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System Design and Performance Analysis of a Variable Frequency LED Light System for Plant Factory

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Abstract

Purpose: The purpose of this study was to design a variable frequency LED light system for plant factory which combined red, blue, green, white, and UV lights and controlled the ratio of the light wavelength. In addition, this study evaluated the performance of each combination of LED to verify the applicability. **Methods:** Four combinations of LED (i.e. Red+Blue, Red+Blue+Green, Red+Blue+White, Red+Blue+UV) were designed using five types of LED. The system was designed to control the duty ratio of each wavelength of LED by 1% interval from 0~100%, the pulse by 1Hz interval from 1~20kHz. Response characteristics of the control system, spectral distribution of each combination, light uniformity and uniformity ratio were measured to test the performance of the system. **Results:** Clean waveforms were measured from 10Hz to 10kHz regardless of duty ratio. Frequency distortion was observed within 5% of inflection point at frequencies above 10kHz regardless of duty ratio, but it was judged negligible. Spectra showed a normal distribution, and maximum PPF with duty ratio of 100% was 271.4$\mu mol \cdot m^{-2} \cdot s^{-1}$ for the Red+Blue combination. PPF of the Red+Blue+Green combination was 258.9$\mu mol \cdot m^{-2} \cdot s^{-1}$, and that of the Red+Blue+White combination was 273.9$\mu mol \cdot m^{-2} \cdot s^{-1}$. PPF of the Red+Blue+UV combination was 267.7 μmol·m-2·s-1. Uniformity ratio for the area excepting border showed 0.90 for the Red+Blue and Red+Blue+White combinations, 0.87 for the Red+Blue+Green combination, and 0.88 for the Red+Blue+UV combination. The light was irradiated evenly at the area excepting border, so it was suitable for plant growing. **Conclusions:** From the results of this study, response characteristics of the control system, spectral distribution of each combination, light uniformity and uniformity ratio were suitable for applying into the plant factory.

Keywords: Duty-ratio, LED lighting system, Light uniformity, PPF, Variable frequency

Introduction

The closed-type plant factory provides stable and controlled growth conditions to produce high-quality agricultural products; therefore, the plant factory facilitates plant growth and prevents pests and outside air by increasing the light utilization efficiency (Kozai, 2007).

Conventional plant factory has used metal halide lamps or fluorescent lamps whose wavelengths were distributed evenly over the visible range (Kozai, 2007; Tadahisa et al., 2004). Recently, LED (Light-emitting diode) lamps have been widely used due to their advantages over conventional lamps: the LED lamps are energy efficient, have long lifetime, and have a simple drive circuit to make specified light quality (Hwang et al., 2004).

Numerous studies have been conducted on the plant factory using LED lamps: studies on the effects of light quality on growth of various greenhouse crops (Nishimura et al., 2006(a), 2007(b); 2009(d); Shin et al., 2012; Warrington and Mitchell, 1976; Mortensen and Stromme, 1987; Inada and Yabumoto, 1989; Pack et al, 2013), studies on plant growth with red light (Nishimura et al., 2006(a), 2009(d); Nishioka et al., 2008), and studies on plant growth with blue light (Giliberto et al., 2005; Ramalho et al., 2002; Meng et al., 2004). However, more studies on

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the green light and white light are needed (Park et al., 2012).

Recently studies on functional components (i.e. anthocyanin) and UV wavelength have gained attention (Nishimura et al., 2008; Hrazdina and Creasy, 1979; Oh et al., 2009; Odiddge et al., 2010; Tsormpatsidis et al., 2008; Li and Kuboda, 2009, Kataoka et al., 2003; Khare and Guruprasad, 1993). The purpose of this study was to design a variable frequency LED light system for plant factory which combined red, blue, green, white, and UV light and controlled the ratio of the light wavelength. In addition, this study evaluated the performance of each combination of LED to verify the applicability.

Materials and Methods

LED light system

Chlorophyll a absorbs light most strongly at the wavelengths of 440nm and 660nm, and chlorophyll b at 470nm and 640nm. Therefore, the LED system for this study used 660nm for chlorophyll a, 450nm for chlorophyll b, and 530nm for the wavelength working as a signal in growing and physiological function. In addition, UV of 395nm was used to examine its effects in producing functional components. White LED composed of 440nm, 555nm, and color temperature of 6,500K were used to examine their effects.

Light intensity was investigated to design the light sources. Light saturation point of leafy vegetables was at a photosynthetic photon flux (PPF) of 150~300μmol·m^{-2}·s^{-1}, and light compensation point was at a photosynthetic photon flux (PPF) of 4~18 μmol·m^{-2}·s^{-1} (Watanabe, 2006). The system was designed to keep a 70% level of the light saturation point of leafy vegetables and maintain the intensity at the distance of 300mm away from the LED lamp.

The basic ratio of each wavelength was set as 8:1:1, but different light absorptivity caused by different target crops and environment was not considered. LED lamps were arranged evenly for each wavelength considering the characteristics of the LED package provided by the manufacturer.

The size of the LED light source was 1,400mm (width) * 850mm (height), and 30 LED bars was used (900 LED lamps were used on each plate). In addition, four wavelength combinations of the light source (Table 1) were made to identify the optimal light source.

Table 1. LED light sources by wavelength combination

Type	1		2			3			4		
LED wavelength	R	B	R	B	G	R	B	W	R	B	U
LED ratio	8	2	8	1	1	8	1	1	8	1	1

※ R: Red-660nm, B: Blue-450nm, G: Green-530nm, W: White 6500k, U: UV-395nm

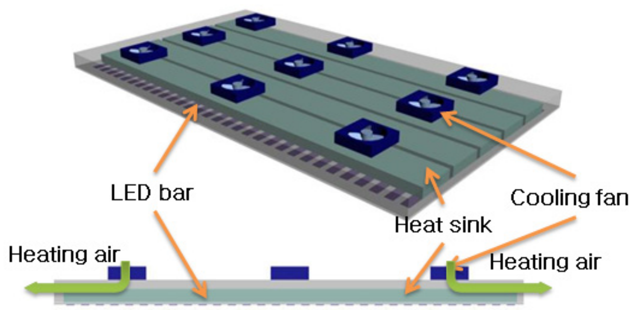


Figure 1. Schematic showing cooling fan and heat sink of LED lighting system.

The LED packages used for the light source should have similar electrical characteristics for control design; therefore, middle LED package (Hana Micron Inc., Seoul, Korea) was used for the red (HL-L650R), green (HL-L650G), blue (HL-L650B), and white (HL-L650W) LEDs. Another LED package (Seoul Viosys, Ansan, Korea) was used for the UV (CUN9AF1A) LED.

Each LED combination was arranged uniformly, and four-layer PCB was made to control pulse and duty ratio of each type of LED.

Two-layer LED light source needed maximum 300W power supply, which may influence on the bed above the LED. Therefore, the LED bar was fixed on a 5mm thick aluminum plate, and a five-column heat sink was attached on the opposite of the plate to keep the system from overheating by absorbing and dissipating the heat into the air. The fan for forced convection also was installed on the top to disperse the heated air to the outside through the side hole (Figure 1).

Light source control system

A control system was designed to examine the influence of light intensity and pulse. The system was designed to control the duty ratio of each wavelength of LED by 1% interval from 0~100%, and it also controlled the pulse by 1Hz interval from 1~20kHz. The system was composed of a power supply unit, a processor unit, a display unit, an input unit, an output unit (Figure 2).

A 150W troidal-transformer (Model: ATRD150-2112B; Asea Electric, Seoul, Korea) with dual tap was used for the power supply unit to supply DC 72V power stably through AC-DC switching. In addition, ±10V power for Op-amp, 5V voltage regulator (LM2596, Texas Instruments, Texas, USA) for other devices (e.g. LCD), and 3.3 V voltage regulator (LM2930, National Semiconductor, California, USA) for MCU were used.

The processor unit (MCU) used a 32-bit ARM Cortex MCU (STM32F103R, STMicroelectronics, Texas, USA) because it provided 512kB flash memory, USB and CAN communication, 11 timers, three ADCs, and 13 communication interfaces. The MCU was designed to control duty ratio and LCD, to implement PWM, and to enable serial communicate with USB.

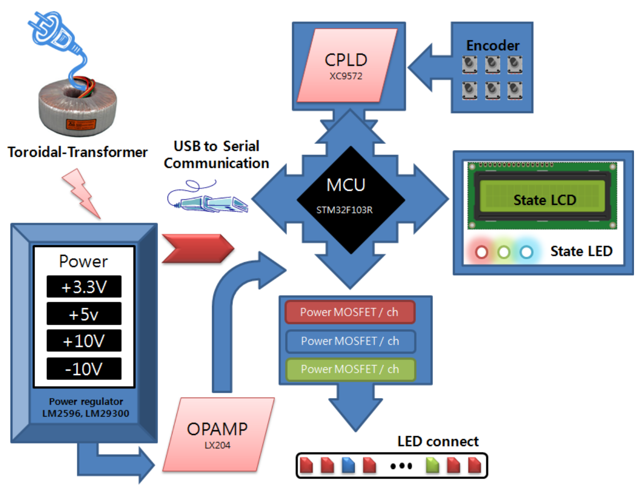


Figure 2. Block diagram of control-board for LED lighting system.

The display unit was designed to check the stable power supply with LED power indicator, and the LCD with built-in backlight which displaying duty ratio value and pulse width of each LED inputted by encoder or serial communication.

The input unit was designed to transmit pulse and duty ratio value for LED control into MCU in two ways: a way using six encoders on the control board and a way via serial communication. The PWM and duty ratio value were inputted using encoder and transmitted into the MCU by Complex Programmable Logic Device (CPLD: XC9572, Xilinx Inc., California, USA), and it detected the direction of the encoder and counting. Data via serial communication were inputted by serial communication with USB.

The output unit transmitted PWM signals generated from the MCU into LED module using MOSFET to control 65V voltages. The MOSFET was designed using IRFR9120N of P-channel and IRF730 of N-channel, and it controlled each wavelength of LED.

Experimental procedures

Control tests of LED bar were performed by changing duty ratio data and pulse of each wavelength. Oscilloscope with 40MHz bandwidth and 500MS·s^{-1} sample rate (TDS1001B, Tektronix, USA) measured waveform to test performance of the control system. The pulse was measured by four levels (10Hz, 100Hz, 1kHz, and 10kHz), and duty ratio was measured with sample of 10, 50, and 90%.

Spectra of four combinations were measured using a spectrometer (AvaSpec-2048, Avantes, Colorado, USA) with LED frequency of 2.5kHz and duty ratio of 50% at a distance of 450mm from the light source in order to find

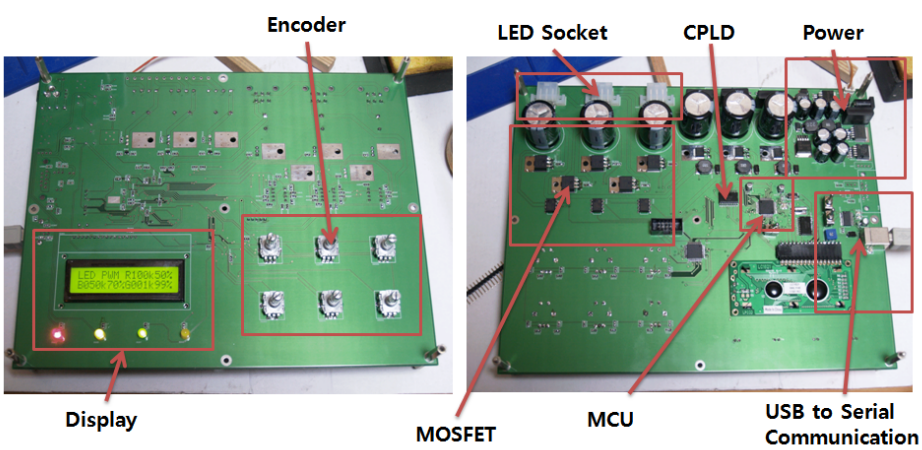
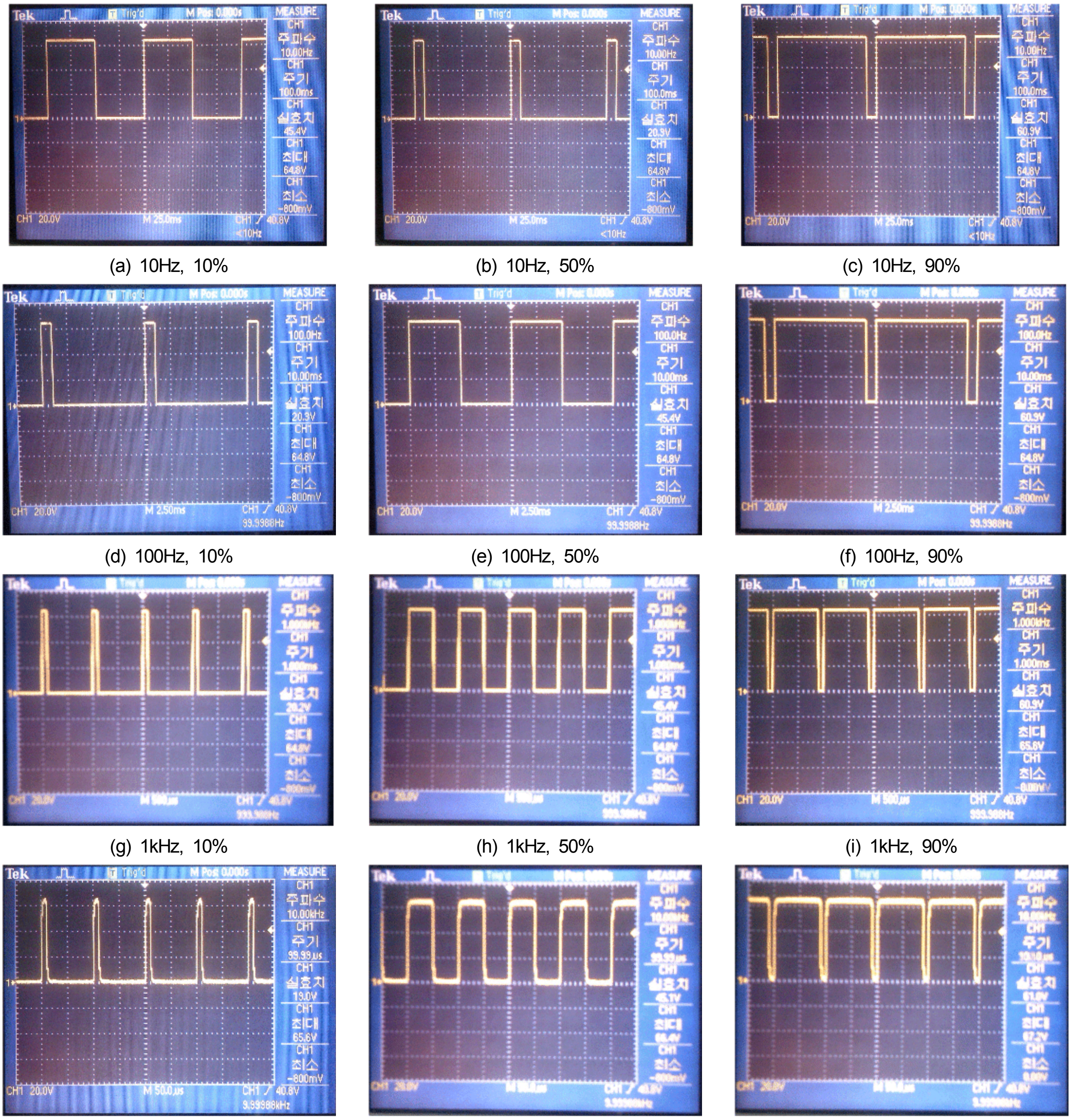


Figure 3. Controller of LED lighting system.

out the spectral characteristics of the LED.

In order to investigate maximum PPF, quantum light-meter (LI-250A, Li-cor, Nebraska, USA) was used with duty ratio of 100% at the center of the light source and the distance of 450 mm from the light source. In addition, five LEDs were measured by increasing the duty ratio by 5% to investigate the PPF changes based on the duty ratio.

Light uniformity was checked to see if the light was irradiated evenly. The light uniformity was defined as a ratio of the minimal to maximum PPF of the space assessed. PPF was measured with LED frequency of 2.5kHz and duty ratio of 50% at the distance of 450mm from the light source after dividing the area into seven points horizontally and five points vertically. Light uniformity was presented by whole area and by the area excepting border.



(a) 10Hz, 10% (b) 10Hz, 50% (c) 10Hz, 90%
(d) 100Hz, 10% (e) 100Hz, 50% (f) 100Hz, 90%
(g) 1kHz, 10% (h) 1kHz, 50% (i) 1kHz, 90%
(j) 10kHz, 10% (k) 10kHz, 50% (l) 10kHz, 90%

Figure 4. Response characteristics of LED lighting system by frequency and duty-ratio.

Results and Discussion

Response characteristics of the control system

Figure 4 shows the waveform measured by oscilloscope to investigate response characteristics of the control system. Clean waveforms were measured from 10Hz to 10kHz regardless of duty ratio. Frequency distortion was observed within 5% of inflection point at frequency above 10kHz regardless of duty ratio, but it was judged negligible because included in the tolerance range of the controller.

Spectral distribution

Figure 5 shows the spectral distributions of four LED combinations. Peak points were observed from red light (660nm) and blue light (450nm), but green light (530nm) showed broad spectral range which needs to be controlled. White light showed low spectral output, and this was caused by current LED manufacturing technology. UV light (395nm) showed the peak point. The results were satisfactory in all combinations

Photosynthetic photon flux (PPF)

Maximum PPF with duty ratio of 100% was 271.4μmol·m^{-2}·s^{-1} for the Red+Blue combination, and minimum PPF was 258.9μmol·m^{-2}·s^{-1} for the Red+Blue+Green combination. Low spectral output of green LED caused the minimum PPF with the Red+Blue+Green combination. PPF of the Red+Blue+White combination was 273.9μmol·m^{-2}·s^{-1}, and that of the Red+Blue+UV combination was 267.7μmol·m^{-2}·s^{-1}. The Red+Blue combination with frequency of 2.5 kHz and duty ratio of 50% showed maximum PPF of 164.7 μmol·m^{-2}·s^{-1}, minimum of 87.0μmol·m^{-2}·s^{-1}, and average of 129.7μmol·m^{-2}·s^{-1}. With the same conditions the Red+Blue+Green combination showed maximum PPF of 161.8 μmol·m^{-2}·s^{-1}, minimum of 86.4μmol·m^{-2}·s^{-1}, and average of 123.3μmol·m^{-2}·s^{-1}, while the Red+Blue+White combination showed maximum PPF of 160.9μmol·m^{-2}·s^{-1}, minimum of 74μmol·m^{-2}·s^{-1}, and average of 119.4μmol·m^{-2}·s^{-1}. In addition, the Red+Blue+UV combination showed maximum PPF of 163.3μmol·m^{-2}·s^{-1}, minimum of 81μmol·m^{-2}·s^{-1}, and average of 123.8μmol·m^{-2}·s^{-1}.

The Red+Blue combination with duty ratio of 50% showed maximum PPF, and the Red+Blue+White combination

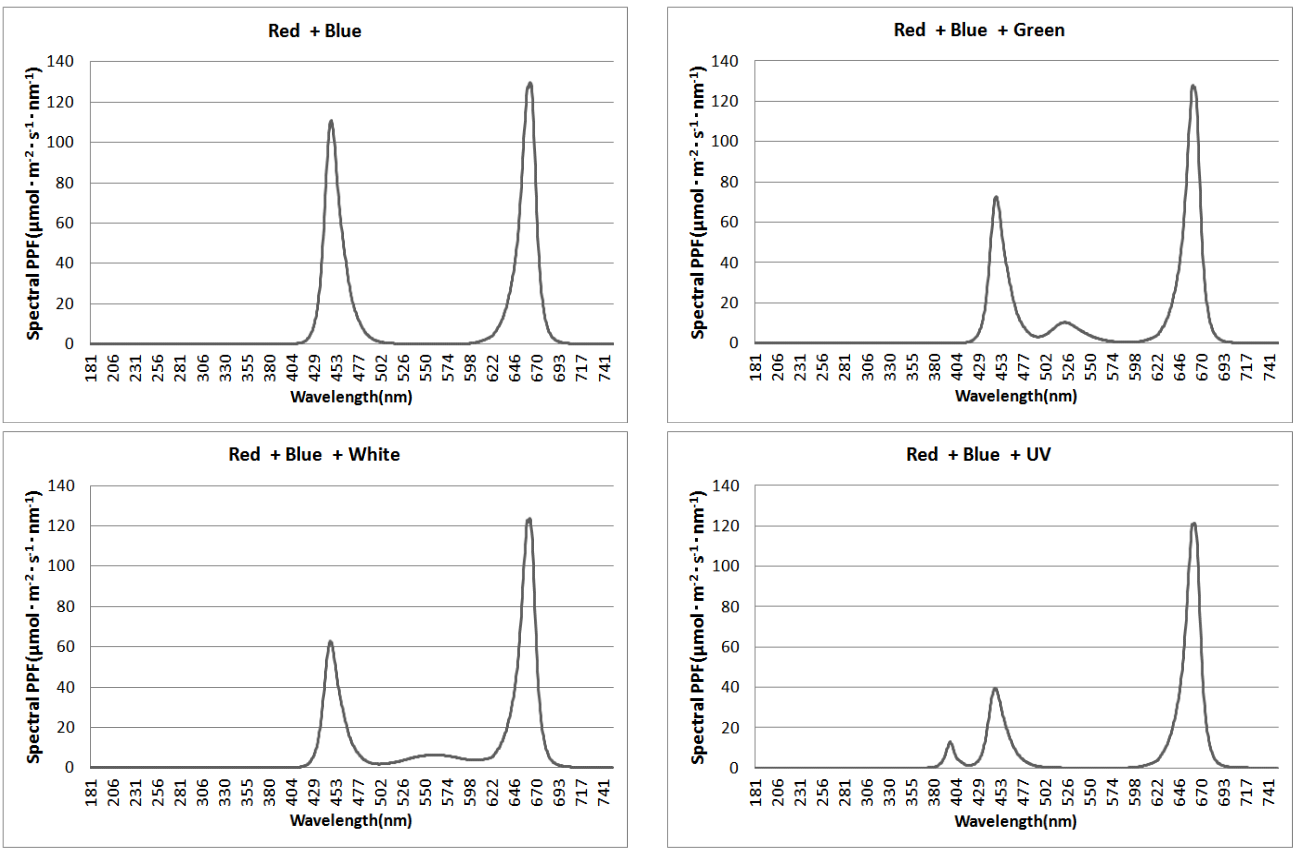


Figure 5. Spectral distributions of four LED combinations.

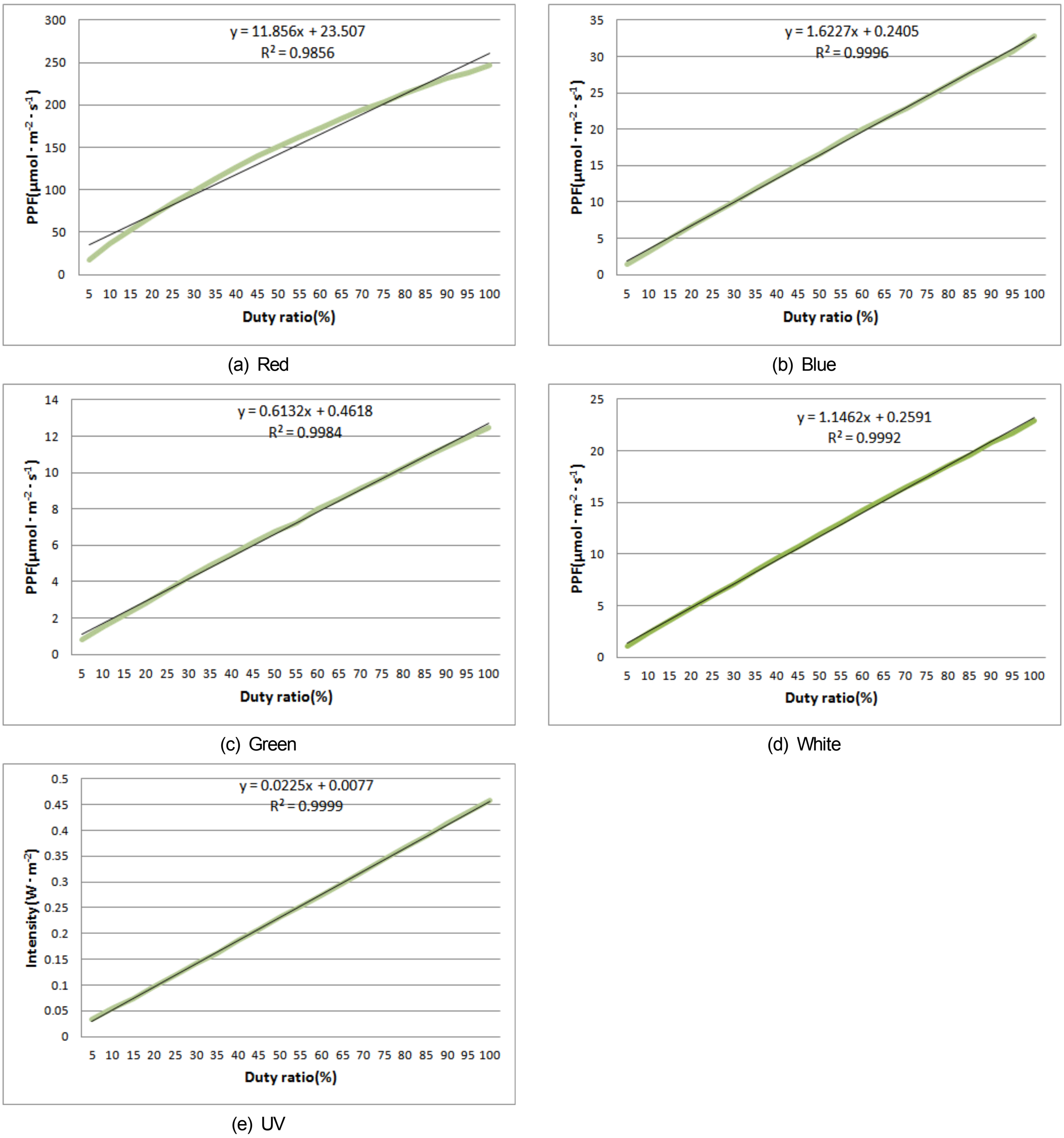


Figure 6. PPF of red, blue, green, white, and UV LEDs as affected by duty ratio.

showed minimum PPF. Minimum PPF with the Red+Blue+White combination was caused by the characteristics of white LED which had lower spectral output than other LED when duty ratio was high.

Figure 6 shows the PPF of red, blue, green, white, and UV LEDs as affected by duty ratio. The control system performed well in that all spectra represented a linear change with duty ratio.

Light uniformity

Figure 7 shows the intensity of LED light by wavelength combination. The intensity decreased from the center to the border, and it was over 100μmol·m^{-2}·s^{-1} in the area excepting border, which represented sufficient light.

Table 2 shows uniformity ratio of the LED lighting system. Uniformity ratio for the whole area showed 0.67 for the Red+Blue combination, 0.7 for the Red+Blue+

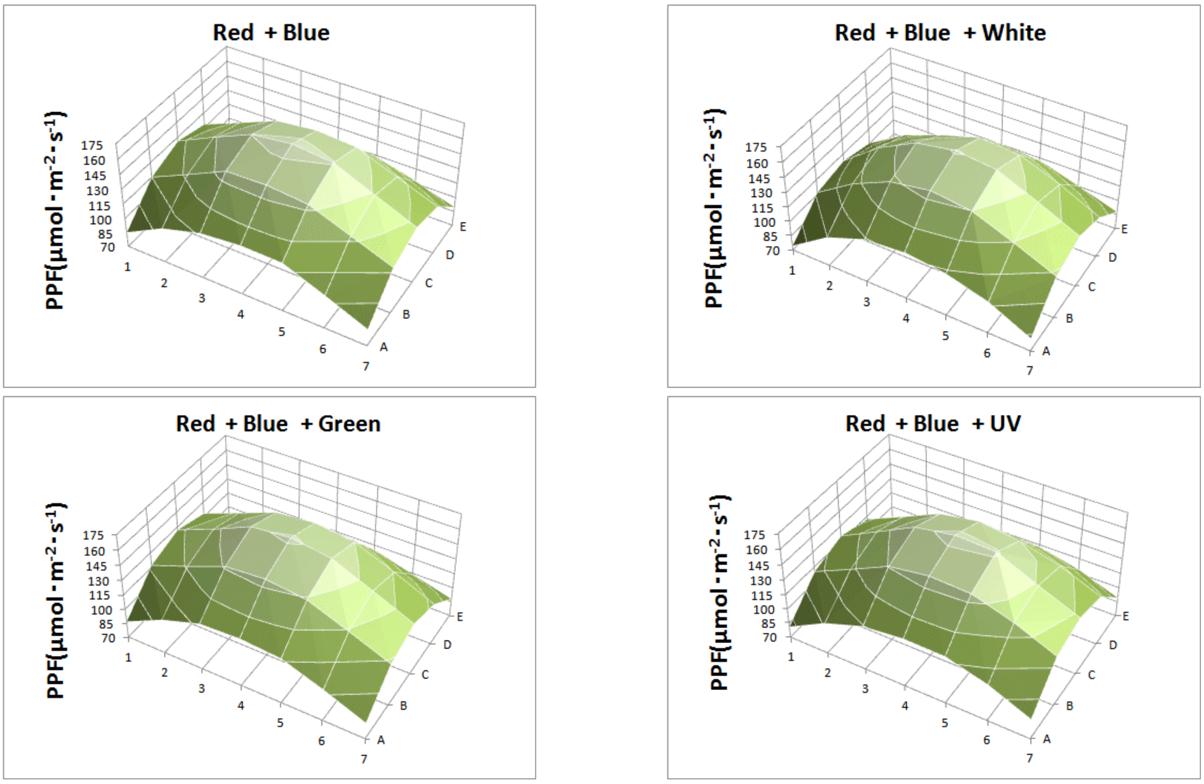


Figure 7. PPF distribution measured under LED lamps treated in this study.

Table 2. Uniformity ratio of LED lighting system (frequency 2.5 kHz, duty-ratio 50%)

Field	Red+Blue	Red+Blue +Green	Red+Blue +White	Red+Blue +UV
A	0.67	0.70	0.62	0.65
B	0.90	0.87	0.90	0.88

※ A: whole field, B: field excepting border

Green combination (maximum value), 0.62 for the Red+Blue+White combination (minimum value), and 0.64 for the Red+Blue+UV combination.

Uniformity ratio for the area excepting border showed 0.90 for the Red+Blue, and Red+Blue+White combinations, 0.87 for the Red+Blue+Green combination, and 0.88 for the Red+Blue+UV combination. The light system was irradiated evenly at the area excepting border, so it was suitable for plant factory.

Conclusions

This study aimed to design a variable frequency LED light system for plant factory which combined red, blue, green, white, and UV light and controlled the ratio of the light wavelength. In addition, this study evaluated the performance of each combination of LEDs to verify the applicability.

Four combinations of LED (i.e. Red+Blue, Red+Blue+Green, Red+Blue+White, Red+Blue+UV) were designed using five types of LED. The system was designed to control the duty ratio of each wavelength of LED by 1% interval from 0~100%, and it also controlled the pulse by 1Hz interval from 1~20kHz.

Clean waveforms were measured from 10Hz to 10kHz regardless of duty ratio. Frequency distortion was observed within 5% of inflection point at frequencies above 10kHz regardless of duty ratio, but it was judged negligible.

Spectra showed a normal distribution, and maximum PPF with duty ratio of 100% was 271.4μmol·m^{-2}·s^{-1} from Red+Blue combination. PPF of Red+Blue+Green combination was 258.9μmol·m^{-2}·s^{-1}, and the one of Red+Blue+White combination was 273.9μmol·m^{-2}·s^{-1}. PPF of Red+Blue+UV combination was 267.7μmol·m^{-2}·s^{-1}.

Uniformity ratio for the area excepting border showed 0.90 with both Red+Blue, Red+Blue+White combinations, 0.87 with Red+Blue+Green combination, and 0.88 with Red+Blue+UV combination. The light was irradiated evenly at the area excepting border, so it was suitable for plant growing.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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