Development and Experimental Characterization of an IoT-Controlled RGB LED Lighting System for Hydroponic Applications

S. Worsoongnern, W. Yindeesuk, S. Kamoldilok, K. Srinuanjan * and P. Limsuwan

Department of Physics, School of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand
*Corresponding author: keerayoot.sr@kmitl.ac.th

Abstract. This study presents the development of an Internet of Things-based RGB LED lighting system for precise, flexible light control in hydroponic plants. The system consists of 480 high-power RGB LEDs controlled by an ESP8266 microcontroller, enabling real-time adjustment of light intensity, photoperiod, and color ratios via a smartphone. Pulse-width modulation duty-cycle modulation enables the generation of white light suitable for different stages of plant growth. Experimental results show a linear correlation between illuminance and duty cycle for all color channels. Spectral analysis confirms stable emission within the photosynthetically active radiation range (400–700 nm), with the spectral composition remaining unchanged even when brightness is reduced (dimming). The system demonstrates high control accuracy and adaptability for regulating plant growth lighting, particularly for leafy vegetables such as lettuce.

1. Introduction

In recent years, the rising global demand for food, coupled with climate change and limited arable land, has accelerated the adoption of controlled-environment agriculture (CEA). Hydroponics is widely used in modern society to grow plants due to limited land, including in greenhouses and indoor farming systems [1, 2].

Hydroponics is a method of growing plants in a nutrient-rich water solution without soil, supplying essential nutrients directly to the plant roots [3,4]. It is widely used for several advantages, including not requiring a large area, reduced use of water, pesticides, and nutrients, accurate nutrient monitoring, uniform control over plant development, and lower labor requirements [5-8].

Hydroponics is commonly used for short-cycle crops that take only about 40-60 days to harvest, such as red oak lettuce, green oak lettuce, butterhead lettuce, and leaf lettuce [9-12]. However, other types of vegetables, such as tomatoes and strawberries, can also be grown hydroponically [13,14].

Currently, a hydroponics monitoring system has been developed using a microcontroller and various sensors, including temperature, moisture, pH, water level, and total dissolved solids [15]. Furthermore, IoT- and machine-learning-based hydroponic systems have been developed to revolutionize modern agriculture [16-17]. The user can then view hydroponic parameters through the Blynk application on a smartphone.

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It is well known that light is an important factor among the environmental conditions that affect plant growth. Light is the energy source for plant photosynthesis. For conventional or outdoor plant cultivation, plants receive natural sunlight for photosynthesis. Therefore, hydroponics requires artificial light for photosynthesis. Among the light sources used in plant culture, light-emitting diodes (LEDs) have been widely adopted due to their small size, low power consumption, long lifetime, tunable spectral composition, high light conversion efficiency, and low radiant output compared with other light sources [18-21].

Over the past five years, considerable research has focused on developing LED-based artificial light sources that offer adjustable spectral properties and automated control systems to enhance energy efficiency in smart agriculture. In particular, integrating LED lighting with IoT and sensor feedback technologies has enabled real-time monitoring and control of light intensity. For instance, [22] proposed an IoT-based lighting system that optimizes energy use by dynamically adjusting LED brightness based on environmental and sensor data. Similarly, [23] introduced an adaptive lighting framework that leverages IoT and machine-learning algorithms to regulate spectral balance and intensity across different plant growth phases, thereby improving both energy savings and crop quality.

From the optical design perspective, [24] developed a multi-channel, high-power RGB LED array system capable of producing uniform light distribution and precise color tuning. This approach allows for the generation of artificial white light with variable color temperatures and high luminous efficiency. Concurrently, [25] developed a method for controlling the color mixing of red, green, and blue LEDs based on photometry theory and pulse-width modulation (PWM) duty-cycle adjustment, demonstrating that changes in the drive ratio can accurately shift the chromaticity coordinates of RGB LED systems. In addition, [26] reviewed more than seventy studies on artificial lighting technologies, emphasizing that the convergence of LEDs with IoT, artificial intelligence (AI), and sensor feedback represents a significant trend in next-generation innovative lighting systems. Furthermore, [27] presented one of the earliest concepts for generating white light through RGB color mixing, in which the color temperature and luminous intensity can be finely controlled by adjusting the relative drive ratios of the red, green, and blue channels. This concept has become the foundation of modern LED light-source design, particularly for agricultural systems requiring specific spectral characteristics to stimulate plant growth.

Regarding applications in crop cultivation, [28] investigated the effects of R–G–B spectral combinations on the growth of 'Elizium' romaine lettuce and demonstrated that the ratio of red and blue wavelengths significantly influences biomass accumulation and biochemical composition. Similarly, [29] showed that LED illumination with controlled spectral distribution and intensity in indoor environments can effectively enhance crop quality and yield, especially in systems where artificial light substitutes for natural sunlight. These findings collectively highlight that controlling the intensity and ratio of RGB lighting via IoT-based systems is crucial to advancing artificial light technologies for indoor agriculture. In particular, adjustable RGB-based white-light generation can be tailored to meet plant requirements across different growth stages, thereby improving photosynthetic efficiency while optimizing energy use.

In recent years, commercial LED lighting systems have been widely used in both indoor and outdoor farms by most researchers, as mentioned in References [22-29]. However, the

commercial LED lighting systems did not provide the details on some important light parameters, such as the light (red, green, and blue) ratios, photosynthetic photon flux density (PPFD) value, and photosynthetically active radiation (PAR) value.

Therefore, this study focuses on the development and experimental characterization of a simple RGB LED lighting system. Each light color: red, green, and blue light can be easily controlled via an ESP8266 microcontroller, connected to the Blynk smartphone application, which enables real-time light intensity adjustment, automatic scheduling, and color mode selection. In addition, the illuminance (in lux) and two key parameters for plant growth (PPFD and PAR) were measured. Finally, the relationships between illuminance and PPFD, which can be used as a calibration curve of the lighting system, were obtained. This provides convenience and flexibility for precise light management for hydroponic plants and greenhouse applications.

2. Development and methods

In this study, an RGB LED lighting system was designed for agricultural applications. The system allows control of light intensity, exposure duration, and wavelength, all of which can be adjusted through an IoT -based control interface. After the lighting system was constructed, experiments were conducted to measure its light intensity and spectral characteristics. The experimental procedures were carried out as follows.

The light source used in this work is the 3W LED chip (Lisung, China, model 5050). It consisted of red, green, and blue (RGB) light sources, as shown in the photo in Fig. 1 and in Table 1.

Table 1. Electrical and optical characteristics of 5050 RGB 3W
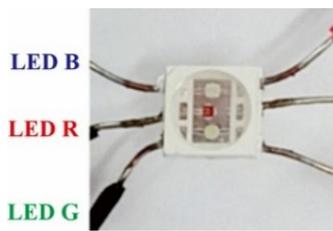
Fig. 1. Photo of an LED chip.

| Type	Dominant wavelength, nm	Luminous Intensity, lumen	Forward voltage, V	Forward current, mA
Red	620-625	30-35	2.1-2.3	300
Green	525-530	55-60	3.1-3.3	300
Blue	460-465	13-18	3.0-3.2	300

One row of light source consisted of 4 LED chips connected in series, and 10 rows of 40 LED chips were connected in parallel to form an LED-chip panel. Then, 4 LED-chip panels were connected in parallel as shown in Fig. 2.

The control system consisted of three main parts: Node MCU-V3, electronic switches, and a power supply. Node MCU-V3 consisted of an ESP8266 CPU and a printed circuit board (PCB). It is a microcontroller board manufactured by Espressif Systems (Shanghai, China). It can be used to control the turning on or off of lights in a plant lighting system. This board has a built-in WiFi module that can connect to the internet for data transmission or be remotely controlled without additional hardware. There are 9 GPIO (General Purpose Input/Output) pins labeled D0 to D8 that support digital input/output. In this work, the control pins for the RGB LED are as follows: PIN D5 controls the blue light, PIN D6 controls the red light, and PIN D8 controls the green light. The electronic switch (AllNewStep, model HW-548) can stand for a maximum current of 100 A. A dual-output switching power supply (15V, 30A; PBA Supply, Thailand) with two output voltages of 5 and 15 V was used to supply the Node MCU-V3 and electronic switches.
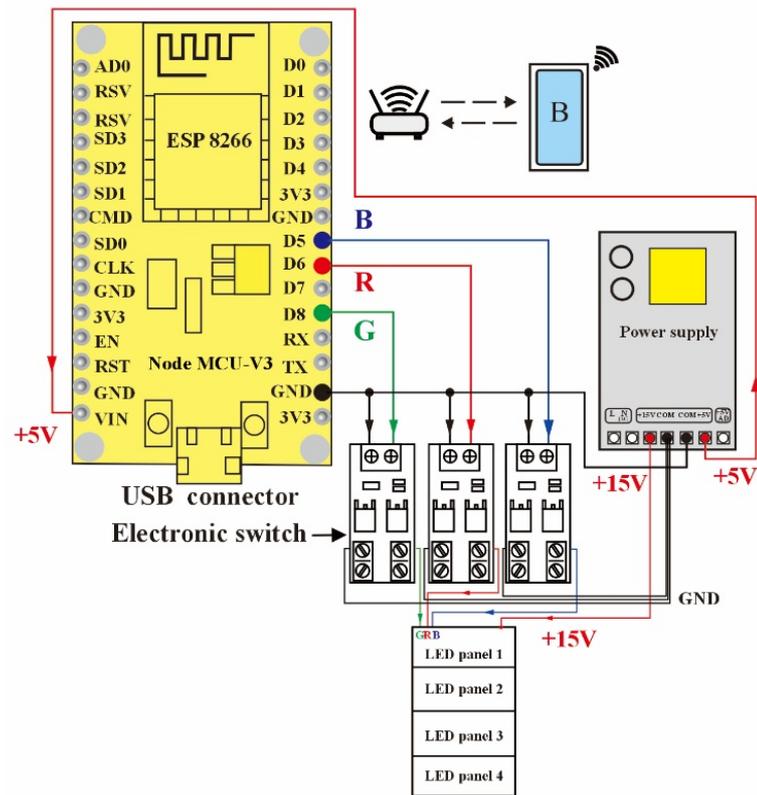
Fig. 2. Schematic diagram of an LED lighting system.

One set of LED-chip panels was connected with Node MCU-V3, electronic switches, and a power supply, as shown in Fig. 2. It is noted that 3 electronic switches were used to connect with the LED-chip panels to control independently green (G), red (R), and blue (B), respectively. In this work, 3 sets of LED-chip panels were prepared, and each set was connected to a single Node MCU-V3. Each set comprised 160 individual LED chips was mounted on a 5 cm × 50 cm printed circuit board (PCB). Finally, the panels were attached to an aluminum frame measuring 28 cm wide and 70 cm long. The aluminum frame was used as a heatsink to dissipate heat from the LED chip panels. The actual picture of the complete LED panels with an aluminum frame is shown in Fig. 3. Three sets of LED-chip panels were connected to the control system. Each set of LED panels was connected to 3 electronic switches (Fig. 2), and a complete LED lighting system was obtained, as shown in Fig. 4.
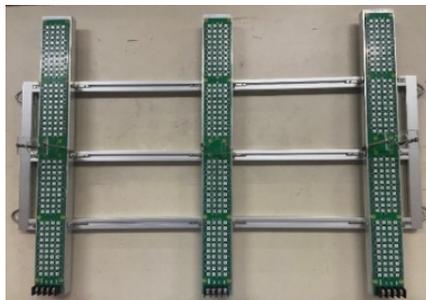
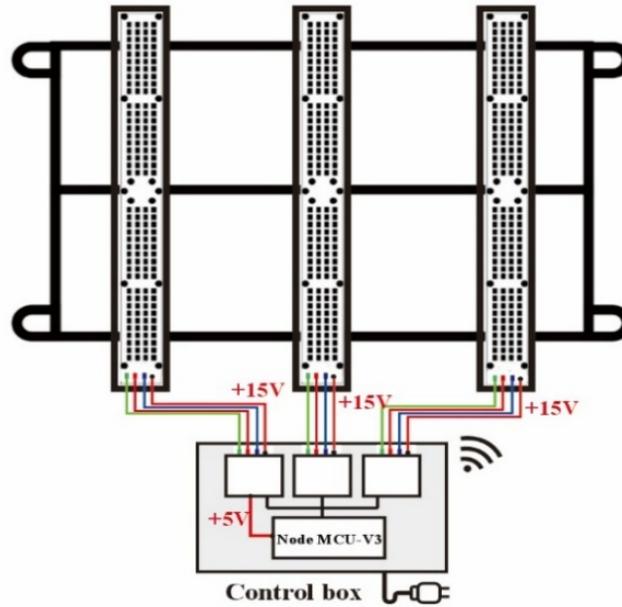**Fig. 3.** Photo of complete LED-chip panels.

Fig. 4. Schematic diagram of the complete LED lighting system.

The assembled LED lighting system was subsequently installed in the experimental greenhouse, as shown in Fig. 5a. The cultivation or illuminated area was 60 cm × 60 cm. It was divided into nine subsections, as shown in Fig. 5b, each 20 cm × 20 cm, to obtain detailed data on the spatial distribution of light intensity in the illuminated area. In the experiment, the table of the illuminated area can be adjusted by moving it up and down at distances of 20, 30, 40, and 50 cm from the lighting system.
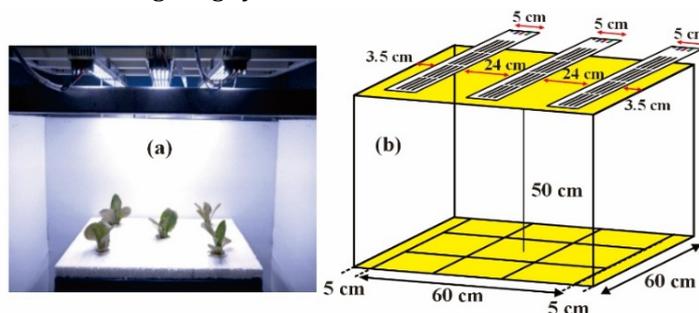

Fig. 5. Showing: (a) a photo of the cultivation of butterhead lettuce and (b) a schematic diagram of the illuminated area.
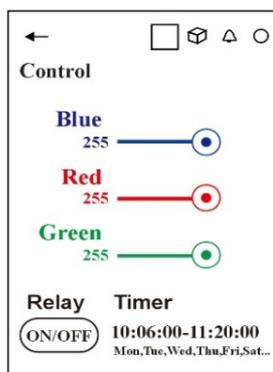

Fig. 6. IoT-based control interface for the RGB LED lighting system using the Blynk mobile application

The illuminance and spectral distribution of the LED lighting system were measured to investigate the relationship between the driving signal brightness level (duty cycle) and the corresponding light intensity and spectral characteristics of each color channel. The illuminance measurements were performed by adjusting the PWM duty cycle to 25%, 50%, 75%, and 100%. This was done using a digital light meter (Model LM-230). Measurements of illuminance on the cultivation area were conducted independently for the red, green, blue, and white light channels at various distances from the lighting system.

For spectral measurements, a spectrometer (Hopoocolor, HPCS-330P) was used to record the spectral irradiance (intensity) within the wavelength range of 380–780 nm. The device also computed key photometric parameters, including PPFD, PAR, and the intensity ratio among the three color channels (red: green: blue). Spectral measurements were conducted at a fixed distance of 40 cm from the lighting system and a duty cycle of 100%. The PWM driving signals and color channel selection were controlled via an ESP8266 microcontroller integrated with the Blynk IoT application, enabling real-time independent adjustment of the light intensity of each color component via a single control panel or a smartphone, as shown in Fig. 6.

Statistical analysis was employed to describe the controllability and stability of the developed RGB LED lighting system. Illuminance values of red, green, blue, and white light were measured at duty cycle levels of 25, 50, 75, and 100%, and at distances of 20, 30, 40, and 50 cm from the light source. For each experimental condition, illuminance measurements were repeated for 3 times, and the results are presented as mean ± standard deviation (SD). Error bars shown in the figures represent the variability of repeated measurements and indicate the repeatability of the lighting system.

To investigate the relationship between duty cycle and illuminance, linear regression analysis was applied for each light color at each distance. The coefficient of determination (R^2) was used to evaluate the strength of the linear relationship and the predictability of illuminance output under PWM control. The statistical analysis was intended to characterize the performance and operational behavior of the prototype lighting system, rather than to test hypotheses. Therefore, the analysis focused on evaluating trends and controllability of the lighting system rather than on inferential statistical comparisons.

3. Results and discussion

Fig. 7 shows a typical example of red, green, and blue light when all three sets of LED-chip panels (with 480 LED chips) were on at a duty cycle of 100%, with the distance between the LED lighting system and the cultivation area set to 50 cm. The desired light color (red, green, and blue) can be controlled to turn on independently as shown in Figs. 7a-c, respectively. The white light in Fig. 7d was obtained by turning on the red, green, and blue lights simultaneously.
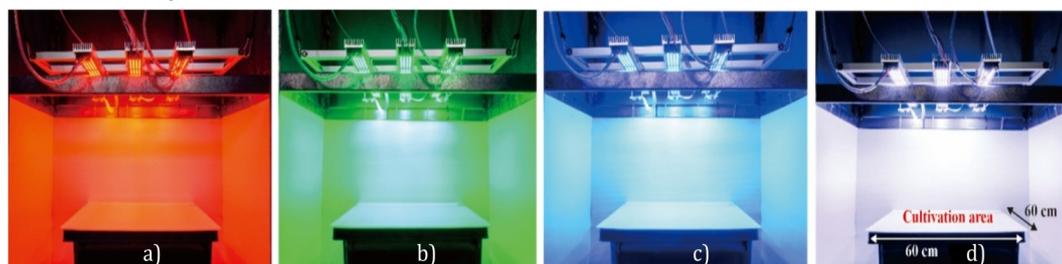

Fig. 7. Typical lighting systems of: (a) red, (b) green, (c) blue, and (d) white light.

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The illuminance at duty cycles of 25%, 50%, 75%, and 100% was measured at distances of 20, 30, 40, and 50 cm between the LED lighting system and the illuminated area of the table. The relationship between illuminance and duty cycle for the red, green, blue, and white light is shown in Fig. 8.
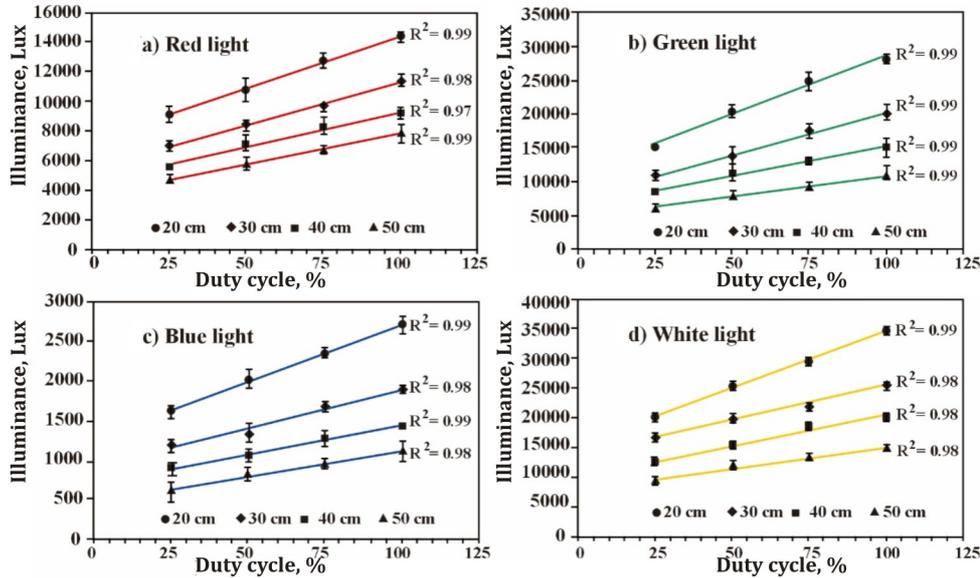
Fig. 8. Relationship between illuminance and duty cycle at different distances for red, green, blue, and white light.
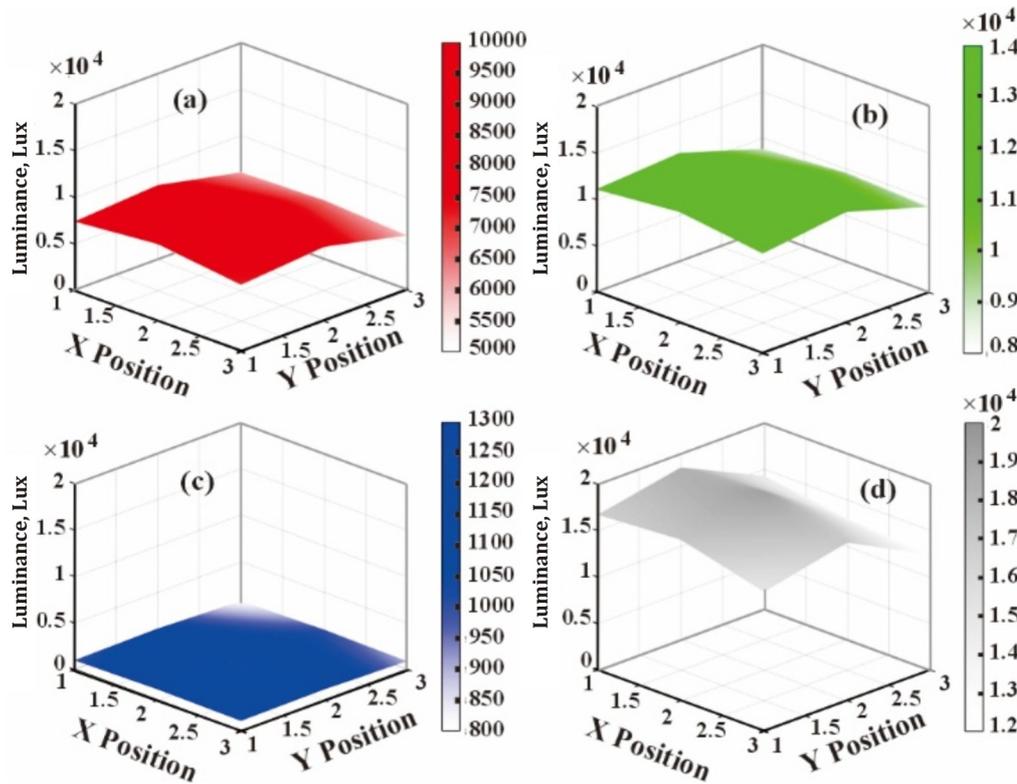

Fig. 9. Illuminance distribution of the lighting system at a distance of 40 cm on the cultivation area of 60 cm × 60 cm for: (a) red, (b) green, (c) blue, and (d) white light.

From Fig. 8, it was found that, in all cases, the illuminance consistently increased with higher duty cycles. This indicates a clear linear relationship between the PWM on/off control signal and the LEDs' brightness. The highest illuminance observed at 20 cm gradually decreased as the distance increased to 30, 40, and 50 cm. The overall illuminance of red, green, blue, and white light ranges between 4,700 -14,300, 6,400-28,500, 600- 2,700, and 9,500 -35,000 lux, respectively. The illuminance values for each section area were used to generate a 3D surface plot in MATLAB, as shown in Fig. 9, to visualize the distribution of red, green, blue, and white light across the cultivation area.

From Fig. 9a-d, the results revealed that the illuminance values for red, green, blue, and white light range from 5,900 - 9,000, 8,900-13,300, 800-1,200, and 12,400-19,300 lux, respectively. It is observed that the blue light has the most uniform distribution due to its lowest illuminance. Overall, the illuminance distribution across all colors is rather uniform.

The spectral analysis of red, green, and blue light was carried out using a spectrometer in the wavelength range of 380-780 nm. The spectral distribution of each RGB light was analyzed at a distance of 40 cm and a duty cycle of 100%. Each color exhibited a distinct narrow-band spectrum, as illustrated in Fig. 10.
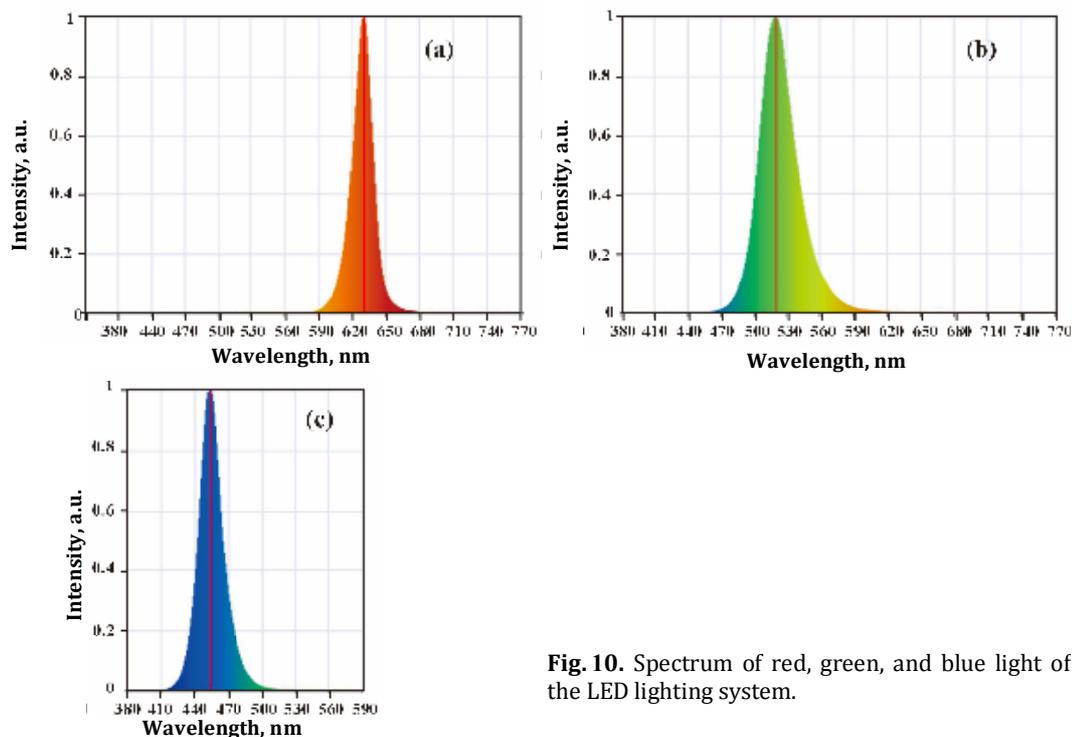
Fig. 10. Spectrum of red, green, and blue light of the LED lighting system.

The red, green, and blue lights showed a spectral peak at 630, 520, and 455 nm, respectively. It is seen that the measured peak wavelengths are about ±5 nm difference from the dominant wavelength in Table 1.

The PAR and PPFD values were also measured using a spectrometer at a distance of 40 cm with PWM duty cycles of 25, 50, 75, and 100%, and the results are summarized in Table 2. From the measured illuminance values in Fig. 8 and the measured PPFD values in Table 2, we can plot the relationship between illuminance and PPFD for red, green, and blue light as shown in Fig. 11.
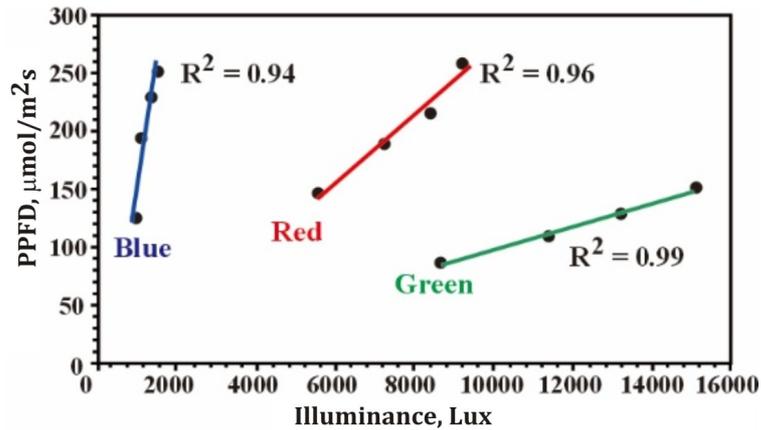
Fig. 11. Relationship between illuminance and PPFD at a distance of 40 cm and a duty cycle of 100%.

Table 2. Measured PAR and PPFD values of red, green and blue light.

Light	Duty Cycle,%	PAR, mW/cm²	PPFD, µmol/m² s
Red	25	2.8	148
	50	3.6	190
	75	4.1	216
	100	5.0	261
Green	25	2.0	88
	50	2.5	111
	75	2.9	129
	100	3.5	152
Blue	25	3.3	126
	50	5.1	194
	75	6.3	230
	100	6.6	252
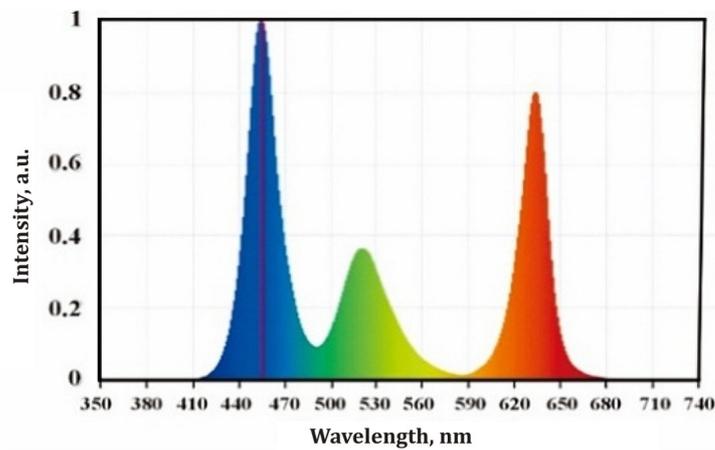
Fig. 12. Spectrum of white light at a distance of 40 cm and a duty cycle of 100%.

From Table 2, the red light had a PAR of approximately 5.0 mW/cm² and a PPFD of about 261 µmol/m² s, which falls within the photosynthetically active region. The spectral wavelength was in the 590-680 nm range. This corresponds to the absorption bands of chlorophyll a and b [30], which play a vital role in stimulating photosynthesis and promoting stem elongation in plants.

The green light had a PAR value of approximately 3.5 mW/cm² and a PPFD value of about 152 µmol/m² s. The spectral graph shows the light distribution within the 500–550 nm range, corresponding to the green region of the visible spectrum. Although chlorophyll absorbs green light less efficiently than red or blue light [31], green light can penetrate more deeply into the lower leaf layers, thereby enhancing canopy-level photosynthetic efficiency and promoting uniform leaf growth [32].

The blue light showed a PAR value of approximately 6.6 mW/cm² and a PPFD value of about 252 µmol/m² s. The blue light plays a critical role in chlorophyll synthesis, stomatal opening, and photomorphogenic regulation [33]. The blue light with high-energy photons can stimulate leaf expansion, chloroplast development, and compact plant morphology, thereby improving overall physiological quality and growth uniformity.

Overall, the measured PAR values indicate that the RGB LED system delivers controllable radiant power across the 400–700 nm photosynthetically active range. The proportional variation of PAR with PWM duty cycle confirms stable regulation of radiant output, indicating that the system can reliably adjust energy delivery according to predefined lighting conditions.

From Fig. 11, the graphs showed the linear relationship between illuminance and PPFD. It indicates that these graphs can be used as a calibration curve of the lighting system. The system controls the light intensity by adjusting the PWM duty cycle, which is displayed in lux and converted directly into PPFD without a conversion factor. It can be observed that the PPFD values, a key parameter in plant science, varied proportionally to the lux value. Therefore, when defining light ratios in terms of PPFD, such as a red-to-blue ratio of 2:1, these graphs can be used to convert the desired PPFD value for each color into the corresponding lux value.

The spectrum of white light was measured at a distance of 40 cm for PWM duty cycles of 25%, 50%, 75%, and 100%. The typical spectrum of white light at a duty cycle of 100% is shown in Fig. 12. The PAR and PPFD values were also measured and presented in Table 3. The spectrometer calculated the areas of the intensity peaks in Fig. 12. Then, the red, green, and blue ratios in white light were determined, as shown in Table 3.

Table 3. Measured PAR and PPFDs of white light at a distance of 40 cm under different duty cycles.

Light	Duty cycle, %	PAR, mW/cm²	PPFD, µmol/m² s	Red ratio	Green ratio	Blue ratio
White	25	6.1	272	32.9	24.5	42.6
	50	7.5	332	32.6	24.6	42.8
	75	8.3	368	31.1	25.5	43.4
	100	9.2	380	32.4	25.1	42.5

The results, summarized in Table 3, demonstrate that increasing the duty cycle led to a proportional increase in both PAR and PPFD, confirming the system's precise ability to modulate light intensity without spectral distortion.

As shown in Table 3, the proportions of the color components in white light (red, green, and blue ratios) remained stable across all duty cycle levels, with average values of approximately 32, 25, and 43%, respectively. This indicates that increasing light intensity via duty-cycle adjustment did not significantly alter the spectral balance of each color channel. In other words, the system

can increase the light quantity without changing the light quality, demonstrating the spectral stability of the developed LED lighting system. The consistently high blue ratio (around 42–43%) also confirms that the emitted light corresponds to a "cool white" spectrum, which is suitable for leafy green crops such as lettuce and salad greens that benefit from high-blue, low-heat illumination to promote chlorophyll synthesis and reduce heat stress.

In practical applications, the measured PPFD values ranging from 200 to 400 µmol/m² s fall within the optimal range for photosynthesis in leafy vegetables such as lettuce and spinach. According to Miao et al. [34], both crops exhibit enhanced growth rates as PPFD increases up to approximately 300 µmol/m² s. Therefore, the developed LED lighting system in this work can be applied in a controlled environment. From the measured illuminance values in Fig. 8 and the measured PPFD values in Table 3. We can plot the relationships between illuminance and PPFD, and between duty cycle and PPFD, for white light, as shown in Fig. 13.
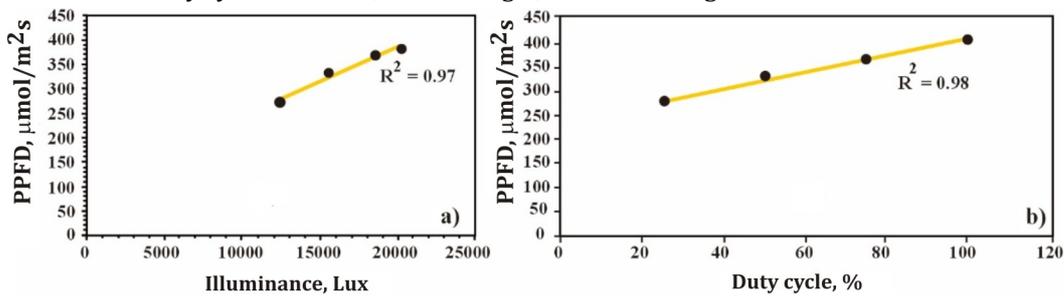
Fig. 13. Relationship between: (a) illuminance and PPFD, and (b) duty cycle and PPFD at a distance of 40 cm for white light.

The relationship between illuminance and PPFD in Fig. 13a for white light is also linear, which agrees with that of red, green, and blue light in Fig. 11. The relationship between PPFD and duty cycle of white light obtained from the lighting system in this work is linear, as shown in Fig. 13b. It indicates that the system can precisely regulate the "quantity of photons for photosynthesis" while maintaining consistent "spectral quality". This feature is essential for horticultural lighting in controlled environments.

4. Conclusions

This study developed an IoT-based RGB LED lighting system capable of precisely controlling light intensity, photoperiod, and spectral composition in real time for Hydroponic plants applications. The system integrates 480 high-power RGB LED chips with an ESP8266 microcontroller, enabling flexible duty-cycle adjustment and seamless control through the Blynk smartphone application. Experimental results confirmed a clear linear relationship between duty cycle and illuminance across all color channels.

Spectral analysis revealed that each RGB channel exhibited distinct and stable peaks within the PAR range (400–700 nm). When combined to generate white light, the system maintained consistent color-channel ratios (approximately 32% red, 25% green, and 43% blue) across all duty-cycle levels, indicating that changes in brightness altered only the amount of light without affecting its spectral quality.

In addition, the developed system demonstrates fine quantitative control of photosynthetic photon flux density (PPFD) via PWM duty-cycle modulation, while preserving spectral consistency without requiring any modifications to the lighting hardware. The measured PAR values exhibited proportional variation with PWM duty cycle. This capability

allows cultivation conditions to be adjusted dynamically according to plant developmental stages. Moreover, integrating IoT-based control enhances operational flexibility by enabling real-time monitoring, remote adjustment, and automated scheduling of lighting parameters.

Conflict of interest. Authors declare no conflict of interest.

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Анотація. *У цьому дослідженні представлено розробку системи світлодіодного освітлення RGB на основі Інтернету речей для точного та гнучкого керування світлом гідропонних рослин. Система складається з 480 потужних RGB-світлодіодів, керованих мікроконтролером ESP8266, що дозволяє регулювати інтенсивність світла, фотоперіод та співвідношення кольорів у режимі реального часу за допомогою смартфона. Широтно-імпульсна модуляція дозволяє генерувати біле світло, придатне для різних стадій росту рослин. Експериментальні результати показують лінійну кореляцію між освітленістю та прогальністю для всіх колірних каналів. Спектральний аналіз підтверджує стабільне випромінювання в діапазоні фотосинтетично активного випромінювання (400–700 нм), при цьому спектральний склад залишається незмінним навіть при зменшенні яскравості (затемненні). Система демонструє високу точність керування та адаптивність для регулювання освітлення росту рослин, особливо для листових овочів, таких як салат.*

Ключові слова: *світлодіодне освітлення RGB, гідропонні рослини, спектральний аналіз, широтно-імпульсна модуляція, керування на основі Інтернету речей*