, respectively, in the production of high-quality shiitake mushrooms, the door opening to the outside of the variable opening chamber was closed, and another door facing the high-quality shiitake mushroom area was opened to provide a large amount of hot air. Hot water from the thermal storage tank was supplied to the fan coil unit installed inside the cultivation facility during winter to heat the greenhouse, to the radiator inside the mushroom dryer to dry the mushrooms, or to the hot water tank of the boiler of the rural farmhouse for daily use.

Figure 6 shows the control and monitoring system of the developed environmental control system. To produce high-quality shiitake mushrooms, the environmental

control was divided into multiple stages such that the temperature and relative humidity could be set for daytime and nighttime use, respectively. In particular, a stage was added in which the inside temperature of the cultivation facility could be drastically increased whenever necessary for the production of high-quality shiitake mushrooms. In addition, the heat pump, humidifier, dehumidifier, ventilation fan, and fan coil unit operations could be set, and a shading screen and multi-layer thermal curtain could be applied for manual/automatic operation.

Performance analysis

Heat pumps were operated between October 25 and November 10, 2016. The daytime and nighttime temperatures of the cultivation facility were maintained at 10°C and 5°C, respectively. Figure 7 shows the measurements obtained from 15 positions, which are displayed in Figure 4. The analysis revealed that the maximum variations in the average temperature and relative humidity inside the cultivation facility were approximately 1% and 3%, respectively. This indicates that uniform environmental control is possible in each position of the cultivation facility. The average temperature of the sawdust substrate was a little higher than the air temperature owing to the respiration energy of the mushrooms and the solar radiation. However, there was no significant variation among the positions. The illuminance at the upper position of the cultivation bed reached 9,000 lx during the day, whereas the maximum illuminance at the lower positions was only 2,500 lx; however, this exceeded the optimum illuminance of 2,000 lx recommended for log cultivation.

Figure 8 shows high-quality and ordinary shiitake mushrooms produced when supplying hot air from the radiator in the variable opening chamber during the early stage of cultivation. The high-quality shiitake mushrooms with many white cracks on the cap surfaces are *hwaggo* or *dongo*. Because these mushrooms taste and smell good, they are sold on the market at high prices. However, the ordinary shiitake mushrooms, that is, *hyanggo* or *hyangsinsin*, are produced through log cultivation under natural conditions of high temperature and excessive humidity. The caps of these mushrooms tend to be smooth with few cracks.

Figure 9 shows the analysis results for the variations in temperature and relative humidity in the control and



Figure 6. System control and monitoring system.

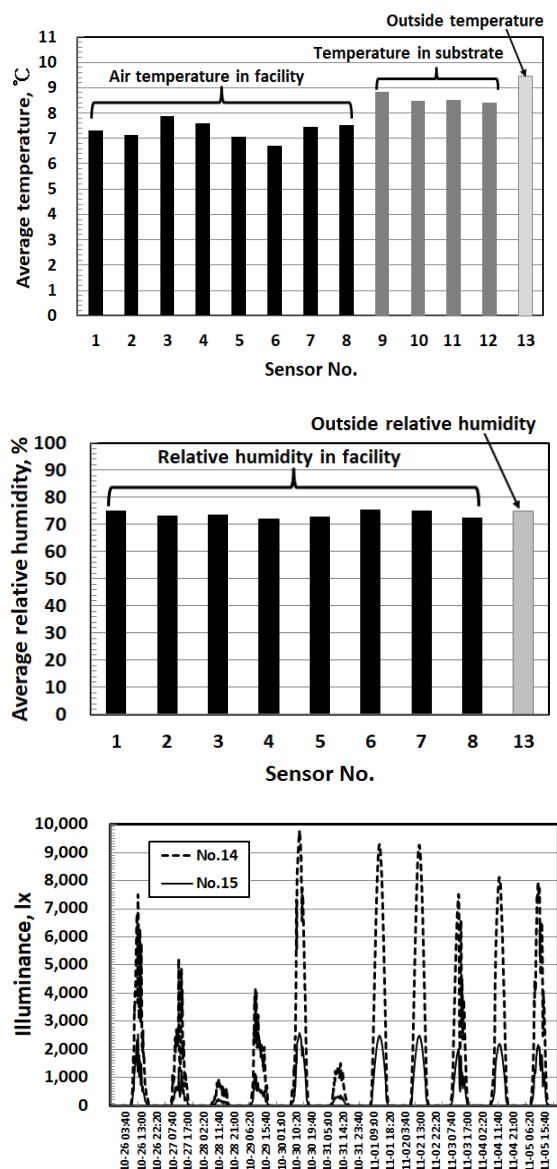


Figure 7. Estimation of environmental uniformity of cultivation facility with average temperature (upper), humidity (middle), and change in illuminance (lower) according to the position.

high-quality shiitake mushroom areas on July 25, 2017. The control areas using a conventional cooler-condensing unit and electric hot water boilers showed limited variations in terms of both temperature and relative humidity. The minimum temperature was 10°C, and the maximum temperature was 20°C, which correspond to a maximum temperature difference of 10°C. The minimum humidity was 60% and the maximum humidity was 80%, which correspond to a maximum difference of 20%. However, the high-quality shiitake room using the developed system, where hot air was supplied by heat pumps and a radiator in the variable opening chamber, achieved a maximum temperature difference of 30°C (maximum temperature of 35°C, minimum temperature of 5°C) within 30 min, and decreased the relative humidity from 90% to 60% within a very short period of time. Such drastic control of the cultivation environment caused cracks on the cap surfaces and improved the hardness of the mushrooms, thereby enabling high-quality shiitake mushrooms to be produced.

Figure 10 shows the variations in yield of the high-quality and ordinary shiitake mushroom areas, which used conventional cooling and a heating control system, and the proposed control system with heat pumps and a radiator in a variable opening chamber, respectively (2017.7.1–9.31.). Both the high-quality shiitake room and the ordinary shiitake room showed a significantly larger yield of high-quality shiitake mushrooms than the control types. The yield of ordinary shiitake mushrooms was larger than that of their high-quality counterparts. The cultivation period of the high-quality mushrooms was longer than that of the ordinary mushrooms, and the yield was constant throughout the three cycles. However, the ordinary mushrooms showed the peak yield in the first, second, and third cycles. Table 2



Figure 8. Ordinary (left) and high-quality (right) shiitake mushrooms during the early cultivation stage

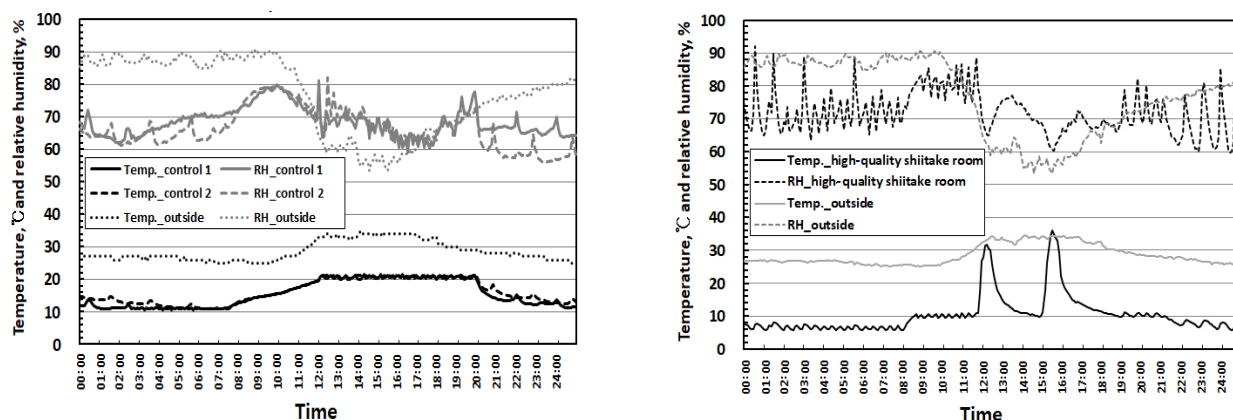


Figure 9. Comparison of temperature and relative humidity between the control room (left) and high-quality shiitake room applying the developed system (right)

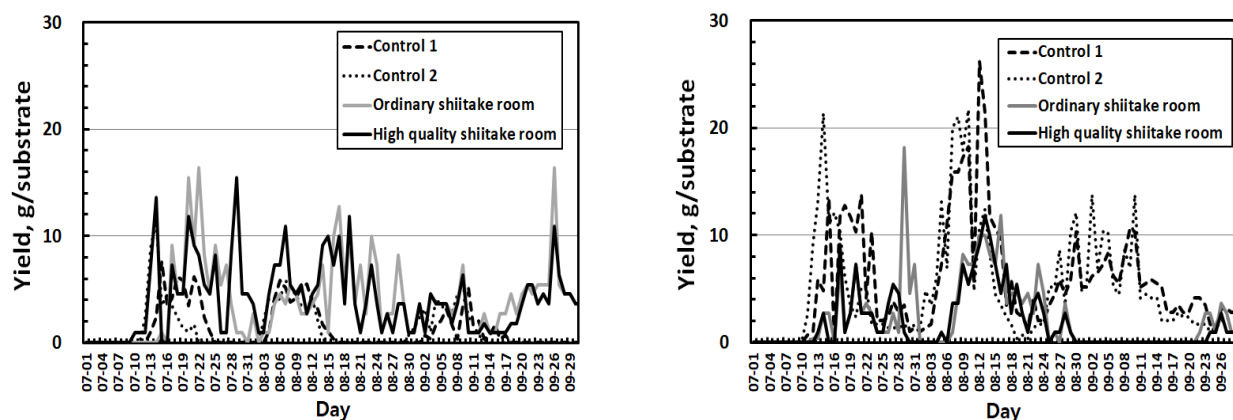


Figure 10. Comparison of high-quality (left) and ordinary (right) shiitake mushroom yields between control and cultivation facility using the developed system (2017.7.1-9.31.)

compares the total yields. The yield of high-quality shiitake mushrooms under the control conditions accounted for 18–19% and 64–74% in the ordinary and high-quality shiitake rooms, respectively. The latter case

increased the yield of the high-quality shiitake mushrooms by approximately 3.6 times. Table 3 compares the average yield and gross income of the ordinary and high-quality mushrooms between the control room and the high-

Table 2. Comparison of yield between control and cultivation facility using the developed system

Yield (g/substrate)							
Control 1		Control 2		Ordinary shiitake room		High-quality shiitake room	
Ordinary	High-quality	Ordinary	High-quality	Ordinary	High-quality	Ordinary	High quality
557	120 (18%)	524	121 (19)	208	371(64)	166	390 (70)

Table 3. Comparison of gross income between control and cultivation facility using the developed system

Control average		Ordinary and high-quality shiitake room averages	
Yield (g/substrate) ^{a)}			
Ordinary	540		187
High-quality	120		380
Sum	660		568
Gross income (1,000 won) ^{b)}			
Ordinary	9,111		3,156
High-quality	3,702		11,705
Sum	12,813		14,862

^{a)} Based on cultivation facility area of 165 m² and 3,000 substrates (ea. 4kg).

^{b)} Based on 5-year average price of Seoul Agro-Fisheries & Food Co.

quality and ordinary shiitake rooms. The total yield of the control was 660 g/substrate, which was 16% higher than that of the ordinary and high-quality shiitake rooms. However, the total yield of the high-quality mushrooms was 380 g/substrate, which was 217% higher than that of the control. Accordingly, the gross income of the facility using the developed system was 14.862 million KRW, which was 16% higher than that of the control.

Conclusions

This paper described the development of an environmental control system for a shiitake mushroom facility used to produce high-quality mushrooms. The developed environmental control system consists of air-to-water type heat pumps, a thermal storage tank, a radiator in a variable opening chamber, and a fan coil unit. The radiator in the variable opening chamber, connected to the thermal storage tank, is used to control the water temperature of the thermal storage tank or drastically change the temperature and relative humidity of the cultivation facility with the intent of producing high-quality shiitake mushrooms. The developed environmental control system was installed in the cultivation facility of a shiitake mushroom farm located in Jinan-gun, Jeollabuk-do, South Korea, and its performance was evaluated. The environmental uniformity inside the cultivation facility was analyzed. The variations in the average temperature and relative humidity among the various positions inside the facility were within 1% and 3%, respectively. This indicates that the environment can maintain a uniform control. The developed environmental control system can achieve a maximum temperature difference of 30°C (maximum of 35°C, minimum of 5°C) and a maximum relative humidity difference of 30% (maximum of 90%, minimum of 60%) within a 30 min period inside the cultivation facility. Accordingly, the developed system was shown to be more effective in producing high-quality shiitake mushrooms than a conventional system using a unit cooler-condensing unit and an electric hot water boiler. A cultivation experiment was conducted for a three-cycle cultivation period. The analysis of the yields showed the following results. The total yield of the control was 660 g/substrate, which was 16% higher than that of the ordinary and high-quality shiitake rooms; however, the total yield of the high-

quality mushrooms in the facility using the developed system was 380 g/substrate, which was 217% higher than that of the control. Accordingly, the gross income of the facility using the developed system was 14.862 million KRW, which was 16% higher than that of the control.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

This study was carried out with the support of the Cooperative Research Program for Agricultural Science & Technology Development (Project No. PJ01195701), Rural Development Administration, Republic of Korea.

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