Study on light and thermal energy of illumination device for plant factory design

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Abstract. To investigate the effect of illumination devices on the yield of crops cultivated in a plant factory, it is necessary to measure the actual cultivation environmental factors related to the plant growth and understand the distribution ratio of light and thermal energy to the electrical energy injected into the illumination device. Based on cultivation results, we found that light intensity greatly affected the growth of plant weight. Regarding the selection of illumination device, its spectral components also affected the morphological change. Lighting experiments using a high frequency (Hf) fluorescent lamp and a light emitting diode (LED) bulb were performed. A certain difference was found in the distribution ratio of light energy to electrical energy between Hf and LED. It was showed that by placing the safety equipment or internal circuits outside the cultivated site, the air conditioning load could be reduced.

1. Introduction

There is increasing awareness of the destabilizing effects of abnormal weather on crop production, agricultural businesses, and food safety. Therefore, the focus is on plant factories, which allow for stable crop production, and efficient and safe vegetable production. However, plants produced artificially in factories are more expensive than those produced in open air. To lower production costs, the cultivation environment needs to be appropriately controlled, and the growth rate of plants needs to be improved [1]. The following environmental factors are associated with growth: air temperature, humidity, wind speed, CO₂ concentration, light strength, and nutrient components. The decrease in productivity, owing to inconsistency in cultivation quality, is the effect of inconsistent environmental factors in these factories. To optimize the cultivation environment and air-conditioning in plant factories, it is important to evaluate first their air temperature, humidity, wind speed, and CO₂ concentration distribution with a numerical simulation [2]. The relation among the harvest, the light strength and the light quality were discussed, and the required lighting energy consumption was estimated [3]. The effects of lighting on the cultivation state are large. It is required to offer comprehensive information about the lighting to design the plant factory.

In this study, we measured the actual cultivation environmental factors and fresh weights of lettuce in a plant factory, and analyzed the effects of these factors on its growth. Based on the results, we investigated the effects of environmental factors, especially light intensity, on the fresh weights of plants by measuring the distribution of factors and fresh weights of plants cultivated in a plant factory. With
respect to the factor related to the selection of illumination device, the effect of not only light intensity but also wavelength distribution on growth of plants was examined [4-7].

In a fully artificial-light type of plant factory, which uses illumination devices in place of sunlight, there is little cooling load caused by ventilation or wall heat transmission, and approximately 80% or more of the cooling load comes from heat generated by illumination devices [8, 9]. Therefore, the illumination device has a significant effect on the air conditioning load. Further, it is considered that the photosynthetic rate is also affected by the lighting in the cultivation room. The distribution of the various types of energy by the illumination devices has been investigated in the past [10], but LED has not been measured and the other lighting devices have gradually become more efficient. The heating value of the illumination devices, including LED [11], is clarified, but the energy distribution ratio of light in relation to normal rated power has not been investigated.

In this study, in order to comprehend the effect of the latest illumination devices on air conditioning load, lighting experiments using high frequency (Hf) fluorescent lamps and LED are performed, and the distribution rate of light to electrical energy from each illumination device is investigated. The results of these experiments are incorporated into an air conditioning simulation, which included transpiration and photosynthesis of the cultivated plants [2], and its effect on crop yields is investigated. Based on these results, methods for reduction of air conditioning load in plant factories are proposed.

2. Effect of light intensity on plant growth

2.1. Effect of light intensity on plant growth weight

2.1.1. Cultivation room and measurement method. We examined the effect on frill lettuce (Lactuca sativa L.) growth of light intensity, air temperature, and wind speed within the measured cultivation room. In addition, by comparing them against the results of cultivation experiments performed in an environment-simulator room, in which air temperature, humidity, and wind speed were regulated in turns, we evaluated the regulated conditions of these environmental factors in the cultivation room.

Figure 1 shows plane and cross-section views of the actually measured cultivation room for this study, and the measurement locations of each cultivation shelf. The cultivation room had six four-tier cultivation shelves. We measured the air temperature, humidity, and wind speed, and light intensity from the top to the third tier of one shelf.

The regulated air temperature of the cultivation room was 22 °C, the light period (daytime) was 16 hours, the dark period (nighttime) was 8 hours, and the CO₂ concentration was kept at 600 ppm. An Hf fluorescent lamp (NEC, FHF32EX-D-HX-S, 32 W, 1200 mm) was used as lighting equipment. The number of lamps was four per shelf. The lettuce grew on the cultivation shelf three weeks after seeding, and therefore it was harvested three weeks after cultivation. Each tier of the cultivation shelf was divided into six sections, and 4 x 9 plants of lettuce were cultivated per section. The air temperature, humidity, wind speed, and CO₂ concentration in each section were constantly measured at the positions shown in figure 1, at five-minute intervals from planting to harvest. Furthermore, the light intensity affecting photosynthesis was evaluated in terms of photosynthetic photon flux density (PPFD). PPFD is a value expressed in number of light quanta in the wavelength range of 400 nm to 700 nm, which is the effective for photosynthesis. We measured the PPFD per cultivation position in the state prior to lettuce planting. The lettuce was harvested over three days, and then winnowed according to the cultivation day (21 to 23 days). We measured not only the weight of the lettuce after harvesting, but also the fresh weight of seedlings before planting.

2.1.2. Experimental results and discussion. The harvest took 3 days (cultivation period of 21 to 23 days) owing to the very large number of lettuces. A lettuce with 23 days of cultivation was larger than that harvested in a different day or that had been cultivated in the third stage of the shelf. Therefore, using the fresh weight after 23 days cultivation, the effect of each environmental factor on plant growth was investigated. Figure 2 shows the relationship between light intensity and fresh weight of the harvested
lettuce. The light intensity distribution within the shelf was determined. The tendency that light intensity was lower around the shelf than at the center was confirmed. The fresh weight of lettuce increased with increasing light intensity. It is known that the photosynthetic rate of lettuce increases proportionally with increasing light intensity, and converges to a constant value when it reaches 350 μmol m² s⁻¹ [12]. In this cultivation room, it was found a range that increased with increasing light intensity, as shown in figure 2. There was a high correlation of produced weight with light intensity, but a certain deviation was recognized. Besides light intensity, the effects of other environmental factors, such as wind speed, and the individual differences of cultivated plants should be examined [1].

Figure 1. Actual cultivation room and measurement points (dimensions in mm).

Figure 2. Relationship between light intensity (PPFD) and fresh weight.
2.2. Effect of light quality on plant growth rate

2.2.1. Cultivation equipment and conditions. The experiments were carried out in the cultivation environment simulation room at the R&D Center of the Plant Factory, Osaka Prefecture University. In this facility, there is a ventilator located on each cultivation rack, and environmental factors such as air temperature and wind speed can be controlled by manipulating the position of the ventilation duct, wind direction, and wind speed. The facility has Hf fluorescent lamps (Panasonic, FHF16EX-D-H, 23 W, 600 mm) and LED lighting (Shibasaki, DP-10344-01, 17 W, 600 mm). Because LED is small in size, has long life and strong intensity, and the wavelength of emitted light can be freely changeable, its introduction to the plant factory has been an advance [8]. The experimental cultivation was carried out in various cultivation zones, which were established by altering the air temperature, wind speed and CO₂ concentration.

Frill lettuce (Lactuca sativa L.) was cultivated during the experiments. Seedlings were selected based on their weight three weeks after sowing. After the seedlings were replanted, they were cultivated for two weeks under the following basic conditions, light: dark cycle 14:10 h, relative humidity: 70 %, and feed: Otsuka House 1/2A (EC 1.3–1.5, pH 5.0–6.5). Four lighting condition zones were established, as listed in Table 1, and figure 3 shows these lighting condition zones in practice. Hf3, Hf4, and Hf7 indicate that the number of lamps is 3, 4, and 7, respectively. Under these conditions, cultivation was carried out for various air-conditioning factors (air temperature, wind speed, and CO₂ concentration). Nine plants, as shown in figure 4, were cultivated in each condition zone; five of them (positions A, C, E, G, and I) were used for growth analysis, and the other four were utilized for component analyses [13]. In this study, the adopted condition was 20 °C in air temperature, 1000 ppm in CO₂ concentration, and 0.55–1.12 ms⁻¹ in wind speed. Air temperature, relative humidity, and CO₂ concentration were controlled within ±0.3 °C, ±5 %, and ±80 ppm, respectively. We measured not only the fresh and dry weight of the lettuce after harvesting, but also the fresh weight of seedlings before planting. The leaf total area was also measured by separating all leaves from a stem, and displaying them planarly. The net assimilation rate (NAR) g cm⁻² day⁻¹ was obtained by dividing the average dry weight change rate during the cultivated period by leaf total area.

2.2.2. Experimental results and discussion. Regarding lighting conditions, the light intensities of LED and Hf3 were the same, as presented in Table 1. For these conditions, the effect of light quality on plant growth was investigated. The spectral distributions are shown in figure 5. The relative values of lighting energy per unit wavelength are indicated, with 100 % for each maximum value. A peak value is recognized at one wavelength for Hf, but there are three peak values in wavelength for LED.

The NAR of plants cultivated with LED was around 2 times that of plants cultivated with Hf fluorescent lamps, as shown in figure 6(a). On the other hand, the total leaf area of plants cultivated with Hf was larger than that with LED, as shown in figure 6(b). Finally, with a similar level of light intensity, the fresh weight increase, i.e., the growth rate, was similar with LED and Hf, as shown in figure 6(c). As shown in figure 6(d), the dry weight of plants cultivated with LED was slightly larger than that of plants cultivated with Hf, because of the difference in the water content. The morphological change was caused by the quality of light expressed by the spectral distribution of the illumination device [4–7, 14]. The lettuce cultivated with LED had a large weight per leaf area and its leaf became thick, while that with Hf had a large leaf area, and its volume became large.
Table 1. Light intensity at cultivation point.

| No. | LED | Hf3 | Hf4 | Hf7 |
|-----|-----|-----|-----|-----|
|     |     | [μ mol m$^{-2}$ s$^{-1}$] |     |     |
| A   | 202.3 | 206.0 | 288.0 | 567.7 |
| C   | 183.0 | 182.0 | 254.3 | 465.3 |
| E   | 237.7 | 236.0 | 315.7 | 628.0 |
| G   | 196.7 | 199.0 | 293.0 | 539.0 |
| I   | 184.0 | 185.7 | 265.0 | 465.3 |
| Average | 200.7 | 201.7 | 283.2 | 533.1 |

Figure 3. Lighting condition zones in cultivation environment simulation room.
Figure 4. Cultivation situation.

Figure 5. Spectral distribution of Hf and LED.
3. Energy distribution of illumination device

3.1. Experimental equipment and method

The experimental equipment is shown in figure 7. There are insulation materials (polystyrene foam 30 mm thick) on areas without ceiling, and the ceiling section has glass with a thickness of 5 mm (float board glass). The illumination device is placed in the center so that it shines on the ceiling area. Two small fans are placed inside, which operate during the experiment to maintain internal uniformity of air. The inside of the illumination device and experimental equipment, including the fan, are tightly sealed. The internal air temperature and wall, floor, and ceiling internal and external surface temperatures are measured using thermocouples (type T, wire diameter of 0.65 mm). Further, the small fan and illumination device voltage and current are measured using a clamp wattmeter. The measurement positions for the air temperature, and floor, wall, and glass surface temperatures are shown in figure 8.

Figure 9 shows the internal air temperature over time during the experiment. The experiment first runs the fan internally, in a lights-off state. After operation of the internal fan, the air temperature becomes constant in about 2 hours and reaches a steady state. At this time, the differences between internal and external temperatures at the measurement locations are constant, in the same way as the internal temperature. After reaching a steady state, the light is turned on and measurement continues until the differences between internal and external temperatures at each measured location become constant. As in the case of the illumination device, the temperature increased immediately after turning on the light, but approximately 2 hours after, it became constant. The temperature external to the experimental equipment was controlled to become constant, and maintained at approximately 24 °C ± 2 °C. Illumination of the lighting device was not controlled. Based on the above measurement results, the energy distribution ratio $\omega$ can be obtained according to the following procedure.

The electrical energy is converted to heat and light in the illumination device. The thermal energy heats the illumination device, and the heat generated by the illumination device heats the surrounding air through convective heat transfer, and this is finally transmitted to the wall, floor, and ceiling surfaces. This amount of energy is calculated as heat transmission from the differences between internal and external temperatures of the wall, floor, and ceiling. The heat transfer amount $Q_{tw}$ for the floor and wall
can be obtained from equation (1). The ceiling heat transmission amount $Q_G$ can be obtained in the same way as equation (2).

\[
Q_w = k_w \frac{(T_{win} - T_{wout})}{d_w} A_w \quad \text{(1)}
\]

\[
Q_G = k_G \frac{(T_{gin} - T_{gout})}{d_G} A_G \quad \text{(2)}
\]

where, for each of the variables in equations (1) and (2), the subscript $W$ expresses the values for the floor and wall surfaces, $G$ represents the values for the ceiling surface, and the subscripts of internal and external are expressed as “in” and “out,” respectively. $k$ is thermal conductivity, $T$ is surface temperature, $d$ is material thickness, and $A$ is the area. $Q_w$ is the sum of the floor heat transfer amount $Q_{w1}$ and the wall heat transfer amount $Q_{w2}$. Visible lights are driven outwards through the glass of the ceiling. This transmitted light energy $E_L$ can be obtained by subtracting the heat transfer $Q_{w1}$, $Q_{w2}$ and $Q_G$ for each surface from the electrical energy $Q_E$ injected into the internal fan and illumination device. Further, the heat transmission amount $Q_G$ can be thought of as the sum of $Q_{Gi}$ from the illumination device and $Q_{G2}$, which occurs when light passes through the glass. From the above, the distribution ratio $\omega$ is found, according to the following equation:

\[
\omega = \frac{E_L}{Q_E} = \frac{E_L/C_G}{Q_E} = \frac{(Q_E - Q_{w1} - Q_{w2} - Q_G)/C_G}{Q_E}
\]

where $C_G$ in equation (3) is the glass board transmission rate. When the light energy $E_L$ obtained from equation (3) is multiplied by the glass board absorption, the value of $Q_{G2}$ is calculated. The value of $Q_{Gi}$ is given by subtraction of $Q_{G2}$ from $Q_G$.

In this experiment, 32 W type Hf fluorescent lamps (Hitachi Appliances, HNK4205V-MEN14) and 20 W type LED bulbs (Hitachi Appliances, NHE4205-JI14D) are employed. The number of lamps and bulbs is two, as shown in figure 7. The illumination of both devices is essentially the same, and it is that usually required in plant factories. Further, it is known that heat is also generated from areas without fluorescent lamps, such as the ballasts in Hf or internal circuits in LED. It was considered possible to reduce the internal load by locating the ballast or internal circuit outside of the cultivation room; thus, the experiments are performed with the respective ballast and internal circuit located outside of the cultivation room.

Figure 7. Experimental equipment of lighting experiment.
3.2. Experimental results and discussion

Figure 10 shows the internal surface temperature $T_{in}$ of the floor surface and the difference between external and internal surface temperatures on the floor $\Delta T$ after turning on the lights. The internal surface temperature on the floor surface was higher with Hf than with LED. The difference between the internal and external temperatures of the floor surface was smaller with LED than with Hf. The temperature differences of glass and wall also showed the same tendencies. The temperatures with both Hf and LED were slightly higher around the center, but this is considered to be influenced by the heat generated by the ballast and internal circuit.

The difference between the internal and external surface temperatures on the floor surface in the experiment with the Hf without ballast and with LED without internal circuit is shown in figure 11. The ballast or internal circuit was placed outside of the experimental box as shown in figure 7. By removing the ballast and internal circuit, the difference between the internal and external temperatures decreased. The amount of this decrease was more significant in the case with LED than in that with Hf.

The values used for the calculation are shown in Table 2 [15, 16]. The results of the analysis of energy distribution by equations (1) and (2) with the experimental results are shown in figure 12. The
The number of lighting experiments was three for Hf and two for LED, respectively. The heat transfer amount of the wall $Q_{w2}$ and glass $Q_{G} = (Q_{G1} + Q_{G2})$ are virtually the same, and the heat transmission amount of the glass is approximately 2.5 times that of the floor $Q_{w1}$. However, no difference in the distribution ratio was seen between Hf and LED. As the power consumption of the illumination device measured with the clamp wattmeter showed a difference of approximately ±1 W from the normal rated power, $Q_{E}$ in equation (3) is treated as the normal rated power. Further, the float glass transmission and absorption ratios were 0.83 and 0.10, respectively [16]. Based on the above assumption, the energy distribution rate $\omega$ can be obtained from equation (3). The result for LED, 0.56, was slightly larger than that for Hf, 0.52.

Figure 13 shows the results of the energy distribution with Hf without the ballast and with LED without the internal circuit. The number of lighting experiments was two for LED and Hf, respectively.
The values of $Q_{w1}$, $Q_{w2}$, and $Q_G$ were calculated from the measured data. As the value of $E_L'$, the averaged value shown in figure 12 was used. From the diagram, it can be seen that when the ballast is removed from the Hf, the amount of heat generated by the illumination device is reduced by approximately 2 W. In the same way, the amount of heat generated by LED is also reduced by 3 W. The $\omega$ of Hf is 0.52 and the generated heat amount is 31.2 W. Therefore, this is a reduction in the lighting load of approximately 6%. The heat amount generated by LED is 19.8 W, representing a decrease in the load of about 15%. From the above, it is thought that placing the ballasts or internal circuits outside of the cultivation room can reduce air conditioning load. It is considered that the reduction is more effective in the case of LED than that of Hf.

### Table 2. Physical values of experimental equipment.

|                      | Thermal conductivity [W m$^{-1}$ ℃$^{-1}$] | Thickness [m] | Area [m$^2$] |
|----------------------|------------------------------------------|---------------|--------------|
|                      |                                          |               | Floor      | Wall   | Roof |
| Extruded polystyrene foam | 0.038*                                  | 0.030         | 0.524      | 1.316  | -    |
| Glass                | 0.030**                                 | 0.005         | -          | -      | 0.524 |

* and ** refer to [15] and [16], respectively.

![Figure 12. Heat and light energy distribution of illumination device.](image1)

![Figure 13. Effect of ballast on Hf and internal circuit on LED.](image2)
The distribution ratio of light energy against electrical energy obtained in the lighting experiments was incorporated into the air conditioning simulation and the effect of different illumination devices on the temperature distribution within the cultivation room was investigated. An analytical model based on the cultivation room of a plant factory is shown in figure 14. Regarding the analysis conditions, air flow velocity is 0.1 ms\(^{-1}\), supply air temperature is 23 °C, and relative humidity is 70 %. In the lighting experiment, simulations of both Hf and LED lighting were conducted by applying the temperature distributions obtained in the experiments. The cultivated plants were assumed as leaf lettuces, for which the characteristic values had been investigated in previous research [2]. The analytical results of the temperature distribution in the cultivation room for Hf and LED are shown in the thermal distribution diagram in figure 15. The amount of heat generated by the illumination device increased the air temperature surrounding it. Further, it was recognized that the temperature surrounding the plants was higher in the case of Hf than with LED. From the above, it is considered that Hf has a greater effect on air temperature distribution within the cultivation room than LED. Thus, it is suggested that the cooling load can be reduced by using LED instead of Hf.

The photosynthetic rate is estimated under the condition of 22.5 °C in air temperature, 75.5 % in relative humidity, 0.8 ms\(^{-1}\) in wind speed, and 1000 ppm in CO\(_2\) concentration [2]. The electric power consumption of LED was assumed the same as HF, with 65 W. The heat amount generated from both illumination devices is almost the same. The value of PPFD of LED is larger than that of Hf. The results are shown in figure 16 as a function of the distribution ratio of light energy for each illumination device. It was found that there is a difference in photosynthetic rate, i.e., product amount, between the illumination devices, even though the electric power consumption of the devices and their cooling loads are the same. If an illumination device with higher conversion efficiency is developed, a decrease in air conditioning load and an increase in harvest can be expected.
4. Conclusion
To study the effect of lighting devices on air conditioning load in plant factories, lighting experiments were performed, and by incorporating those results into an air conditioning simulation with plant activity, the following results were obtained.
1) The light intensity distribution within the actual cultivation shelf was recognized. The fresh weight of lettuce increased with increasing light intensity.
2) The light spectral components affected the morphological state.
3) From the lighting experiment, the distribution rate $\omega$ of light to electrical energy was 0.52 for Hf and 0.56 for LED, and no major differences were seen.
4) By removing the ballasts and internal circuits, there was a reduction in lighting load of 6% for Hf and 15% for LED. Therefore, by placing the ballasts or internal circuits outside the cultivation room, air conditioning load can be reduced.
5) The result of integrating the experiment results in the simulation showed that Hf had a greater effect on increasing temperature in the vicinity of the plants than LED. By using LED, therefore, it is possible to suppress temperature increases in the area around plants.
6) The photosynthetic rate is higher for LED than for Hf under the same power consumption. Therefore, a greater yield can be expected by using LED.

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