OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 12, No. 11-12, Nov.-Dec. 2018, p. 652 - 659

Design and analysis of the PAR spectrum of the tunable red: blue actual photon flux ratio of the LED lighting system

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The goal of this study is to design and analyse the PAR spectrum, R/B photon flux ratio of the LED light. Six types of LED were used as light sources. The R/B ratio was controlled by the tunable resistor technique with LabVIEW. LED photon flux was measured by the spectroradiometer. The result confirmed that supplying the specific high quality of PAR spectrum is possible. This idea could be applied to plant experiments that involve the effect of red and blue LED light with more advantages than the previous LED light sources that mixed the R/B ratio by varying number of LED.

(Received April 11, 2018; accepted November 29, 2018)

Keywords: R/B photon flux ratio, Tunable R/B ratio, LED for plantation, PAR spectrum

1. Introduction

Light is one of the most important environmental factors that affects plant's growth. [1] The light source is necessary for indoor plant cultivation systems or in circumstances where there is an absence of sunlight or insufficient natural light for plants. Since the year 2000, the LED (Light Emitting Diode) was applied for indoor plantation system such as in the plant cultivation and in the university. In many universities with an agricultural research laboratory, a light source for the indoor cultivation system is needed. Most of the laboratories chose LED lights as the light sources because of several advantages that LED has over the other light sources regarding their small size, long life span, energy efficiency. Moreover, LED lights require no warm up time and the light color and wavelength can be manipulated and adjusted [2]. Many researchers studied the effects of different light: red, far-red, green, blue, violet, ultra-violet, and the white LED on the morphology, photochemistry, plant biology, photosynthesis and growth development of the plants.

The early LED light sources for the laboratories' indoor plant cultivation has a fixed light colour ratio. However, what is required is, in fact, LED light sources that is adjustible (in wavelength and light) or the tunability of the light spectrum and intensity. LED lighting systems that can adjust the red and blue light were developed at the University of Florida, (UF) in 2005 [3]. The adjustable red-green-blue LED light array was designed and developed to support research in plant growth and development at horticultural sciences department of the UF and Kennedy Space Center. The quantity of light is controlled by a manual switch and the quality of light is controlled by the PWM tunable control (manual). There are two prototypes being (1) 4×5 RGB array for 1.0 m×2.5 m of irradiance area, and (2) 1×36 RGB array for the same irradiance area at PPF = 150 μmol $m^{-2}s^{-1}$. In 2016, Sharifah Yusof developed the LED lighting system for four tires of vertical rack growth chamber. There are three sets of LED array with fixed R/B ratio: R/B = 7/3, R/B = 5/5, and R/B = 3/7. The light intensity is 1000 to 2000 lux in the plant's area of 30cm×30cm, however, it is not possible to tune the R/B ratio [4]. In the same year, Y. Chao Xu implemented an LED supplementary lighting system for plants. This design has a tunable red and blue LED ratio in two modes (4:1 and 9:1), adjustable by the mechanical switch. This was achieved by using 45 of 1W red LED (620-645 nm), 10 of 1W blue LED (450-460 nm) and was used for a planting area of about 50 cm×70 cm at 2076.3 lumens [5]. Zhou et al reported the light uniformity simulation results of the mixed- color red, blue, and for-red LED array on the test area of 50 cm×50 cm. The imperfect Lambertian model was applied to optimal the distance between adjacent red and blue LEDs. The results show that the ratio of R/Fr in the case of even number N is less uniform than that in the case of odd number N, and the ratio of R/B in the case of even number N is more uniform than that in the case of odd number N. The array of red, blue, and far-red LEDs is more suitable than the array of red and blue LEDs for the production of plants [6].

There are some intelligent lighting system for plant growth that use digital control systems with environmental sensors (FPGA, Embedded technology, and Web based) to control the light and microclimate in the greenhouse, [7-9] and a closed microalgae crop [10-11].

However, the adjustment of the previous light systems by controlling the R/B ratio with the number of LEDs cannot produce a real R/B ratio of the quantum light. This is because the luminance efficiency of the red and blue LED is different. This study is focusing on the design and development of the multi-channel tunable ratio of red and blue LED that can produce the precession of R/B photon flux ratios for supporting the research on plant growth. The goal of this study is to confirm the design by measuring the LED light spectrum and analysing the corresponding PPFD, R/B ratio, and the PAR spectrum.

2. Material and method

2.1. Simulation tool

This study used the open access online software "Horticulture Lighting Calculator" (www.Lumiled.com) to design and simulate the spectrum distribution and the electrical power consumption of the R (620 nm – 670 nm) and B LEDs (420 nm – 480 nm). The evaluation of the photosynthetic photon flux and R:B ratio was conducted by using the LEDs LUXEON SunPlus 20 model L1SP-DRD0002000000 (deep red) and L1SP-RYL0002000000 (royal blue) as the light source. The number of R and B LED is 32 each. The simulation condition is varied by changing the LED forward current and the program will display the results of R/B ratio at 2/8, 3/7, 4/6, 5/5, 6/4, 7/3, and 8/2.

2.2. LEDs

The LED panel (12.5 cm × 26 cm) was fabricated by using 72 of 3W bleed-type of 7.3 mm in diameter. All LEDs were produced from Chanzon Company, China. There are eight LED types: violet (420 nm), blue (440 nm), green (550 nm), orange (590), red (640 nm), deep red (660 nm), warm white (3000k), and cool white (6000k). The quantities of each color are violet (16), blue (16), green (2), orange (2), red (16), warm white (2) and cool white (2). These LEDs provide the wavelength range essential for photosynthesis and plant development (Fig. 1a). An LED panel is able to generate the PAR spectrum in accordance with the McCree Action Spectrum [12-14].

The LED is divided into three main arrays, which are red LED array, mixed LED array, and blue LED array. Red LED and Blue LED array were separated into two sub-arrays each: R1-R2 sub-array and B1-B2 sub-array. R1 sub-array comprised of four LED elements (Fig. 1b). The R2, B2 and B1 sub-array comprised of four LED elements in the same manner as R1 sub-array. The Mixed LED array has two elements of one green LED, one orange LED, one warm-white and one cool-white LED (Fig. 1c). The installation pattern of the LED panel is shown in Fig. 1A.

The author implemented the design so that the control the power of LED is determined by their set of commercial type LED driver. Red LED is a 150 Watts 36V dimming control LED driver HLG-150-36B, and the HLG-150-42B LED driver is used for driver Blue LED array at 42V 150 watts (Meanwell Enterprise Co., Ltd. Taiwan). The LED driver for Mixed LED array is un-dimming control 12V 35W as a DC constant current of power supply.

2.3. Red/Blue ratio control system

The authors proposed a setup where it is possible to define the tunable ratio of red and blue LED in seven modes. There are R/B is 8/2, 7/3, 6/4, 5/5, 4/6, 3/7 and 2/8 in accordance to the previous studies showing mixed ratio between 20% to 80%. For example: R/B is 8:2 [15] ,R/B is 7:3 [16-17], R/B is 1:1 [18-21] or R/B is 3:7 [22]. The author designed the multi-channel tunable R/B ratio circuit by using external resistance dimming control mode. The variable resistor (10kΩ) was applied for adjusting and controlling the dimming operation of the LED driver (HLG-150-36B, and HLG-150-42B). The author established control via the PC and LabVIEW programme (Fig. 1c).

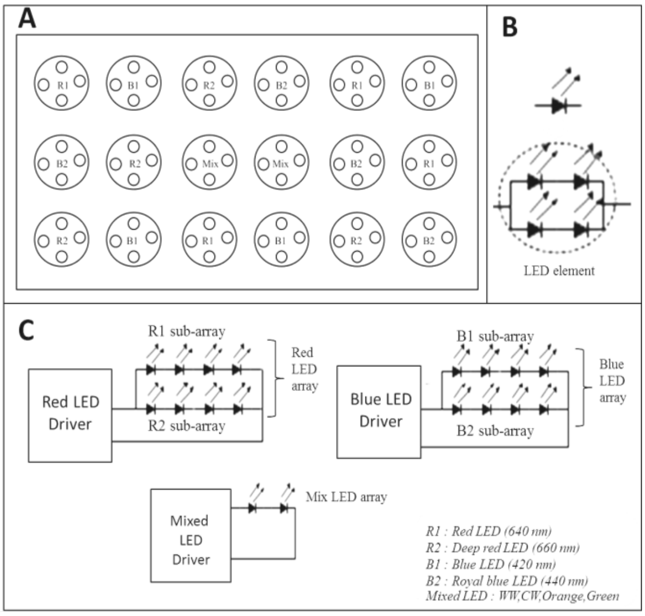

Fig. 1. LED panel fabricated with 72 LED and control diagram (a) LED panel comprises of 18 of aluminum plate with diameters of 28 nm. 4 LEDs installed with a total of 72 LEDs. (b) The circuit of aluminum plate as two series and two parallel. (c) Connecting diagram of LED are driving with three of commercial type LED driver modules

The digital control signal (8 channels, Po0-Po7) of the LED light source was programed using LabVIEW software (National Instruments Corp., Texas, USA). Each signal is active high pulse which is sent to control relay. When the relay's contact is closed, the external resistor will connect to the dimming control input of HLG-150-36B and HLG-150-42B LED drivers. The control panel (on the PC screen) can select the mode of R/B ratio in seven modes. When the author clicked at 7/3 button, a digital signal (+5V) will be sent from the PC to port D6 (Po6). When the electronic switch (ULN2803) is closed, the relay coil will be activated. When the contact relay (CH-6) is closed, the resistor R6.1 and R6.2 will be connected to the dimming control input of LED driver. LED driver will drive the current to Red LED array, which would subsequently generate the quantum light at 70% of maximum intensity, and drive the blue LED array at 30% of maximum intensity of the blue light. For the other R/B ratio, we can use the same method of control (Fig. 2a). The Mixed LED array will be driven by constant current mode, and it is not possible to adjust the irradiance. The stop button is used for stopping the main power supply of the lighting system (Fig. 2b).

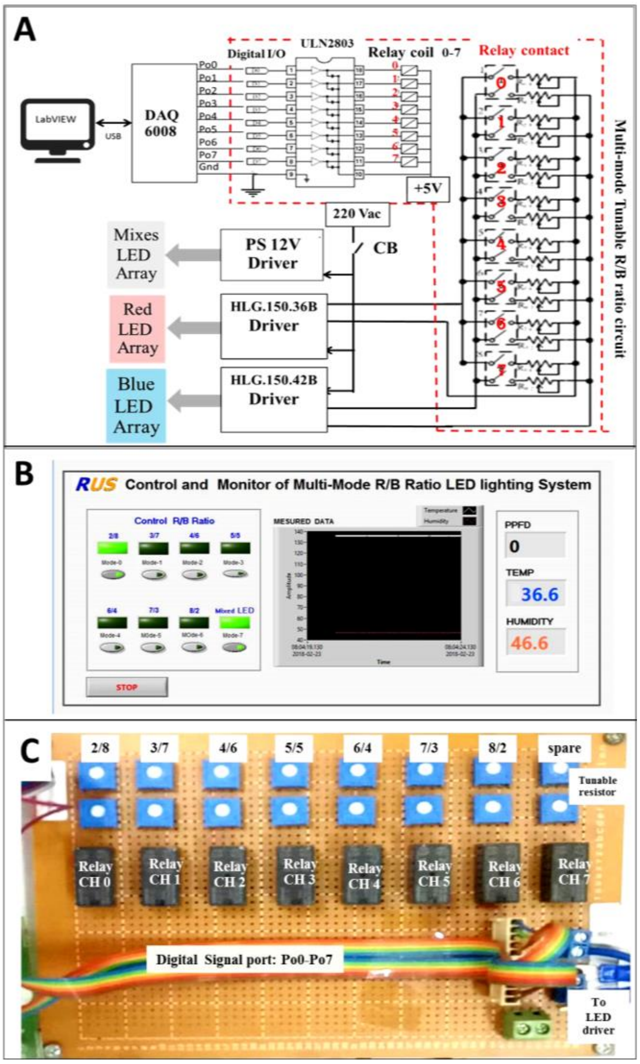

Fig. 2. (a) The control and circuit diagram shows the input port of a multi-channel tunable ratio of LED circuit that was connected to the Digital I/O port of a DAQ device (NI 6008). This was done in order to control the Red and Blue array LED driver to drive constant current mode to the LED. (b) LabVIEW control and monitoring programme of the the tunable red: blue actual photon flux ratio used for controlling the R/B ratio on the LED light source in the growth chamber. (c) The prototype of the print circuit board

2.4. Light measurements

The PPFD and the spectrum of the LED light source measurement were obtained by a spectroradiometer (Fig. 3a) from Lighting Passport Pro Essence (Asensetek Incorporation, Taiwan). The response wavelength range is between 380 nm to 780 nm. The output wavelength pitch is 1 nm. The optical resolution (FWHM) is 10 nm. The Illuminance range is from 5 to 50,000 lux. The reliable chromaticity is from 100 to 50,000 lux. The spectrum analysis software is Spectrum Genius Agricultural Lighting (Asensetek Incorporation, Taiwan). The SGAL software was used to analyse the total PPFD, R/B ratio, temperature, humidity, peak wavelength and specific PPFD in each range of the light spectrum, the illuminance and finally, analysis of the ratio of red and blue quantum light was also conducted.

2.5. Experimental set-up

The experiments were carried out in the growth chamber size (60 cm × 60 cm × 80 cm), growth chamber's wall is the white plastic plate, and the front wall was open (Fig. 3a). On the top of the growth chamber hanged the LED light source. The growth chamber was installed in a room with controlled temperature at 25± 2˚C and humidity 65±10%. The distance from the light source to the chamber's floor is about 65 cm. The spectroradiometer is placed at the centre of the chamber's floor. The control software (Fig. 3b) set the R/B ratio to be 2/8. The PPFD, R/B ratio, Illuminance, and peak wavelength (λ_p) of the light is measured and recorded.

Subsequently, the R/B ratio is adjusted at 3/7, 4/6, 5/5, 6/4, 7/3, and 8/2 and the experiment is repeated on each ratio. The experiment is conducted again by reducing the distance from the light source to 60 cm, 50 cm, 40 cm, and 30 cm.

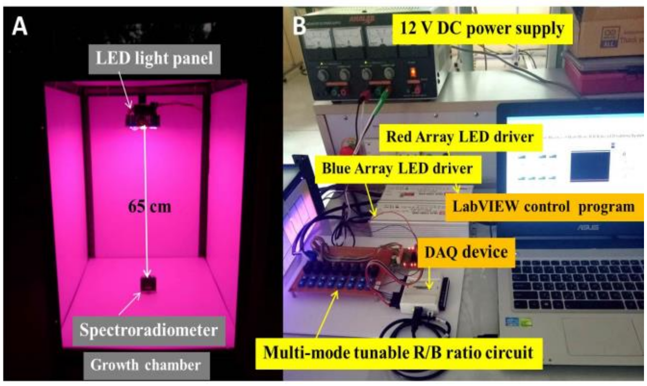

Fig. 3. An experimental set-up of the tunable red: blue actual photon flux ratio of LED lighting system

3. Results

3.1. Simulation results

The resultant R and B light that were generated from the LED lighting system that the author propose is as shown in Table 1. The total PPFD is 154.61µmol $m^{-2}s^{-1}$ ± 4.75. The R and B light spectrum at various R/B ratios are 0.25 at 2/8, 0.43 at 3/7, 0.67 at 4/6 1 at 5/5, 1.5 at 6/4, 2.32 at 7/3 and finally, 4.01 at 8/2. These values are very similar to the theoretical aspects. The simulation results were used to compare the experimental results in the next section.

The total power consumption of the LED light source will be hight when the PPFD from R light more than B light (Table 1), because the photon flux efficacy of R LED higher than B LED.

Table 1. The simulation results of the LED lighting system on the R/B differences ratio

Parameters	**Percentage of R/B**						
	2/8	**3/7**	**4/6**	**5/5**	**6/4**	**7/3**	**8/2**
PPFD (400 - 700 nm)	150.72	154.52	150.1	157.49	159.86	155.22	154.38
PPFD R (600 - 700 nm)	27.89	42.79	54.49	70.07	84.34	94.02	105.5
PPFD B (400 – 500 nm)	113.25	99.56	81.65	70.41	56.3	40.53	26.34
R/B	**0.25**	**0.43**	**0.67**	**1.00**	**1.50**	**2.32**	**4.01**
Power of R LED(W)	11.85	18.78	24.61	33.05	41.14	47.03	54.35
Power of B LED(W)	64.31	54.75	42.91	35.91	27.6	18.94	11.76
Total power(W)	76.16	73.5	67.52	68.96	68.74	65.94	66.11

3.2. PPFD spectrum and R/B ratio

The ratio of red and blue LEDs (R/B) were set at 2/8, 3/7, 4/6,5/5, 6/4, 7/3, and 8/2 and the PPFD and PAR spectrum were measured. The results were tested in the laboratory with the ambient temperature of 25±2 ℃ and relative humidity of 65±10 %. Each picture shows the measured results for both light colour and PAR spectrum at different R/B ratio. Fig. 4a shows that when the colour of R/B light is at 2/8 in the growth chamber, the red LED spectrum (600 nm-700 nm) is 20% and 80% blue LED (400 nm-500 nm). The PPFD (400 nm-700 nm) is equal to 151.86 µmol m^{-2} s^{-1} and a λ_P = 424 nm (Table 2).

Fig. 4b shows a spectrum of LED light source at R/B ratio of 3/7 has the PPFD (400 nm-700 nm) of 155.08 µmol m^{-2} s^{-1} a λ_P = 424 nm (Table 2). Fig. 4c shows that when the light spectrum is at R/B ratio of 4/6, the PPFD (400 nm-700 nm) is 152.09 µmol m^{-2} s^{-1} a λ_P = 423 nm (Table 2). Fig. 4d shows that when the R/B ratio is about 5/5, the PPFD (400 nm-700 nm) is 151.24 µmolm^{-2} s^{-1} a λ_P = 423 nm (Table 2). Fig. 4E shows that the R/B ratio of 6/4 gives the PPFD (400 nm-700 nm) of 150.53 µmol m^{-2} s^{-1} a λ_P = 423 nm (Table 2). Fig. 4f demonstrated that when the R/B ratio is about 7/3, the PPFD (400 nm-700 nm) is 149.47 µmol m^{-2} s^{-1} a λ_P = 659 nm, and Fig. 4g shows that when light spectrum R/B ratio is at 8/2, the PPFD (400 nm-700 nm) is 146.02 µmol m^{-2} s^{-1} a λ_P = 659 nm (Table 2). Additionally, it should be noted that each R/B ratio is mixed with the green PPFD (500 nm-599 nm) of about 8.93±0.5 µmol m^{-2} s^{-1} (Table 2).

Moreover, the green, yellow and orange lights were also generated from our LED light source. The PPFD of green light (500 nm - 600 nm) is at 8.93 ± 0.5 µmol m^{-2} s^{-1} in all different of R/B ratio (Table 2). The R/B ratio was proven by the analysed results (Table 2). The results showed that the R/B measured are closely to the result of simulation (Table 1), and related to the R/B ratio that the author proposed. For example, our proposed R/B ratio is at 2/8=0.25 or 5/5=1.00 or 8/2=4.00 while the measured R/B was shown to be 0.25, 0.97 and 4.19 respectively (Table 2). The results indicated that the LED light source are to be of a very high quality. The overall PPFD (400 nm-700 nm) that our LED light source can produce five variation ranges are UV (380 nm - 399 nm), blue (400 nm - 499 nm), green(500 nm-599 nm), red (600 nm -700 nm) and Far red (FR) (701-780 nm). The comparative results of overall PPFD of UV, blue, red, green, and FR of different R/B ratio from 2/8 to 8/2 were shown in Fig. 5. Subsequently, the FR spectrum shows the relative proportion when the red light is more than the blue light (Fig. 5). These data confirmed that our idea is capable of being implemented in order to achieve 7 modes of tunable LED light source matching to the objective of this study.

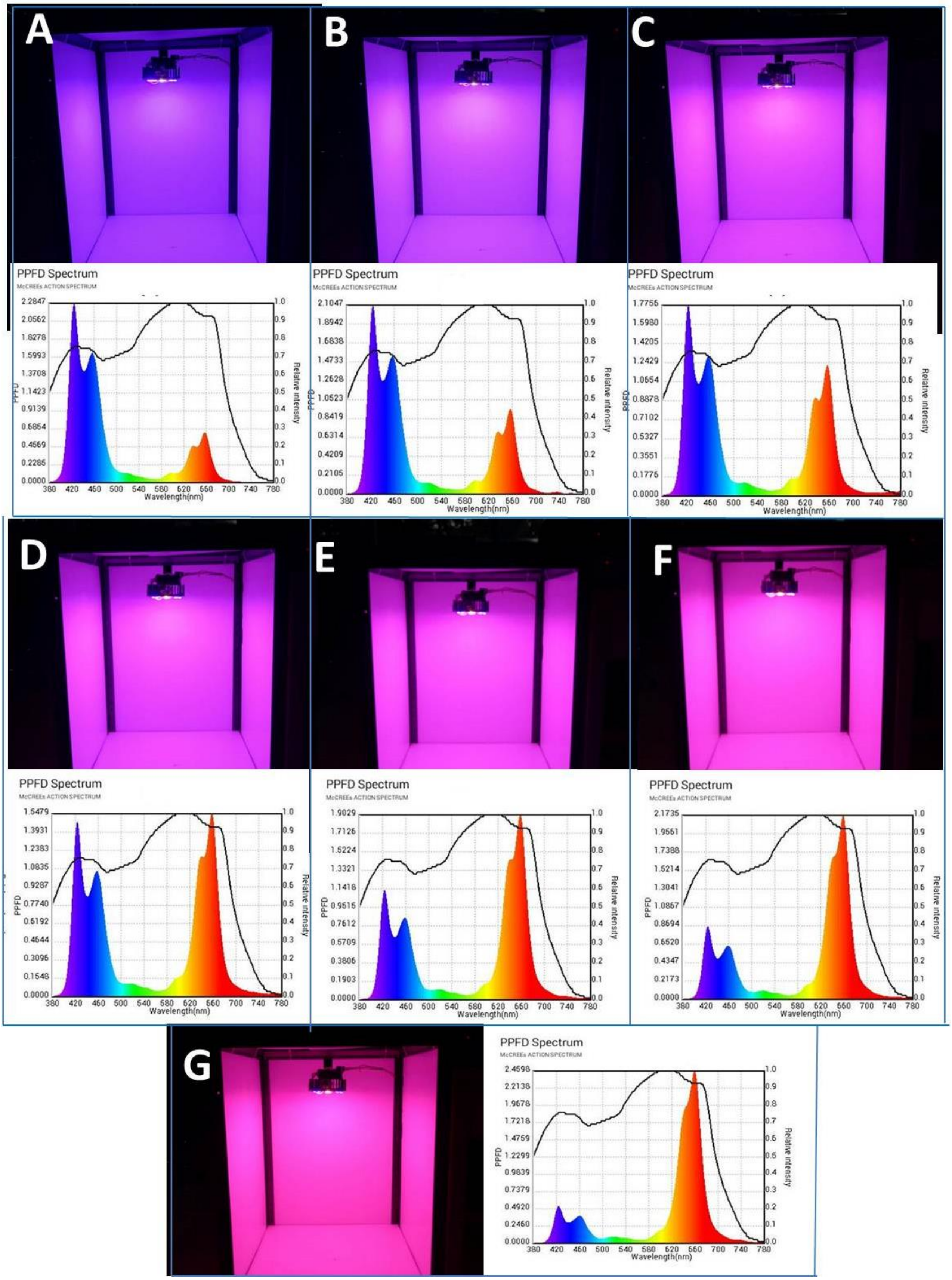

Fig. 4. The measured results of light colour and PPFD spectrum compare to McCree action spectrum from a LED light source. (a) 151.86 μmol $m^{-2} s^{-1}$ at R/B ratio =2/8, (b) 155.08 μmol $m^{-2} s^{-1}$ at R/B ratio = 3/7 (c) 152.09 μmol $m^{-2} s^{-1}$ at R/B ratio = 4/6 (d) 151.24 μmol$m^{-2} s^{-1}$ at R/B ratio = 5/5 (e) 150.53 μmol $m^{-2} s^{-1}$ at R/B ratio = 6/4 (f) 149.47 μmol $m^{-2} s^{-}1$ at R/B ratio = 7/3 and (g) 146.02 μmol $m^{-2} s^{-1}$ at R/B ratio = 8/2

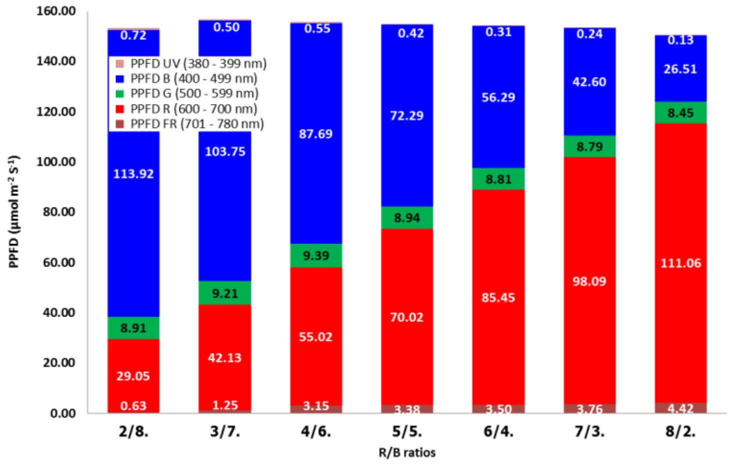

Fig. 5. The comparative results of PPFD of UV, blue, red, green, and FR of difference R/B ratio from 2/8 to 8/2

Table 2. Analysesd data results from a tunable LED light source (65 cm from the light source)

Parameters	**Percentage of R/B**						
	2/8	**3/7**	**4/6**	**5/5**	**6/4**	**7/3**	**8/2**
PPFD (400-700 nm)	151.86	155.08	152.09	151.24	150.53	149.47	146.02
PPFD FR (701-780nm)	0.63	1.25	3.15	3.38	3.50	3.76	4.42
PPFD R (600 - 700 nm)	29.05	42.13	55.02	70.02	85.45	98.09	111.06
PPFD G (500 - 599 nm)	8.91	9.21	9.39	8.94	8.81	8.79	8.45
PPFD B (400 - 499 nm)	113.92	103.75	87.69	72.29	56.29	42.60	26.51
PPFD UV(380-399 nm)	0.72	0.50	0.55	0.42	0.31	0.24	0.13
R/B	**0.25**	**0.41**	**0.63**	**0.97**	**1.52**	**2.30**	**4.19**
R/FR	45.94	33.84	17.49	20.73	24.43	26.06	25.13
DLI	13.12	13.40	13.14	13.07	13.01	12.91	12.62
Illuminance(lux)	2452.90	2674.10	2816.10	2887.50	3012.00	3096.60	3092.30
λp	424	424	423	423	423	659	659

3.3. PPFD of the light source

The level of PPFD is very important for the plant's growth because different types of plants need different PPFD. The author proposed an LED light source that is able to adjust the ratio of R/B in seven different ratios. These results show that the level of PPFD can be changed by adjusting the distance between the light source and the plant canopy. The relationship between the distance of the light source and PPFD was shown in Fig. 6. The PPFD is approximately 150 ±5 μmol m^{-2} s^{-1} when adjusting the R/B ratio from 2/8 to 8/2 at the distance of 65 cm. When the distance is about 50 cm, the PPFD was increased to 195 ±10 μmol m^{-2} s^{-1}. At 40 cm, the PPFD is increased at 258 ±15 μmol m^{-2} s^{-1}. Finally, the PPFD is equal to 415 ±24 μmol m^{-2} s^{-1} at 30 cm. The PPFD decreases when the distance of the light source increases. The inverse square law of the light could explain these measured results. Our LED light source could generate a constant PPFD (65 cm to 30 cm). However if the distance increases, the PPFD will have more absolute errors.

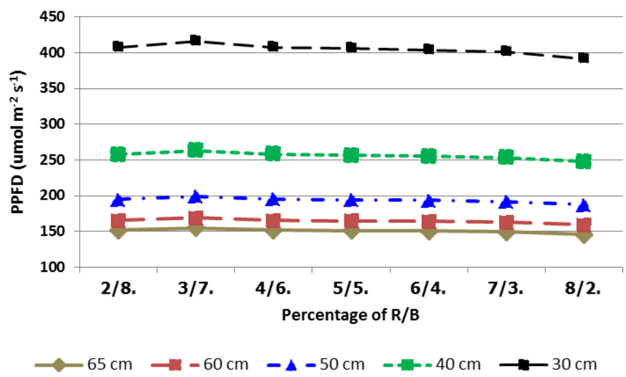

Fig. 6. The measured of PPFD (400 nm-700 nm) at difference distant of the LED light source

4. Discussion

The ratio of red light and blue light was controlled by the method that the author proposed. This method has an advantage, because of the ease of operations for the adjustment of the R/B ratio of the LED light by tuning the value of the resistance at the external resistor. The potentiometer is on the tunable red: blue actual photon flux ratio circuit, hence, there is no need to change or reconnect the hardware (Fig. 2a).

The R/B ratios that were produced from our LED light source showed with high precision the R/B actual photon flux ratio. There are seven modes of controlling the R/B ratio of the LED (2/8, 3/7, 4/6, 5/5, 6/4, 7/3, and 8/2) from the simulation and experimental results (Table 1, 2), The both results show a bit differences. This confirms that the method proposed by the author could increase the light quality. When good quality light is applied to indoor plant cultivation, it can increase the plant production [23]. The PPFD spectrum and the R/B mixing ratio that the author presented (Fig. 4) are in accordance with the study of Akira Yano [9].

The PPFD of our lighting system could be adjusted by moving the distance of the light source. The PPFDs range from 150 μmol m^{-2} s^{-1} to 400 μmol m^{-2} s^{-1}. The range of PPFD could support many types of plant researches and many cases of plants growth such as seedling of plants, vegetative growth state, and flowering and fruit states.

Moreover, the author can tune to the others R/B ratio that might be needed. This means that the LED light source could adjust the light quality in others ratios. Therefore, this could support the specific need for special light source that the researchers need. For example, R/B = 7/3 of LED light on the production of strawberry in a growth chamber [16], and applied on the growth and photosynthesis, phytochemical contents in Lactuca sativa L. cv. 'Grizzly'[17]. For the R/B = 9/1, this ratio could be applied to study the physiological indices (net assimilation rate, hypocotyl-to-leaf ratio, leaf area, leaf dry weight, hypocotyl length and diameter, plant length, developed leaves), variation of photosynthetic pigments and non-structural carbohydrates in radish (Raphanus sativus L., var. 'Faraon') [24].

Furthermore, LED light at R/B ratio of 2/1 is applied to study the growth and nutritional properties of lettuce [25], and some research applied the R/B= 10/1 to studies the effect of spectral quality of monochromatic LED Lights on the growth of Artichoke seedlings [1]. The physiological responses of cucumber seedlings under red LED and blue LED light at the ratio of 1/10 was presented by R. Hernabdez [25].

The PPFD spectrum (Fig. 4) measurement results showed that these spectra are in accordance with the reference spectrum which is the McCree Action Spectrum [12]. This result confirms that the PPFD spectrum from our LED lighting system is appropriate for supplying to the plants. The plants could absorb the PAR spectrum (400 nm - 700 nm) from this light source with high efficiency. The photosynthesis process will complete and support the plant's growth with the blue light (400 nm - 500 nm) and red light (600 nm - 700 nm). The blue light could promote the growth of tissue and stem, and the red light promotes flowering and fruit yield [16-17], [27].

5. Conclusion

The tunable R/B actual photon flux ratio of LED lighting system could generate specific PAR spectrum in several R/B ratios with the high quality of light. This idea matches with the plant research's needs. This method could be applied to other cases of the plant experiments that need to study the effect of blue (420 and 440 nm) and red (640 and 660 nm) LED light. The benefits for this system include the ease of control and give the light with better quality than the previous LED light sources that mixed the R/B ratio by the number of LEDs. The plant research laboratory at Rajamangala University of Technology Suvarnabhumi (Thailand) is receiving the benefit from this study. Subsequently, this benefit can support the research in the modern agricultural area. This is the main important issue in Thailand accordance to the vision Thailand 4.0.

Acknowledgements

The authors wished to show gratitude for the research budgets from the National Research Council of Thailand in year 2018. Project code is 607088.

References

[1] R. C. Rabara, G. Behrman, T. Timbol, P. J. Rushton Front Plant Sci. Feb. **17**(8: 190), 1 (2017).
[2] K. M. Folta, K. S. Childers, Hort Science **43**(7), 1957 (2008).
[3] K. M. Folta, L. L. Koss, R. McMorrow, H.-H. Kim, J. D. Kenitz, R. Wheeler, J. C. Sager, BMC Plant Biology **5**(17), (2005).
[4] S. S. Yusof Sharifah, M. Thamrin Norashikin, Mohd K. Nordin, A. S. Mohd, Y. N. Jaafar Sidik, IEEE (I2CACIS). 7-10.(2016).
[5] Y. Xu, Y. Chang, G. Chen, H. Lin, Optik – International 436 Journal for Light and Electron. Optics **127**(18), 7193 (2016).
[6] T. Zhou, Y. Xu, Z. Ji, G. Zhou, Progress In Electromagnetics Research C **81**, 181 (2018).
[7] E. O. Gonzalez, D. A. Lumbreras, R. I. Tsonchev, J. W. Hernández, C. O. Olvera, E. G. Ramírez, M. A. Esquivel, V. T. Argüelles, V. Castaño Computers and Electronics in Agriculture **92,** 48 (2013).
[8] Z. Kang, L. Xu, F. Xiao, Telkomnika **13**(3), 752 (2015).
[9] A. Yano, K. Fujiwara, Int. J. Light Electron. Opt. **127**, 7193 (2012).
[10] L. M. Beltran, C. L. Garzon-Castro, D. F. Valencia, V. A. Uribe, Ije. Transactions C: **26**(3), 219 (2013).
[11] A. Khalili, G. D. Najafpour, G. Amini, F. Samkhaniyani, Biotechnol. Bioproc. E **20**(284), (2015).
[12] K. J. McCree, Agricultural Meteorology **9**(71), 191 (1972).

[13] G. Trouwborst, S. W. Hogewoning, O. V. Kooten, J. Harbinson, W. V. Ieperen, Environmental and Experimental Botany **121**, 75 (2016).
[14] K. M. Folta, S. D. Carvalho, Hortscience **50**(9), 1274 (2015).
[15] A. Brazaityte, P. Duchovskis, A. Urbonaviciute, G. Samuoliene, J. Jankauskiene, J. Sakalauskaite, G. Sabajeviene, R. Sirtautas, A. Novickovas, Zemdirb- Agric. **97**, 89 (2010).
[16] H. G. Choi, J. K. Kwan, B. Y. Moon, N. J. Kang, K. S. Park, M. W. Cho, Y. C. Kim, Scientia Horticulturae **189**, 22 (2015).
[17] A. Amoozgar, A. Mohammadi, M. R. Sabzalian, Photosynthetica **55**(1), 85 (2017).
[18] S. J. Kim, H. Eun-Joo, H. Jeong-Wook, P. Kee-Yoeup, Sci. Host. **101**, 143 (2004).
[19] L. Y. Chin, K. K. Chong, Int. J. Phys. Sci. **7**, 1773 (2012).
[20] H. R. Kim, Y. You, Han, Korean Journal of Horticultural Science and Technology **31**(4), 415 (2013).
[21] J. Tomohiro, K. Kimura, R. Matsuda, K. Fujiwara, Sci. Hort. **198**, 227 (2016).
[22] T. Godo, K. Fujiwara, K. Guan, K. Miyoshi, Plant Biotechnol. **28**, 397 (2011).
[23] G. Cocetta, D. Casciani, R. Bulgari, F. Musante, A. Kołton, M. R. Antonio, The European Physical Journal Plus **132**(43), (2017).
[24] G. Samuolienė, R. Sirtautas, A. Brazaitytė, J. Sakalauskaitė, S. Sakalauskienė, P. Duchovskis, Central European Journal of Biology **6**(5), 821 (2011).
[25] X. L. Chen, Q. C. Yang, W. P. Song, L. C. Wang, W. Z. Guo, X. Z. Xue, Scientia Horticulturae **223,** 44 (2017).
[26] R. Hernández, C. Kubota, Environmental and Experimental Botany **121**, 66 (2016).
[27] X. Yang Yao, X. Ying Liu, Z. Gang Xu, X. Lei Jiao, Journal of Integrative Agriculture **16**(1), 97 (2017).

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