

Article

# Power Controllable LED System with Increased Energy Efficiency Using Multi-Sensors for Plant Cultivation

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**Abstract:** In this paper, a power-controllable light emitting diode (LED) control system is proposed for plant cultivation. The proposed LED system measures environmental data, such as the distance between the plant and LED system using an infrared sensor and the ambient illuminance based on an illuminance sensor. Then, it converts the illuminance to the photosynthetic photon flux density (PPFD) for plant cultivation. It analyzes the relationship between the data and LED PPFD, and generates an optimal pulse width modulation (PWM) signal. Therefore, it controls the LED PPFD dynamically. The proposed LED system is also implemented in hardware, which consists of red and blue LED arrays with suitable wavelengths and a micro-controller. In the experimental results, the proposed LED system preserved the target PPFD regardless of the change of the distance and ambient PPFD. Additionally, the proposed LED system maximally reduced the power consumption of a conventional system by up to 68%.

**Keywords:** light emitting diode (LED); power control; lighting control

## 1. Introduction

These days, food shortages have become a significant concern because of the volatility of outdoor plant production caused by unusual weather [1]. In this case, artificial light for plant cultivation is needed, and a technique to reduce its energy and enhance its efficiency is also required [2]. It is also used in conjunction with renewable energy systems, such as offshore wind power generators incorporating plant cultivation systems [3]. In this case, it is important to maximize the energy efficiency by reducing the power consumption in plant cultivation. The light emitting diode (LED) is one of the most popular lighting devices because they have high efficiency, a long lifetime, and high controllability [4] compared to conventional lighting devices, such as cold cathode fluorescent lamps (CCFLs). Currently, LEDs with various wavelengths have been developed, and plant cultivation techniques based on these LED devices have been studied [5]. In this case, a light control system for LED devices is the most important component because it significantly affects the productivity and quality of the plants [6]. Therefore, it is very important to have a system that can control the optimum brightness depending on the plant. Especially, it is very important to control the brightness by considering the environmental factors because it affects the plants by combining the brightness of the LED and the ambient light.

In this paper, a power-controllable LED control system that can consider environmental factors is proposed for plant cultivation. The proposed LED system measures the ambient illuminance using an illuminance sensor for calculating the photosynthetic photon flux density (PPFD) and measures the plant–LED distance using an infrared sensor. Then, the ambient illuminance is converted into the

PPFD for plant cultivation, and it calculates the optimal pulse width modulation (PWM) using the target PPFD for the plant–LED distance and the ambient PPFD. In this case, the final PPFD is controlled by the PWM signal and, hence, the proposed system generates the optimal level of the PWM signal while also reducing power consumption.

This paper is organized as follows: Section 2 gives the background for plant cultivation and conventional LED systems. In Section 3 we describe the proposed adaptive LED control method. Section 4 shows the hardware implementation of the proposed method. In Section 5, we evaluate the performance of the proposed and conventional methods. Finally, in Section 6, we conclude the paper.

## 2. Background

Table 1 shows results for the effects of LEDs with various wavelengths on the plants [7–12]. Ref. [7] experimented with materials produced in lettuce using red and blue LEDs separately. Red LEDs (660 nm and 635 nm) increased the phenolic concentration, and blue LEDs (476 nm) increased anthocyanin and carotenoids. Ref. [8] showed an experiment on cabbage. Anthocyanin was increased when red LEDs (660 nm) were used alone, and petiole elongation was promoted with increasing chlorophyll when using only blue LEDs (470 nm). Ref. [9] experimented with lettuce and green onions using red LEDs (638 nm) and natural light, and nitrate was decreased. Several studies have also under way to promote plant growth using both red and blue LEDs [10–12]. In Ref. [10], anthocyanin content, antioxidant potential, and leaf area increased. Ref. [11] could slow down the flowering time of mustard and basil using red LEDs (660 and 635 nm) and blue LEDs (460 nm). In Ref. [12], the stem length was reduced by using red LEDs (660 nm) and blue LEDs (450 nm).

**Table 1.** Effects of light emitting diode (LEDs) with various wavelengths on the plant.

Reference	Plant	Light Source	Effect on Plant
[7]	Baby lettuce	Red LEDs (658 nm)	Increase of phenolics concentration
	Baby lettuce	Blue LEDs (476 nm)	Increase of anthocyanin and carotenoids
[8]	Cabbage	Red LEDs (660 nm)	Increase of anthocyanin content
	Cabbage	Blue LEDs (470 nm)	Higher chlorophyll content promotion petiole elongation
[9]	Lettuce, Green onions	Red LEDs (638 nm) Natural illumination	Reduction of nitrate content
[10]	Red leaf lettuce	Red LEDs (640 nm); Blue LEDs (440 nm)	Increase of anthocyanin content, antioxidant potential and total leaf area
[11]	Indian mustard, Basil	Red LEDs (660 and 635 nm); Blue LEDs (460 nm)	Delay in plant transition to flowering
[12]	Tomato seedlings	Red LEDs (660 nm); Blue LEDs (450 nm)	Reduction of stem length

Table 2 shows how different kintypesds of light sources affect plants. Specifically, Ref. [10] increased the anthocyanin, antioxidant potential, and leaf area of the lettuce when  $300 \mu\text{mol m}^{-2} \text{s}^{-1}$  was maintained using red LEDs (640 nm) and blue LEDs (440 nm). Ref. [13] increased vitamin C in mustard and spinach when  $300 \mu\text{mol m}^{-2} \text{s}^{-1}$  PPFD was maintained using red LEDs (638 nm) and high-pressure sodium (HPS) lamps. Ref. [14] increased phenolics, tocopherols, and antioxidant capacity of lettuce when maintained at a fixed value of  $210 \mu\text{mol m}^{-2} \text{s}^{-1}$  for LED and  $300 \mu\text{mol m}^{-2} \text{s}^{-1}$  for HPS under the same conditions as [13]. Ref. [15] increased total dry weight of the lettuce when maintained at 100, 200, and  $300 \mu\text{mol m}^{-2} \text{s}^{-1}$  using red LEDs (660 nm) and blue LEDs (450 nm). In conclusion, various wavelengths and intensities could affect plants directly or indirectly depending on the type of plants.

**Table 2.** Effects of light sources with the different photosynthetic photon flux density (PPFD) on the plant.

Reference	Plant	Light Source	PPFD ( $\mu\text{mol m}^{-2}\cdot\text{s}^{-1}$ )	Effect on Plant
[10]	Red leaf lettuce	Red LEDs (640nm); Blue LEDs(440nm)	LED: 300	Increase of anthocyanin content, antioxidant potential and leaf area
[13]	Mustard, Spinach	Red LEDs (638nm) and HPS lamp	Total: 300	Increase of vitamin C content
[14]	Baby lettuce	Red LEDs (638nm) and HPS lamp	LED: 210 HPS: 300	Increase of phenolics, tocopherols, antioxidant capacity, sugars
[15]	Lettuce	Red LEDs (660nm); Blue LEDs(450nm)	LED: 100 LED: 200 LED: 300	Increase of total dry weight

Figure 1 shows specific experimental results for 50 days that compare plant cultivation using sunlight and LED light of various wavelengths [16]. LED light is classified into red, blue, and combined red and blue wavelengths. In these experimental results, the growth rates of different plants were most highly influenced by the various conditions of light. Specifically, when looking at the plant height (stem length) results, camella grew the largest in sunlight, while melany showed the best efficiency when red and blue LEDs were used together. In terms of leaf area, both camella and melany crops showed the highest efficiency when combined with red and blue LEDs. This suggests that the optimal wavelength for the plants should be changed according to each plant and that the combination of red and blue LEDs has the best tendency.

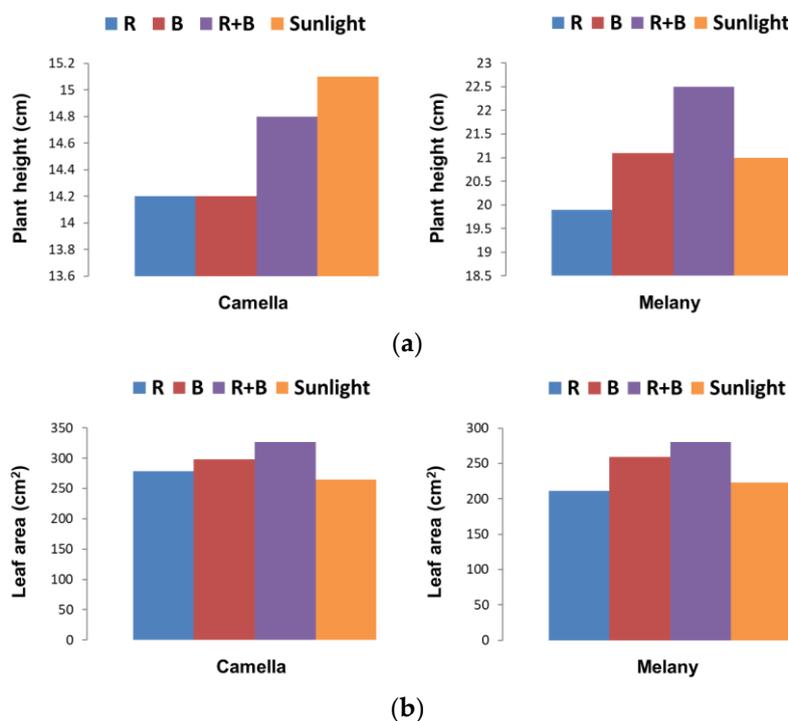
**Figure 1.** Comparison of plant growth using sunlight and LED lights [16].

Figure 2 shows experimental results for the growth of the leaf area and number of leaves in three *Lycoris* species for various illuminance [17]. In these results, different illuminance was required according to the plant species, and high illuminance was always detrimental to plants. Therefore,

controlling the wavelength and intensity of light is a basic requirement for various plant cultivation. In this case, Since PPFD is used for plant growth, the PPFD must be controlled when controlling LEDs.

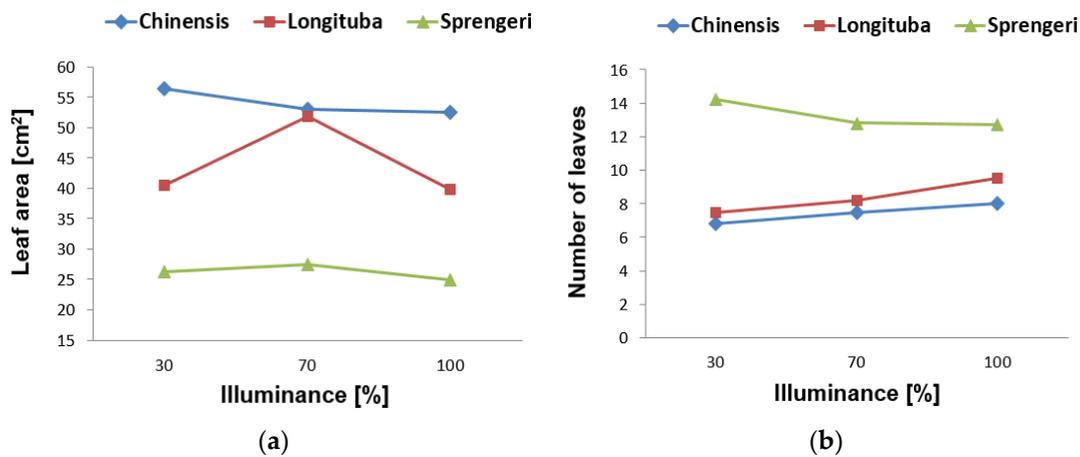


Figure 2. Comparison of plant growth according to illuminance [17].

Conventional LED systems always emit a fixed amount of PPFD and, hence, they cannot maintain the amount of PPFD required by a plant considering environmental factors such as the ambient PPFD and distance between the plant and LED system (plant–LED distance). Therefore, in some cases, a conventional LED system emits an excessive amount of PPFD, thereby consuming excessive power. Specifically, the LED system of [18] controls the PWM, but it cannot consider total PPFD adaptively and, thereby, is difficult to use for various plants. Therefore, it cannot emit the optimal PPFD considering the plant properties and consumes excessive power. The systems of [19,20] use bar-type arrays with red and blue LEDs for plant cultivation. However, they also cannot control the PPFD according to changes in environmental factors, thereby inefficiently consuming power. In other approaches, [21] analyzed the spectral characteristics of two white LEDs and analyzed the growth of plants using each LED. In addition, [22] proposed a system that defines parameters that affect growth and adaptively controls these parameters. Ref. [2] reduced power by optimizing the spectral parameters of the LED. Specifically, in order to optimize the spectral parameters, it compared the energy efficiency in the target illumination system with different red and blue ratios of the LEDs.

In order to solve the problems of the above-mentioned systems and utilize the advantages, the proposed system enables controlling the wavelength of red and blue LEDs. It can also reduce power according to the target PPFD by using information from environmental change sensors. In addition, considering the ratio of exhaustion of non-renewable resources based on environmental sustainability and industry sustainability, a system should be developed that is more efficient than existing systems [23–25]. The proposed LED system will contribute to the growth of plants, preserve biodiversity and ecosystems, and consider sustainability with high efficiency compared to existing light sources.

### 3. Proposed Adaptive LED Control Method

Figure 3 shows the overall block diagram of the proposed adaptive LED control method. First, the proposed system measures the plant–LED distance using an infrared sensor and also measures the ambient illuminance using an illuminance sensor. Then, the illuminance is converted into PPFD for plant cultivation. It then calculates the optimal PWM using the target PPFD for the plant–LED distance and the ambient PPFD. In this case, the PPFD is controlled by the PWM signal and, hence, the proposed system generates the optimal level of the PWM signal considering the plant–LED distance and ambient PPFD. The specific operation of the proposed method shown below.

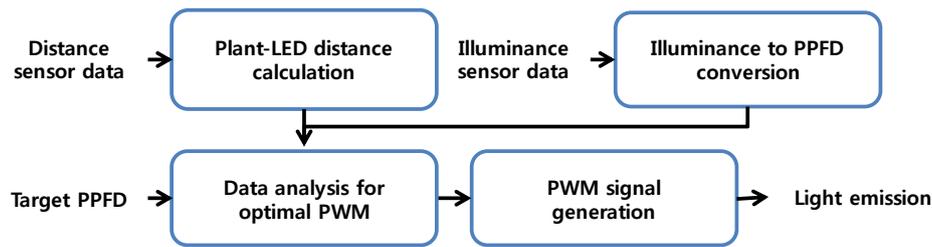


Figure 3. The proposed adaptive LED control method.

### 3.1. Illuminance to PPFD Conversion

Illumination is suitable for human eyes and cannot measure the effect on plants. Therefore, in order to consider plant growth, the illumination should be changed to PPFD. Table 3 shows the illuminance per PPFD [26]. PPFD can be converted using illuminance data and conversion factors. Especially, the proposed system requires these conversion factors because it provides a constant environment for plants considering both the sunlight and LED PPFD. Illuminance to PPFD conversion is as follows:

$$\begin{aligned} PPFD^S &= \frac{I^S}{C^S} \\ PPFD^R &= \frac{I^R}{C^R} \\ PPFD^B &= \frac{I^B}{C^B} \end{aligned} \quad (1)$$

where  $I^S$ ,  $I^R$ , and  $I^B$  denote the sunlight, red LED, and blue LED illuminance data, respectively.  $C^S$ ,  $C^R$ , and  $C^B$  denote the sunlight, the red LED, and the blue LED conversion factor, respectively. PPFD is simply calculated by the conversion factor from Table 3.

Table 3. The conversion from lux to PPFD varies under different light sources [26].

Light Source	Sunlight	Incandescent	Fluorescent Lamp	Red LED	Blue LED
Conversion factor	54.0	50.0	74.0	9.9	11.9

### 3.2. Inverse Square Law

The inverse square law [27] is a property that the intensity of light is inversely proportional to the square of the distance. We use this law to reflect the relationship between illumination and distance in the proposed system. It is defined as follows:

$$I^L = \left( \frac{1}{D_{P-L}} \right)^2, \quad (2)$$

where  $I^L$  denotes the total LED illuminance and  $D_{P-L}$  denotes the plant–LED distance.

We derive Equation (3) from Equation (2) to define the relationship between light and distance as follows:

$$I_{can}^L \times D_{can}^2 = I_{ref}^L \times D_{ref}^2, \frac{I_{can}^L}{I_{ref}^L} = \left( \frac{D_{ref}}{D_{can}} \right)^2, I_{can}^L = \left( \frac{D_{ref}}{D_{can}} \right)^2 \times I_{ref}^L, \quad (3)$$

where  $I_{ref}^L$  and  $D_{ref}$  denote the reference LED illuminance and the reference distance (1 m), respectively. In addition,  $I_{can}^L$  and  $D_{can}$  denote the candidate LED illuminance and the target distance, respectively.

### 3.3. PPF D Consideration

The proposed system converts the illuminance of Equation (3) into PPF D using Equation (1) because the plant should consider the appropriate PPF D. First, in the formula defined in Equation (3),  $I^L$  is the total light quantity of LED, so it is the same as Equation (4):

$$\begin{aligned} I_{can}^L &= I_{can}^R + I_{can}^B \\ I_{ref}^L &= I_{ref}^R + I_{ref}^B \end{aligned} \quad (4)$$

where  $I_{ref}^R$  and  $I_{ref}^B$  denote the reference illuminance of the red and blue LEDs, respectively.  $D_{ref}$  denotes the reference distance (1 m). In addition,  $I_{can}^R$  and  $I_{can}^B$  denote candidate illuminance of the red and blue LEDs, respectively.  $D_{can}$  denotes the candidate distance.

Using the conversion factor, the red and blue illuminance in Equation (4) is converted to Equation (5), which is the PPF D value:

$$\frac{I_{can}^R}{C_{can}^R} + \frac{I_{can}^B}{C_{can}^B} = \left(\frac{D_{ref}}{D_{can}}\right)^2 \times \left(\frac{I_{ref}^R}{C_{ref}^R} + \frac{I_{ref}^B}{C_{ref}^B}\right), PPF D_{can}^L = \left(\frac{D_{ref}}{D_{can}}\right)^2 \times PPF D_{ref}^L \quad (5)$$

where  $PPFD_{can}^L$  and  $PPFD_{ref}^L$  denote the candidate PPF D of the LEDs and the reference PPF D of the LEDs, respectively.

$$PPFD^T = PPF D_{can}^L + PPF D^S, \quad (6)$$

where  $PPFD^T$  and  $PPFD^S$  denote the target total PPF D and sunlight PPF D, respectively.

### 3.4. Optimal PWM Determination

After analyzing the data, the PWM signal levels should be determined for various distances and sunlight PPF D after the target PPF D has been determined. First, the final PPF D is determined when the difference between the target and candidate PPF Ds are minimized as follows:

$$i_p^F = \underset{i_p}{\operatorname{argmin}} \left\{ PPF D_{tar}^T - PPF D^T(i_p, i_d) \right\}, \quad (7)$$

where  $i_p$  and  $i_d$  denote the indices of the PWM signal level and the distance, respectively. In addition,  $PPFD_{tar}^T$  and  $i_p^F$  denote the total target PPF D and the optimal PWM. Using  $i_p^F$ , we can control the LEDs to match the target PPF D.

## 4. Hardware Implementation

Figure 4 shows the overall system, which is divided into the LED arrays, metal–oxide–semiconductor field–effect transistors (MOSFETs), gate driver integrated circuits (ICs), a microcontroller, and the power supply and conversion. As shown in the figure of LED arrays, one line consists of 12 LEDs ( $4 \times 3$  LEDs). In order to meet the electrical specification, one LED is actually modeled as three in the circuit schematic. The wavelengths of the red and blue LEDs are 660 nm and 460 nm, respectively. Their electrical specifications are 2.4 V and 90 mA (red LED) and 2.6 V and 90 mA (blue LED) and, hence, the proposed system consumes almost 40 W power for the LEDs. To control the LED PPF D, a micro-controller and MOSFET-based switching circuit are used. For the micro-controller, an Arduino Mega in an ATmega is used and the adaptive PPF D control method is implemented in software. Specifically, the PWM signal is changeable to match the target PPF D, and the microcontroller controls the duty cycle of the signal, which can vary from 0 V to 5 V in a square form with a frequency of 980 Hz. After the micro-controller generates the PWM signal, considering the plant–LED distance and ambient PPF D, the voltage of its PWM signal switches the MOSFET on or off, thereby controlling the current flow and LED PPF D. The gate driver and

buffer are to prevent the effects of the inverse current and inverse voltage on the microcontroller. The DC-DC convertor converts 12 V, which is for the LED driving voltage, into 5 V for the voltage of control part. In addition, cooling fans were installed to prevent the system from overheating. Each fan operates at 1800 RPM to dissipate heat and each fan consumes additional power of 1.2 W. The power consumption, except for that of the LED array, is almost 12 W and, hence, the power consumption of the total system is 52.5 W.

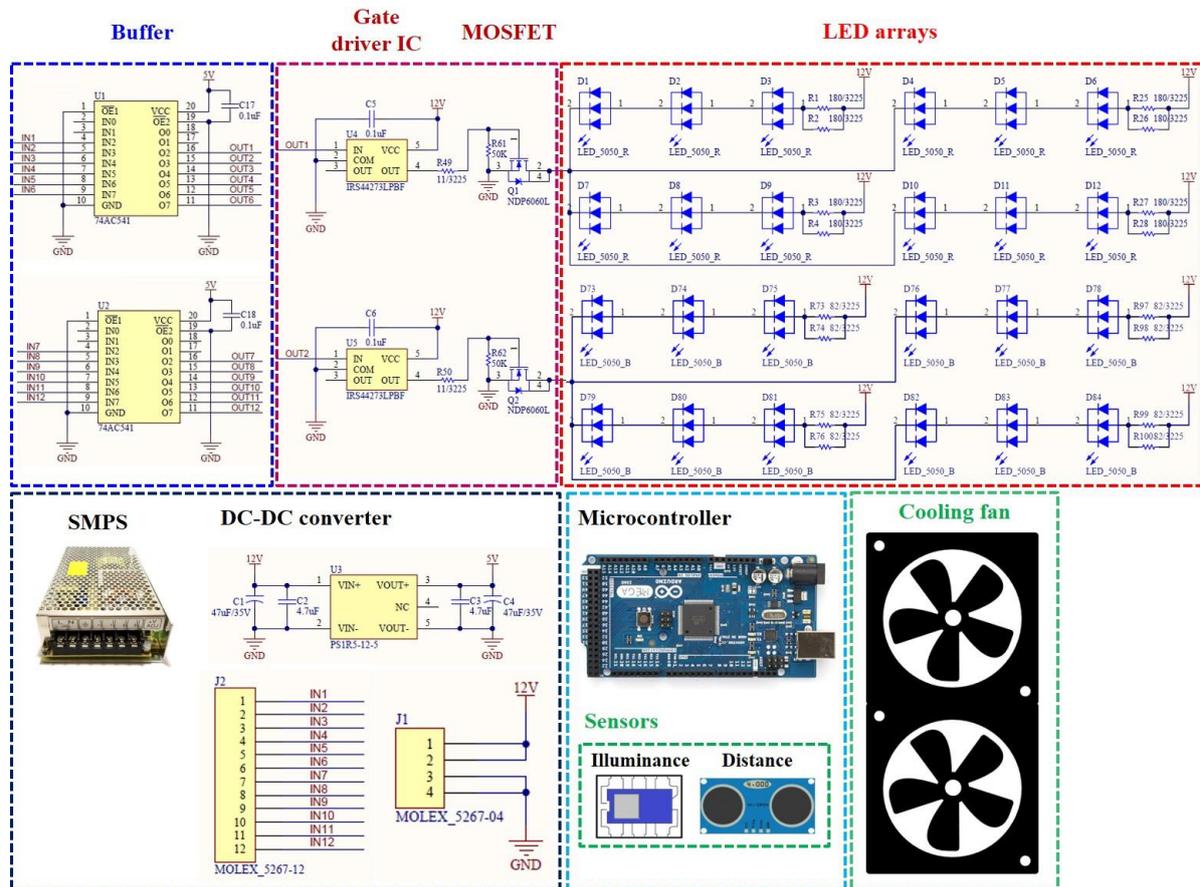
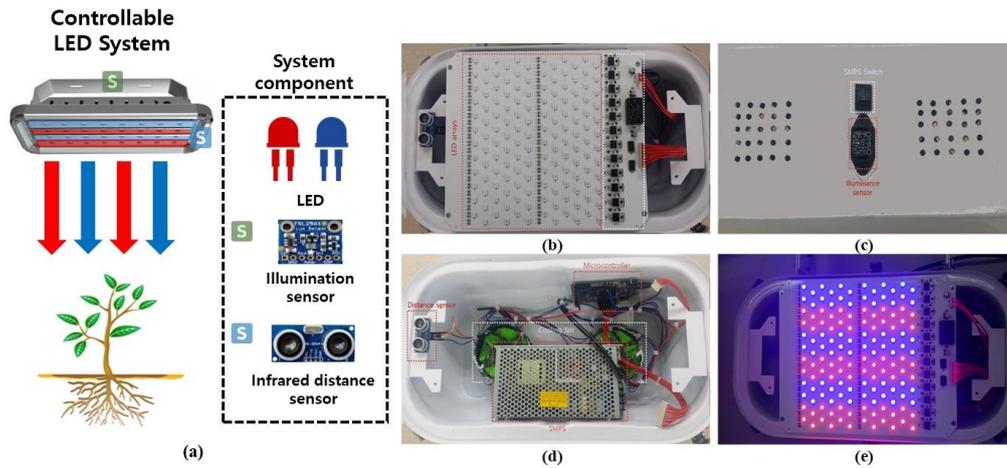


Figure 4. The overall circuit diagram of the proposed system.

Figure 5 shows the implemented prototype of the proposed system. The proposed system uses a stainless steel case to enhance its thermal conductivity. Figure 5a shows the concept of the proposed system. The front side (Figure 5b) consists of the LED array and MOSFETs, and the back side (Figure 5c) has the operation switch and illumination sensor that measures the ambient illumination. The inner part (Figure 5d) contains the microcontroller, switching mode power supply (SMPS), infrared distance sensor, and cooling fan for the system. In the proposed system, the components, except the LEDs, consist of a module for the LED control unit and a cooling fan. The cooling fan increases power consumption, but they are indispensable to the stability of system operation. Specifically, active fans are used to reduce the high temperatures caused by the heat of the LED array and switched-SMPS. Using these system modules, the proposed system can control the red and blue LEDs according to the environmental conditions, as shown in Figure 5e.



**Figure 5.** Implemented prototype of the proposed system: (a) overall system; (b) front side; (c) back side; (d) functional modules; and (e) system operation.

## 5. Experiment Result

### 5.1. Power Model

For the power measurement, the illuminance to power conversion model [28] was used:

$$P_{(W)} = \frac{\phi_v(lm)}{\eta(lm/W)} \quad (8)$$

In this case, the proposed system uses PPFD, where the unit is  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (micromoles per  $\text{m}^2$  per second), but this model is based on the luminous flux, where the unit is lumens. Therefore, first, the PPFD should be converted into illuminance ( $I_v$ ) as follows:

$$I_{V(lum)} = I_{PPFD(\mu\text{mol m}^{-2} \text{s}^{-1})} \times C \quad (9)$$

where  $I_{PPFD}$  and  $C$  denote the PPFD and conversion factor, respectively. Then, the illuminance ( $I_v$ ) should be converted into luminous flux ( $\phi_v$ ) using the following equation:

$$\phi_v(lm) = I_{V(lum)} \times A_{(m^2)} \quad (10)$$

Finally, using Equation (4), the power can be calculated as follows:

$$P_{(W)} = \frac{I_{PPFD(\mu\text{mol m}^{-2} \text{s}^{-1})} \times A_{(m^2)}}{\eta(lm/W) \times \alpha} \quad (11)$$

where  $\eta$  denotes the luminous efficacy, which is the efficiency when the source provides visible light from electricity. The luminous efficacy of the red LEDs was 50 lm/W, and the luminous efficacy of blue LEDs was 26 lm/W in the proposed system.

### 5.2. Power Consumption Evaluation

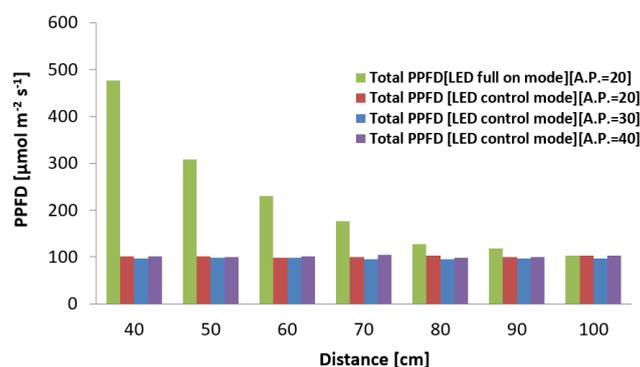
Table 4 shows the specific experimental data for various plant–LED distances and ambient PPFD levels. In addition, the proposed system was also compared with a conventional system that cannot consider the plant–LED distance and ambient PPFD. Specifically, the conventional system could not control the LED PPFD and, hence, the PPFD was significantly increased when the plant–LED distance was small. The maximum PPFD was  $496 \mu\text{mol m}^{-2} \text{s}^{-1}$ , which was almost eight times higher than the target PPFD. On the other hand, the proposed LED system could control the PPFD considering the

environmental conditions and, hence, the target PPFD was maintained and power consumption was changed from 17 to 52.5 W.

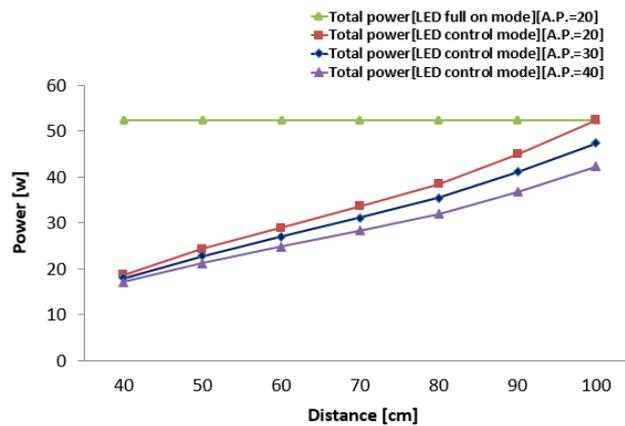
**Table 4.** pulse width modulation (PWM) signal and power consumption when the distance between a plant and the proposed LED system and ambient PPFD is changed.

Ambient PPFD ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Distance (cm)	Conventional System			Proposed System		
		PWM	Power (W)	Total PPFD ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	PWM	Power (W)	Total PPFD ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )
20	100	255	52.5	101	255	52.5	101
	80	255	52.5	127	140	34	102
	60	255	52.5	230	110	28.9	99
	40	255	52.5	476	45	18.7	101
30	100	255	52.5	111	223	47.4	97
	80	255	52.5	137	122	31.1	95
	60	255	52.5	240	96	27	98
	40	255	52.5	486	39	18	97
40	100	255	52.5	121	191	42.3	102
	80	255	52.5	147	105	28.4	98
	60	255	52.5	250	82	24.7	101
	40	255	52.5	496	33	17	101

In Figures 6 and 7, A.P. in the figure means the ambient PPFD. First, Figure 6 compared PPFDs for LEDs with the conventional full-on and proposed modes in the proposed system. When A.P. was  $20 \mu\text{mol m}^{-2} \text{s}^{-1}$  and the LEDs were fully on, the conventional mode emitted  $476 \mu\text{mol m}^{-2} \text{s}^{-1}$ , which is an excessive amount in some cases. On the other hand, the proposed mode maintained  $100 \mu\text{mol m}^{-2} \text{s}^{-1}$  even though A.P. was changed and the distance from the device to the plant was changed. These results show that the proposed method could reduce the power compared to the conventional method while providing the PPFD suitable for the plant. Figure 7 compared the total power consumed in the proposed system in various situations. The results show that the LED full on mode consumed 52.5 W, which was the maximum output power, regardless of the distance, but the proposed method could reduce the total power of the system according to the ambient light intensity and distance.

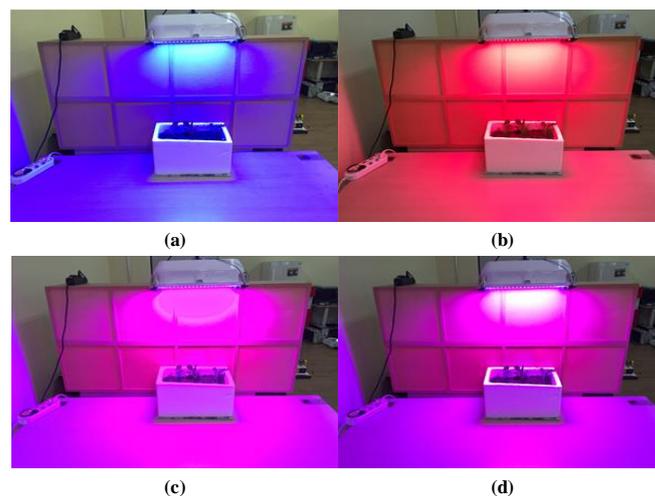


**Figure 6.** Total PPFD comparison according to various distances and ambient PPFD.

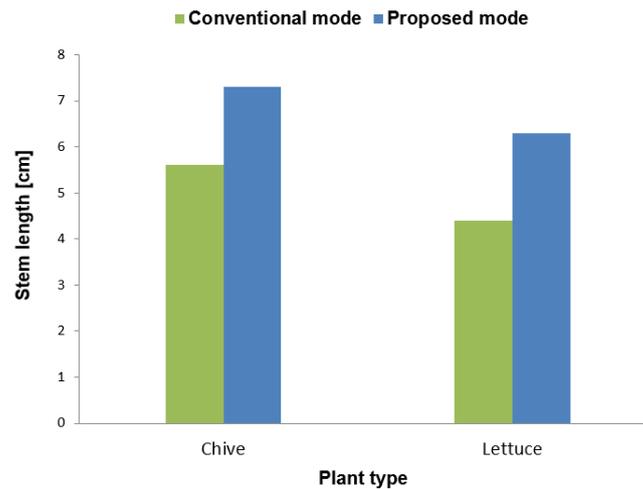


**Figure 7.** Total power comparison according to various distances and ambient PPFD.

Figure 8 shows the changes in the wavelength that the proposed system can emit in a plant cultivation environment. In the proposed system, red or blue LEDs could be operated individually, and red and blue LEDs could be operated simultaneously. Figure 8 shows that an arbitrary wavelength could be emitted as an example of the above. In addition, a plant growth experiment was conducted to estimate the growth of lettuce and leek using the proposed system in the actual room. When referring to [29], the result of 24/0 (light/dark) was better than those of 6/18 (light/dark), 9/15 (light/dark), 12/12 (light/dark), and 18/6 (light/dark) in terms of the growth for stem length and leaf area. We also controlled PWM signals according to the ambient light throughout the 24-h period over two weeks, and emitted a PPFD of  $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ . As a result, as shown in Figure 9, it was confirmed that the leek was raised to 5.6 cm and the lettuce grew 4.4 cm in the sunlight environment. However, when the proposed system was used, it was confirmed that the leeks grew by 7.3 cm and the lettuce grew by 6.3 cm. Therefore, it was confirmed that the average degree of plant growth was improved by 2 cm. This experiment was the result of two weeks. In order to increase the reliability, additional factors to judge the growth of plants, such as chlorophyll content and leaf area, will be needed in future work.

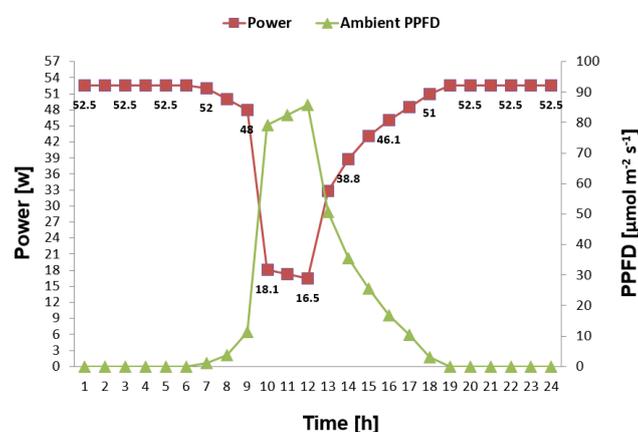


**Figure 8.** Plant cultivation test for the proposed LED control system using red/blue LED PWM signals: (a) 0/255; (b) 255/0; (c) 128/128; and (d) 255/255.



**Figure 9.** Plant cultivation comparison between conventional and proposed modes over two weeks.

In terms of power consumption, the proposed system could change the power consumption from 16.5 W to 52.5 W as shown in Figure 10. Specifically, in the indoor environment, the PPFD could vary greatly depending on the ambient illumination. The proposed system supplied the PPFD to the plant in accordance with this. Power consumption was high until 18:00, and low until 08:00, when the room was not lit, while the lighting was controlled from 09:00 to 17:00 according to the indoor lighting environment to reduce power and provide a constant PPFD to the plants. In the power consumption, the conventional system consumed 625 Wh because they did not control LEDs all day, but the proposed method could reduce the power by 167 Wh per day from 07:00 to 18:00. This result can be expected to vary by season or by weather impact, but can be reduced by approximately 60 kWh over a year.



**Figure 10.** Power consumption with respect to the different ambient PPFDs for a fixed distance of 0.9 m.

## 6. Conclusions

This paper proposed a novel LED control system that considers environmental factors for plant cultivation. The proposed system used an infrared sensor and illuminance sensor to measure the plant–LED distance and ambient illuminance, respectively. Then, the ambient illuminance was converted into PPFD for the plant cultivation. It calculated the optimal relationship between the environmental factors and LED PPFD. For the hardware implementation, red and blue LED arrays were used. In addition, MOSFET-based switching circuits, a microcontroller, and cooling fans were used. In experiments using the implemented hardware, the proposed LED system maintained the

target PPFd even though the distance and ambient PPFd were changed. In addition, the power consumption of the proposed system was maximally 68% lower than that of the conventional system.

The proposed system increased the efficiency of renewable resources in terms of environmental sustainability. In addition, LED power could be adjusted to optimize the power consumption according to the plant. Since the ambient PPFd was taken into consideration, energy efficiency over time also increased and industry sustainability could be considered. In addition, the proposed system was a system with high power efficiency. However, recognizing any plant and automatically outputting the optimized wavelength will help to increase power efficiency and plant growth. Additionally, because it uses only distance and ambient light sensors, it can be vulnerable to growing plants that are sensitive to humidity or temperature conditions. Further research is needed on these subjects. In the future, various solutions to the food shortage problem will be needed. Research on plant growth will continue as a promising method.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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