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Plant Production System Based on Heliostats and LEDs Using Automatic Sliding Cultivation Shelves

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Abstract

In this research we discuss a plant production system based on heliostats and LEDs using automatic sliding cultivation shelves. In our production system, a hybrid lighting system of sunlight and LEDs is adopted to promote plant growth. Sunlight is thus provided to plants by using a solar tracking system during the day. LED lights are then used for illumination during the nighttime or on cloudy or rainy days. We also study reduction ratios of sunlight reflected into the plant production system and uniform irradiation capability of LED light. Safety of proposed sliding cultivation shelves is further investigated through structural analysis. An actual case study is demonstrated by growing ginseng seedlings in our plant production system and their cultivation results are analyzed. As a result, this paper provides useful information and fundamental data for developing a plant production system which uses both sunlight and artificial light.

Keywords: *Plant production system, Heliostat, LED light, Automatic sliding cultivation shelves, Solar tracking system*

1. Introduction

A plant factory is a plant production system that can produce agricultural products by manipulating light, temperature, moisture, water, and fertilizer regardless of local weather conditions and geographical locations. In a broad sense, this system can include traditional greenhouses which use natural light. Plant factories are representative of eco-friendly green technologies, which offers strong prospects for future economic growth. Plant factories are typically equipped with devices to control cultivation environment and many other automation devices, which requires to converge interdisciplinary technologies including electronic and electrical, mechanical, and bio engineering. A plant factory can trace its history back to the Christensen farm in Denmark where a mass production system for cress was adopted in 1957. In USA, General Electric (GE) company started developing a fully controlled plant factory in the 1960s. However, it was not commercialized due to low profitability. In Japan, plant factory research started in the early 1970s and a closed plant factory was studied in 1990s. In particular, LEDs were studied considerably as artificial light sources for plant growth. Many research results [1-2] have shown LED light has been effective for plant growth. In Korea, plant factories drew researchers' attention in the 1990s and have been studied converging IT and LED technologies since the mid-2009. Since the 2000s, plant factories have been studied actively while focusing on the selection of light source, environment control, and online monitoring systems [3-7]. If only artificial light is used, plant factories are not profitable due to higher installation and maintenance cost compared to traditional cultivation methods. If only sunlight is applied, plant production critically depends on sunlight availability such that production decreases on cloudy days or during the nighttime. Thus, considerable attention has recently been paid to

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a plant growth promotion system, which can provide sunlight to plants during the day by using heliostats and also provide artificial light to plants on cloudy days or during the nighttime by using LED lamps to promote plant growth. In this research we propose a plant production system, which uses both sunlight and artificial light. We also design sliding cultivation shelves to use sunlight illumination more efficiently. We then show plant production processes in our hybrid production system by discussing (1) solar tracking control, (2) automatic sliding cultivation shelves, (3) an environment controller for temperature, moisture, and atmospheric carbon dioxide (CO_2), and (4) a controller for measuring and recording the growth of plants.

2. Solar Tracking and LED Lighting Systems

2.1. Solar Tracking System

In this research our plant production system is designed to use LED light and sunlight together. A heliostat system is comprised of a sun tracker shown in Figure 1. The heliostat system is desired to reflect light uniformly toward a predetermined target by controlling azimuth and elevation angles as the sun moves in the sky.

Figure 1. A Small Size Heliostat

Figure 2. Mechanical Parts

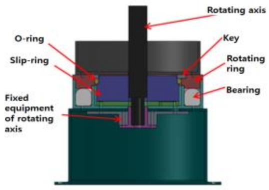


Figure 3. Disposition of a Slip Ring

Power and signal lines are arranged to go through holes under the moving mechanism as shown in Figure 2 and 3. A slip ring is used to wire power and signal lines toward upper parts rotating about azimuth and elevation directions.

Target distance should be considered to reflect sunlight toward the target via heliostat's mirror. Optical sensors are also mounted on the target in a circular configuration to compensate for targeting errors caused by mechanical parts and a target control algorithm. These sensors are set up perpendicular to the direction of light reflected by the mirror. The direction of reflected light at each senor location can easily be determined observing each sensor response for any given light input in our circular sensor array. In our small heliostat, a circular mirror is used such that the shape of the reflection at the target point becomes an ellipse. The shape of the reflection is simulated assuming the target is located due south. In simulation the shape of the reflection becomes closer to a circle for lower altitude. As a result, the reflection shape becomes a more circular ellipse on the winter solstice, which is closest to a circle. Our simulation results, Figures 4-6, show loci of reflected light which are distinguished by using different colors every one hour.

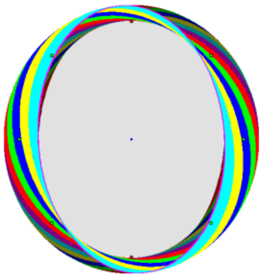


Figure 4. Light Source Locus at the Vernal and Autumnal Equinoxes

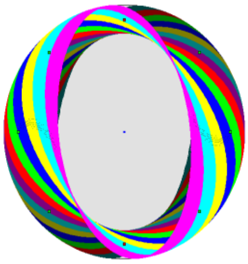


Figure 5. Light Source Locus at the Summer Solstice

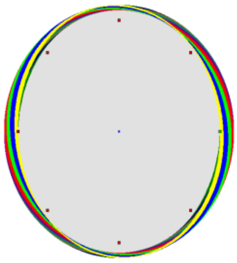
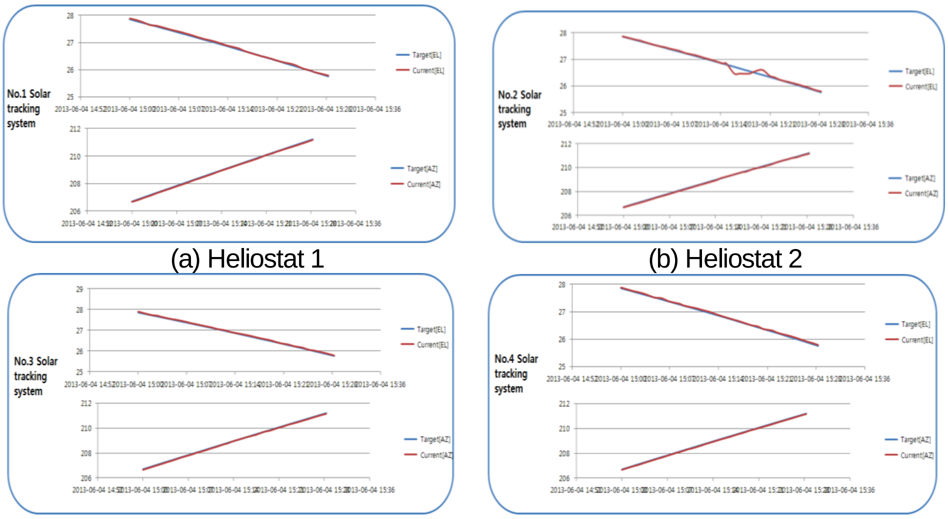


Figure 6. Light Source Locus at the the Winter Solstice

Reflected areas are smaller as it is closer to the summer solstice while they are available for a longer time. In contrast, reflected areas are larger as it is closer to the winter solstice while they are available for a shorter time. The heliostat can be controlled more effectively using simulation results where the target direction and shape of reflected light can readily be predicted.

2.2. Performance Tests for a Solar Tracking System



(a) Heliostat 1 (b) Heliostat 2

(c) Heliostat 3 (d) Heliostat 4

Figure 7. Performance Test Results of the Solar Tracking System

According to a given performance test procedure for the solar tracking system, we conducted initialization and communication tests, measured sensing errors in azimuth and elevation angels, and verified the basic operation of the solar tracker. Performance tests of the solar tracking system were conducted as follows: (1) Four solar trackers are installed in the direction of due south outside the plant production system. (2) Power supply and embedded controller are installed inside the plant production system. (3) The system is checked whether it is configured as illustrated in the test schematics. (4) A solar tracking program is executed. (5) After an initialization test, respective desired and measured values in azimuth and elevation angles are recorded every five minutes.

Figure 7 shows tracking performance test results for four heliostat. These performance tests are conducted to confirm how well the heliostat tracks azimuth and elevation angles of the sun. In Figure 7, a blue line (target) indicates actual movement of the sun and a red line shows actual movement of the heliostat. The xaxis represents time with an interval of 5 minutes and the y-axis indicates the altitude and the azimuth angles, respectively. Note two plots (azimuth and elevation) are obtained from each heliostat test as shown in Figure 7. Our test results verify each heliostat tracks the sun's movement with sufficiently small errors as expected.

2.3. Tests of Light Reduction Rate for Sunlight

Light reduction tests were performed to investigate differences in reduction of light reflected by the heliostat on upper and lower cultivation shelves in the plant production system. Plants are irradiated with sunlight reflected by the heliostats in the plant production system. If the upper cultivation shelf gets more light whereas lower shelf gets less light, plant growth will critically depend on its location in the plant production system. Thus, the goal of these experiments is to determine whether uniform and constant light source will be available for plants. First, while sliding the cultivation shelves, light was measured on upper and lower cultivation shelves using an illuminance sensor. Table 1 provides illumination values measured from experiments. Figure 8 shows how these values are measured. Illumination intensity was measured three times on each location of cultivation shelves (upper, middle, and lower). As a result, an average light reduction rate on the shelves is 4.29% per meter, which is satisfactory for plant cultivation.

Table 1. Reduction Rate of Solar Light

	Location		Reduction rate(%/m)
	Upper cultivation shelf	Lower cultivation shelf	
Measured values (Lux)	551	527	4.36
	552	530	3.98
	550	525	4.54
Average reduction rate of solar light			4.29

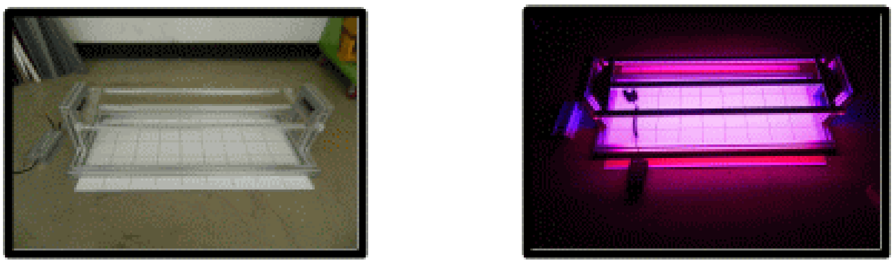
(a) Upper Shelf (b) Middle Shelf (c) Lower Shelf

Figure 8. Illumination Measurement on Three Locations of Cultivation Shelves

2.4. Tests of Uniform Irradiation of LED Light

General greenhouses can absorb sufficient light energy from sunlight. However, in a plant factory with a multi-layer cultivation system it will be difficult to secure a sufficient amount of light for plant growth by using only sunlight. For this reason, artificial light should be used additionally to secure a sufficient amount of light on plant growth. When a high pressure sodium lamp is used in multi-layer cultivation, plants close to the lamp are susceptible to high temperature damage since the lamp generates considerable heat. However, this problem may be resolved simply using LED lights, which generates less heat. LED lights can easily be applied to plant cultivation since they are monochromatic and their wavelength bandwidth is narrow.

That is, light quality of a LED lamp can be selected as the monochromatic light with a specific wavelength required for photosynthesis of the plant. Thus, we can grow plants effectively by using red light (660 nm) and blue light (450 nm) which have most effective wavelengths for photosynthesis. It is also possible to miniaturize LED lighting lamps for uses in a relatively small space. Artificial light can be used during nighttime and inclement weather such as rain or snow to promote the growth of plants. Figure 9 shows the apparatus for uniform irradiation tests of artificial light. As used in actual cultivation shelves, test jigs were made and LED lights were applied. An illumination sensor was used to measure irradiation of LED lights.



(a) Jigs for Tests (b) When the LED Light is Turned On

Figure 9. Setup for Uniform Irradiation Tests of LED Lights

While turning the LED light on, we measured illuminance of the LED light on 16 prescribed points. Resulting measurements are provided in Table 2. In this case, the standard error of measurements is 7.07%, which indicates we can obtain relatively good uniform irradiation of LED lights.

Table 2. Illumination Measurement of the LED Light

Illumination (Lux)				Standard error (%)
658	785	730	717	7.07%
729	749	755	706	
703	725	753	730	
718	736	714	705	

3. Closed-type Plant Production System and Sliding Cultivation Shelves

3.1. Closed Plant Production System

In this research a closed plant cultivation system was built using a commercially available shipping container as shown in Figure 10 since it is relatively cheap and easy to move. Furthermore, polyurethane foam panels were applied to the container to provide enough insulation for plant production.

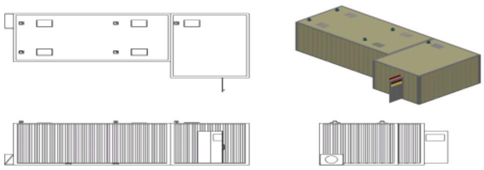


Figure 10. 3D Modeling of a Closed Plant Production System

In the container cultivation and control rooms were physically separated from each other to prevent possible external contamination. Louvers made of 10 mm tempered glass were installed on the roof of the container to use sunlight. Anti-condensation films were attached to indoor windows to minimize the condensation caused by the temperature difference between the inside and outside of the cultivation room, which also increases the effect of maintaining the internal temperature.

3.2. Cultivation Shelves

3.2.1. Mechanical Structure of Cultivation Shelves

Shady areas exist on fixed cultivation shelves when they are illuminated by reflected solar light. Automatic sliding shelves are adopted to maximize illumination of incoming sunlight via heliostat in the plant production system. Fig. 11 shows a 3D modeling of cultivation shelves.

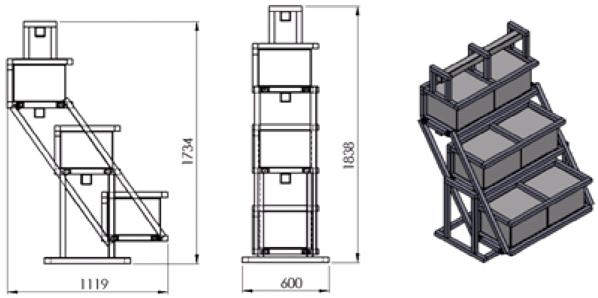


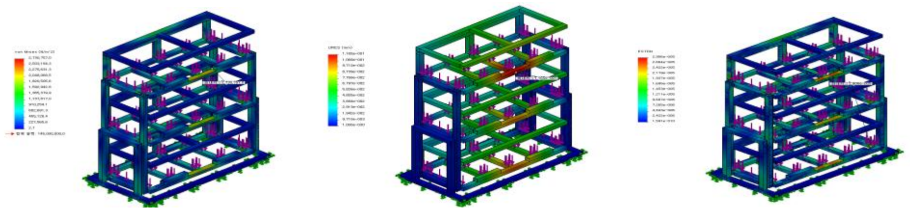
Figure 11. 3D Modeling of Cultivation Shelves

As shown in Figure 11, the cultivation shelves are comprised of three layers such that upper and lower shelves can be slid relative to the middle shelf. LED light lamps can also be attached to these shelves. Sliding cultivation shelf is automatically controlled by using a pneumatic cylinder. Sliding cultivation shelves are activated to uniformly receive reflected solar light from 6 a.m. to 7 p.m.. Sliding cultivation shelves are then deactivated from 7 p.m. to 6 a.m. next day when LED lights are used for continuous promotion of plant growth.

3.2.2. Structural Analysis of Cultivation Shelves

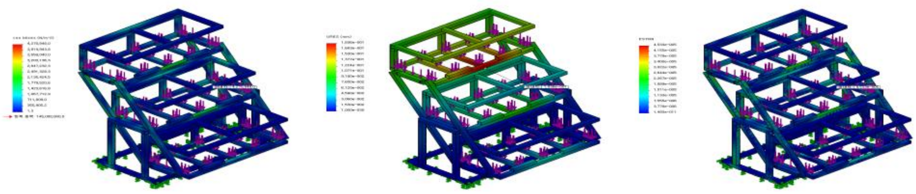
Table 3. Properties of Aluminum

Parameters	Values	Units
Young's modulus	6.9×10^{10}	N/m^2
Poisson ratio	0.33	-
Shear Modulus	2.58×10^{10}	N/m^2
Density	2700	kg/m^3
Tensile strength	185	MN/m^2
Yield strength	145	MN/m^2



(a) Stress (b) Displacement (c) Strain

Figure 12. Stress, Displacement, and Deflection when Cultivation Shelves are not Activated



(a) Stress (b) Displacement (c) Strain

Figure 13. Stress, Displacement, and Deflection when Cultivation Shelves are Activated

Table 4. Structural Analysis Results Applying Static Loads

Sliding of the cultivation shelves	Properties	Maximum values	Locations
Deactivated	Stress	2.73 MPa	Middle of front part on the upper shelf
	Displacement	0.01165 mm	Middle of front part on the upper shelf
	Strain	2.906×10^{-5}	Right of front part on the lower shelf
Activated	Stress	4.26 MPa	Right joint
	Displacement	0.01836 mm	Middle of front part on the upper shelf
	Strain	4.533×10^{-5}	Right joint

Structures of cultivation shelves were analyzed using a commercial software tool, SolidWorks. In a cultivation shelf system with three layers, each layer of the shelf can hold two styrofoam boxes which contain soils. We analyzed the shelf system with three layers applying a distributed load of 100 kg, which considers a margin of safety. Table 3 provides properties of aluminum used for frames of the shelf. Our structural analysis results are summarized in Figure 12-13 and Table 4. Our analysis results show stresses, displacements, and deflections in the sliding cultivation shelves are within the allowable ranges for both deactivated and activated cases, which verifies structural safety of the designed cultivation shelves.

4. Plant Production System

In this research we use both solar and LED lights for plant production. Our production system is also designed to allow us to change cultivation conditions such as mixing ratios of LED light sources. Main components of the production system include a hybrid lighting system of sunlight and LED lamps, a control system for constant temperature and humidity, and a remote control and monitoring system for plant production.

4.1. Hybrid Lighting System and Environmental Controller

As shown in Figure 14, four heliostats are installed on the roof of the plant production system. These heliostats are controlled by an integrated control and monitoring system via CAN protocol. To control LED lighting for each cultivation shelf, PWM control techniques are used via Zigbee control boards which can collect data for each cultivation shelf. LED lamps for artificial light are off from 6 a.m. to 7 p.m. when heliostats are used to provide sunlight to plants. LED lamps are turned on to provide light to plants from 7 p.m. to 6 a.m. next day. Figure 15 shows a network communication board for wireless control.

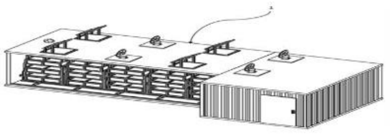


Figure 14. Plant Production System

Figure 15. Network Communication Board

Stable temperature and humidity environment is required for plant production such that a control unit for constant temperature and humidity was installed in the cultivation room. In case the temperature goes up more than 29 ℃, high temperature warning is sent to administrator's mobile phone using Short Message Service (SMS) in our system.

4.2. Control and Monitoring System for Plant Production

A plant monitoring and control system is used to monitor and record plant growth. Our monitoring system can store measured data such as temperature and water content to observe persistent plant growth. Figures 16 and 17 show monitoring software for plant production and a schematic diagram of the monitoring system, respectively. Figure 18 shows a schematic diagram of power connections in plant cultivation shelves.

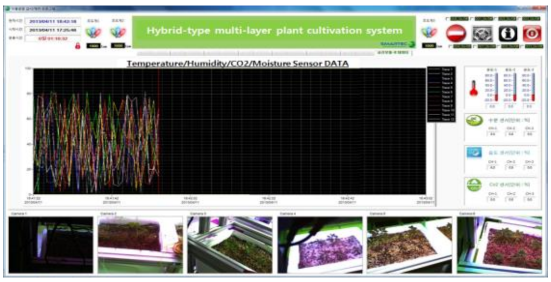


Figure 16. Monitoring Software for Plant Production

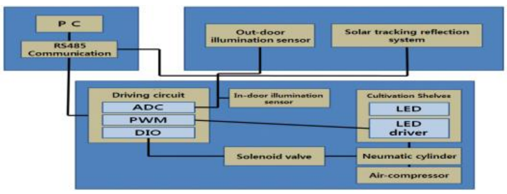


Figure 17. Schematic Diagram of the Monitoring System for Plant Production

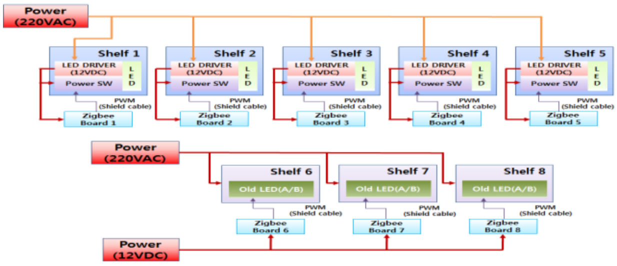


Figure 18. Schematic Diagram of Power Connections in Plant Cultivation Shelves

In the plant production pneumatic cylinders, LED lights, and fans are actuated by a controller based on sensor data such as illumination, temperature, humidity, CO_2, and soil moisture. For this purpose, we use a Zigbee control board with four channels of DIO, four channels of PWM, and 16 channels of ADC. Reference profiles for temperature and humidity are set for two time zones where one is from 6:00 a.m. to 7:00 p.m. and the other is form 7:00 p.m. to 6:00 a.m. Control signals are then sent to actuators to adjust temperature and humidity through RS285.

5. Plant Cultivation

Ginseng seedlings, which is a high-value specialty crop, can be cultivated organically using sterilized nutritional soil in limited space. Damages by diseases and insects during the summer rainy season can be prevented by growing plants in the plant production system. Thus, harvest and marketability of our cultivated ginseng seedlings are expected to increase when compared to bare ground-grown ginseng seedlings. Ginseng seedlings of about 1g were used for this research. Growth of ginseng seedlings were recorded every two hours using cameras. Table 5-9 provide changes in growth of ginseng seedlings by using several different ratios of red to blue LED light while solar intensity is uniform.

Table 5. Changes in the Root Length of Ginseng Seedlings Applying Several Different Ratios of LED Lighting Unit(cm)

Date / Ratio of LED lighting	May 27	June 5	June 11	June 18
1:1	8.0±2.5	11.0±2.2	11.4±1.9	12.8±0.5
1:2	9.9±1.9	9.9±2.7	12.7±2.3	13.0±0.7
1:3	11.2±1.6	12.2±0.3	12.4±0.7	13.1±0.3
1:4	11.6±3.5	12.4±0.9	13.2±0.8	14.4±1.3

Table 6. Changes in the Rootstock of Ginseng Seedlings Applying Several Different Ratios of LED lighting Unit(mm)

Date / Ratio of LED lighting	May 27	June 5	June 11	June 18
1:1	4.9±0.2	5.0±0.0	6.3±1.0	6.8±0.6
1:2	4.5±0.6	4.5±0.0	5.5±0.9	6.6±1.1
1:3	5.1±0.4	5.2±0.1	5.7±0.0	6.6±1.9
1:4	4.6±0.5	5.0±0.5	5.2±0.8	6.2±0.6

Table 7. Changes in the Stem Length of Ginseng Seedlings Applying Several Different Ratios of LED Lighting Unit(cm)

Date / Ratio of LED lighting	May 27	June 5	June 11	June 18
1:1	4.6±0.2	6.1±0.8	7.0±1.0	8.6±0.6
1:2	4.4±0.3	5.5±0.9	5.8±1.5	7.2±1.1
1:3	6.3±0.4	6.8±0.9	7.5±1.6	7.7±1.9
1:4	5.8±0.0	6.0±0.3	6.2±0.8	7.7±0.6

Table 8. Changes in the Leaf Area of Ginseng Seedlings Applying Several Different Ratios of LED Lighting Unit(cm^2)

Date / Ratio of LED lighting	May 27	June 5	June 11	June 18
1:1	29.1±11.2	31.3±0.0	37.9±0.0	39.4±4.1
1:2	22.4±0.0	25.5±4.4	29.6±10.7	36.4±0.3
1:3	28.8±5.7	35.0±4.4	37.4±2.7	40.0±0.4
1:4	28.2±0.0	28.8±1.0	32.2±15.4	32.7±0.1

Table 9. Changes in the Weight of Ginseng Seedling Roots Applying Several Different Ratios of LED Lighting Unit(gram)

Date / Ratio of LED lighting	May 27	June 5	June 11	June 18
1:1	0.7±0.2	0.8±0.3	1.3±0.1	1.9±0.1
1:2	0.6±0.1	0.9±0.3	1.0±0.4	1.9±0.3
1:3	1.0±0.3	1.0±0.1	1.2±0.1	1.9±0.4
1:4	0.6±0.2	0.9±0.2	1.0±0.2	1.7±0.1

When the blue and red LED ratio was 1:4, roots of ginseng seedlings had grown slightly faster compared to other mixing ratios. In summary, we found ginseng seedlings had grown evenly under the blue and red LED ratio of 1:1 even though growth of other parts except roots is similar. Figure 19 shows the growth of ginseng seedlings with an interval of seven days.

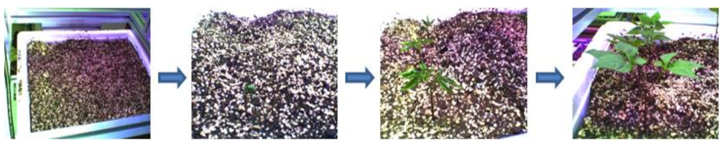


Figure 19. Growth of Ginseng Seedlings (Interval of Seven days)

6. Conclusions

In this research we studied plant production system applying automatic sliding cultivation shelves and a hybrid lighting system based on heliostats and LEDs. We finally conclude our research results as follows: (1) the proposed solar tracking system, heliostat, reflects sunlight uniformly to the target while effectively tracking the sun's azimuth and elevation angles, (2) sunlight can be uniformly illuminated in the plant production system by using the proposed automatic plant cultivation beds with multi-layers, (3) a hybrid illumination system is proposed using both sunlight and artificial light for more effective plant production compared to traditional methods, (4) Implementing monitoring and control systems for plant production, the growth process and environment of plant can be controlled remotely from outside the plant cultivation room. As a result, a prompt action can be taken for a sudden environmental change within the plant production system via the SMS notification, and (5) Ginseng seedlings were cultivated to investigate the effects of various blue and red LED ratios on plant growth. When the blue and red LED ratio was 1:4, roots of ginseng seedlings had grown slightly longer compared to other parts. Overall, we found ginseng seedlings had grown evenly under the blue and red LED ratio of 1:1.

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