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Design and Fabrication of a Microcontroller-Based Automatic LED Grow Light Array System for Leafy Vegetables in Indoor Vertical Hydroponic

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Abstract

Indoor vertical hydroponic systems require precise and energy-efficient lighting to support optimal growth of leafy vegetables. This study presents the design and fabrication of a microcontroller-based automatic LED grow light system tailored for indoor hydroponics. A tailored LED grow light is necessary because each crop responds uniquely to light quality and intensity, and a customized spectrum ensures optimal growth while minimizing energy use. The system integrates a red–green–blue LED configuration (70:10:20%) with an ESP32 microcontroller, real-time clock (RTC), BH1750 light sensor, keypad interface, and LCD. The lighting cycle was programmed for 12 hours per day and tested continuously over two days. The system demonstrated accurate scheduling, with LED activation at 06:00 and deactivation at 18:00 and a timing deviation of only 1–2 seconds. During operation, the system maintained a stable photosynthetic photon flux density (PPFD) of 260–275 μmol/m²/s, producing an estimated daily light integral (DLI) of about 12 mol/m²/day, which is suitable for leafy vegetable production. Light distribution analysis using cubic interpolation showed that increasing the lamp height from 20 cm to 30 cm improved spatial uniformity, with the most uniform distribution achieved at 30 cm despite a slight reduction in intensity. The system consumed 2.65 kWh per day, covering four LED arrays and the control module. Overall, the proposed system offers a reliable, programmable, and energy-efficient lighting solution for indoor hydroponic environments, supporting sustainable crop production through precise scheduling and an optimized spectral configuration.

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1. Introduction

Rapid urbanization and the growing population in major Indonesian cities have led to limited land availability for conventional agriculture (Herdiansyah et al. 2023, Silver 2024). This condition has driven the emergence of modern farming systems that utilize confined spaces, one of which is indoor vertical hydroponic farming (Lindawati et al. 2015, Nanda et al. 2025). Hydroponics is a soilless cultivation method that uses nutrient solutions as the growing medium, enabling plant production in limited areas such as offices, apartments, and commercial buildings (Susilawati 2019, Dwiratna et al. 2022a, Dwiratna et al. 2022b). A key advantage of this system is its ability to provide full control over environmental factors such as light, temperature, and humidity, thereby supporting consistent and high-quality plant growth (Boros et al. 2023).

In the context of indoor hydroponics, lighting is a critical factor determining plant growth due to the absence of natural sunlight (Budavári et al. 2024). As a result, artificial lighting, particularly Light Emitting Diode (LED) systems, has emerged as the primary solution because of its energy efficiency, low power consumption, and ability to emit specific light spectra that align with plant physiological needs. Plants absorb light primarily within the 400–700 nm wavelength range, known as Photosynthetically Active Radiation (PAR) (Singh et al. 2015, Liu et al. 2025). Within this spectrum, red light (approximately 640 nm) and blue light (approximately 440 nm) play significant roles in photosynthesis and morphogenesis, while green light (approximately 510 nm) also contributes to vegetative growth (Johkan et al. 2012, Singh et al. 2015, Gupta & Agarwal 2017).

Previous studies have demonstrated that a combination of red, green, and blue (RGB) light spectra is more effective in supporting plant growth compared to monochromatic lighting. Lin et al. (2013) reported that RGB lighting enhanced both fresh and dry weight of lettuce plants by up to 10% compared to red-blue lighting alone. Similarly, Lim et al. (2023) showed that an RGB ratio of 4:1:1 at an intensity of 200 μmol/m^2/s with a photoperiod of 16 hours per day resulted in optimal plant growth. In addition to spectral composition, the vertical distance between the light source and the plant canopy significantly affects light intensity and quality. Lutfi et al. (2022) found that a 20 cm spacing produced greener leaf color compared to a 60 cm distance, due to higher light intensity reaching the plant surface.

Although numerous studies have investigated the effects of LED spectra on plant growth, most have focused on commercial lighting systems. However, the need for specific and optimized light spectra for certain crops, such as leafy vegetables, presents an opportunity to design custom grow light systems through self-assembly. A notable research gap exists in the development of do-it-yourself (DIY) LED grow lights with adjustable spectral compositions and light intensities tailored precisely to plant requirements. Such custom-built systems offer flexibility in determining the layout configuration, light distribution, cost efficiency, and design optimization for limited indoor spaces. Therefore, this study focuses on the design and development of a prototype automatic lighting system based on a microcontroller, utilizing red (70%), blue (20%), and green (10%) LEDs as artificial light sources for leafy vegetables in an indoor vertical hydroponic system. The system is equipped with a Real-Time Clock (RTC) module to enable automated lighting scheduling that synchronizes with real-time conditions. This approach is expected to provide practical and applicable contributions to the development of efficient and technologically self-reliant hydroponic systems for both household and small-scale commercial applications in the future.

2. Material and Methods

2.1 Indoor Vertical Hydroponics

Figure 1 illustrates a compact and efficient indoor vertical hydroponic system equipped with an automated lighting unit, measuring 130 cm × 60 cm × 150 cm (length × width × height). The tiered structure is designed to maximize space efficiency for cultivating leafy vegetables in indoor, controlled environments. The LED grow light system was developed and tested as a prototype platform targeting common indoor hydroponic commodities such as lettuce, pak choi, and mustard greens. At the top, a control panel houses the ESP32 microcontroller, LCD, and keypad, functioning as the main interface for managing the lighting schedules and system parameters. Each cultivation level was equipped with RGB SMD LED lamps that served as artificial light sources tailored to the photosynthetic needs of the plants. The crops were grown in net pots placed on NFT (Nutrient Film Technique) channels made of PVC, each 130 cm in length and 10 cm in width, allowing a thin layer of nutrient solution to flow over the roots efficiently. The nutrient solution was recirculated from a 25-liter reservoir located at the base of the system, ensuring water efficiency and nutrient stability through a closed-loop design. The integration of structural design, lighting, and nutrient delivery supports optimal plant growth in controlled, indoor environments.

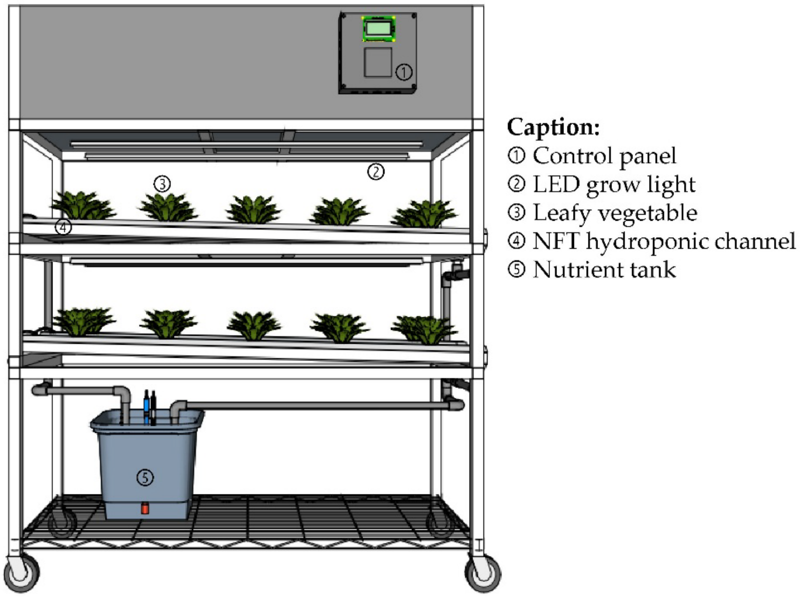


Figure 1. Indoor vertical hydroponic system design integrated with an automatic LED lighting array.

2.2 Design of LED lighting System

2.2.1 Analysis of Plant Light Requirements

The plant light requirements were analyzed to determine the optimal light intensity required for plant growth. This intensity is determined based on the Daily Light Integral (DLI), which is the total amount of light (in the form of active photons) received by plants in one day over a specific area. DLI values vary depending on the plant species and serve as an important indicator for farmers in selecting suitable crops based on light availability and the need for supplemental lighting. The DLI was calculated using the following equation (Equation 1) (Ghazal et al. 2023). Where DLI is the total daily light requirement of the plant (mol/m²/day), PPFD is the photosynthetic photon flux density, which is the intensity of photosynthetically active light that reaches the leaf surface (μmol/m²/s), photoperiod is the lighting duration per day (hours), 3,600 is the number of seconds in one hour, and 1,000,000 is the conversion factor from μmol to mol.

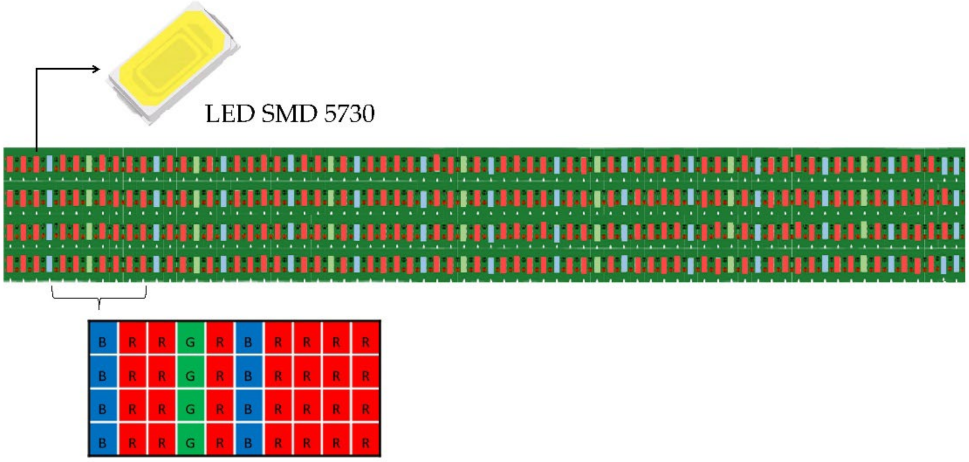
$$\mathrm{DLI} = \frac{\mathrm{PPFD} \times \mathrm{Photoperiod} \times 3{,}600}{1{,}000{,}000} \tag{1}$$

In this study, the primary objective was to design an artificial lighting system capable of fulfilling the light requirements of leafy vegetables, such as lettuce. Runkle (2011) recommended a minimum Daily Light Integral (DLI) of 12–14 mol/m²/day for optimal lettuce production. Gavhane et al. (2023) reported successful use of photoperiods ranging from 12 to 20 hours to determine the optimal DLI for indoor lettuce cultivation. Based on these references, this study adopted a DLI parameter of 12 mol/m²/day with a photoperiod of 12 hours. According to Equation 2, the LED system must deliver a minimum light intensity of 277.77 μmol/m²/s to effectively meet the daily light requirements of the plants.

$$\mathrm{PPFD} = \frac{12 \times 1{,}000{,}000}{12 \times 3{,}600} = 277.77\ \mu\mathrm{mol/m^2/s} \tag{2}$$

2.2.2 Design of the LED Array Configuration

The LED-based lighting system was designed to meet a minimum PPFD requirement of 277.77 μmol/m²/s, as determined from the calculated DLI. The design, assembly, and light intensity testing of the LED grow light system were conducted systematically to achieve this target. The LED chips used in this study were of the SMD 5730 type, selected for their light spectrum suitability for supporting photosynthetic activity. The lighting system was tested using a PPFD meter (Photone, Grow Light Meter, Lightray Innovation, Switzerland). After lamp assembly was completed, PPFD measurements were performed at a vertical distance of 25 cm from the target surface. The measurement results were used to evaluate the system's compliance with the targeted PPFD value. This evaluation served as an essential foundation for further development, including adjustments to the number of LED chips, lamp height, and array configuration, to ensure lighting efficiency and effectiveness that align with the physiological needs of the hydroponic crops.



B	R	R	G	R	B	R	R	R	R
B	R	R	G	R	B	R	R	R	R
B	R	R	G	R	B	R	R	R	R
B	R	R	G	R	B	R	R	R	R

Figure 2. Enclosure of the LED grow light array system and formation of the LED utilizing SMD5730 chips in red (R), green (G), and blue (B) color variations.

Based on the experimental results to meet the minimum PPFD requirement, each LED light set was configured with 202 red chips, 28 green chips, and 58 blue chips, along with 288 resistors. The spectral configuration was designed with a color composition of 70% red, 10% green, and 20% blue (Figure 2). Each chip was soldered onto a PCB and equipped with a resistor to limit the current flow. In total, the system utilized four LED light sets, resulting in 808 red chips, 112 green chips, 232 blue chips, and 1,152 resistors in total. Each LED light set was housed in a casing fitted with a heat sink to dissipate the generated heat, and an aluminum plate was used as a reflector. The detailed dimensions and structural configuration of the LED grow light array system are shown in Figure 3. The casing measured 100 cm × 18 cm × 10 cm (length × width × height). The reflector focused on the light distribution, ensuring that the intensity received by the plants was evenly distributed and optimized to support their growth and photosynthetic processes.

The spectral ratio of 70% red, 20% blue, and 10% green is supported by previous findings showing that red light is the primary driver of photosynthesis and biomass accumulation (Folta & Carvalho 2015), whereas 15–25% blue light is required to regulate stomatal opening, chlorophyll formation, and photomorphogenesis (Hogewoning et al. 2010, Zheng & Van Labeke 2017). The addition of approximately 10% green light enhances light penetration into deeper leaf layers and improves whole-canopy photosynthesis (Kim et al. 2004, Snowden et al. 2016). Collectively, these studies support the use of a red-dominant spectrum supplemented with moderate blue and low green light for the optimal growth of leafy vegetables in controlled environments.

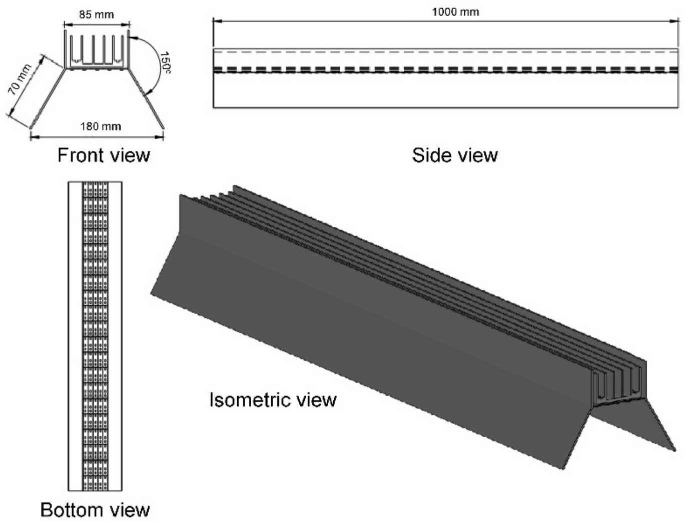


Figure 3. Orthographic projections (front, side, and bottom views) and isometric pictorial view of the designed LED grow-light array system.

2.2.3 Electronic Schematic Diagram

The schematic of the microcontroller-based automatic lighting system is shown in Figure 4. The system was designed based on functional and structural principles to enable scheduled plant lighting control. An ESP32 microcontroller operated the entire system as the central processing unit. The ESP32 receives input from several key components, including: (a) a BH1750 light intensity sensor, which detects the lux value of the LED light and sends analog data to the ESP32 for analysis; and (b) a DS3231 Real-Time Clock (RTC) module, which provides real-time information (seconds, minutes, hours, days, and years), allowing the system to automatically switch the lights on and off according to the programmed schedule.

The control center of the system is the ESP32 microcontroller, which processes the data from various sensors and supporting modules. Light intensity data were obtained from the BH1750 sensor, which measures the amount of lux that the plants receive and transmits to the ESP32 for analysis and decision-making regarding light activation. Additionally, the system integrates an RTC module DS3231 to maintain accurate timekeeping, ensuring that the light schedule aligns precisely with the required photoperiod. A 16 × 4 LCD was used to display system information in real time, including the time, sensor readings, and the system's operational status. User interaction is facilitated through a 4×4 keypad module, allowing users to input scheduling parameters or manually configure the system. All LEDs were controlled via a relay module that received logical signals from the ESP32 to switch the electrical connection on or off according to the programmed light schedule and required intensity. The system was powered by two separate power supplies: a 12V DC power supply dedicated to LED circuits and a 5V DC power supply for the ESP32, sensors, keypad, RTC, and LCD modules.

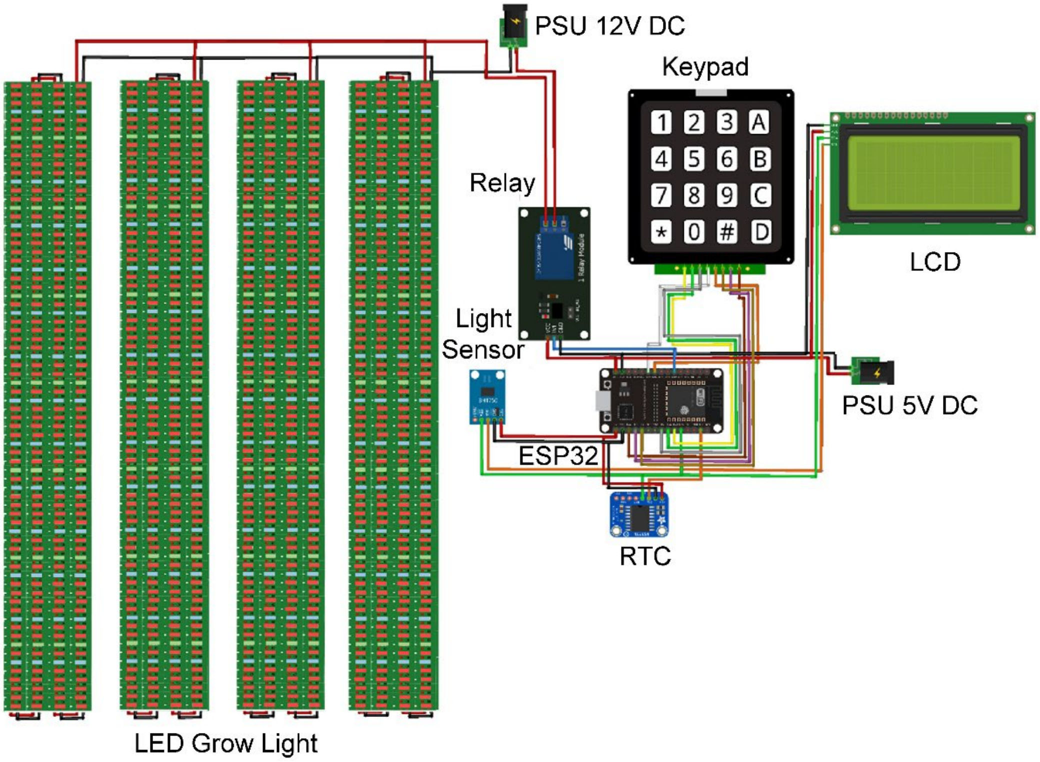


Figure 4. Schematic diagram of the fabricated LED grow light system controlled by ESP32 and integrated with a light sensor, RTC, LCD, and keypad.

2.2.4 Framework LED Lighting System

A flow diagram of the lighting control and light intensity monitoring system based on the ESP32 microcontroller is shown in Figure 5. The system was developed using the C programming language on the Arduino IDE platform and was designed to control the activation time of the LED grow lights while simultaneously monitoring their light intensity in real time. The process began when the system was powered on, triggering the ESP32 to retrieve the current time from the RTC module and read the light intensity data from the sensor. The RTC time was synchronized with the actual time to ensure scheduling accuracy. The user inputs the lighting schedule, including the start time and duration, which are stored in the microcontroller’s memory. The ESP32 continuously monitored the RTC time. When the actual time matches the predefined schedule, the relay is activated to switch on the LED grow lights. The light sensor then measures the light intensity and sends the data to ESP32 for analysis. All relevant information, including the time, scheduling status, and sensor readings, was displayed on an LCD screen as a monitoring interface. This control and monitoring loop operates automatically and continuously, enabling efficient lighting management and accurate real-time intensity monitoring within an indoor hydroponic system.

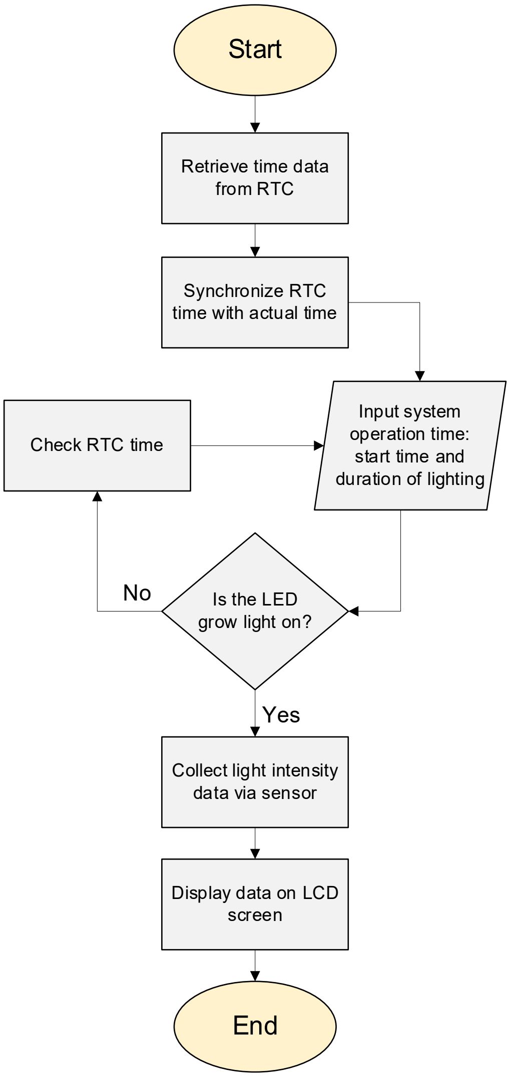


Figure 5. Flow diagram of the ESP32-based lighting control system for scheduling and real-time light intensity monitoring.

2.3 Testing

2.3.1 Lighting Scheduling

This test evaluated the accuracy of the system in automatically switching the LED lights on and off according to a user-defined schedule. The system was tested over two consecutive days, with a lighting period set at 12 hours per day, from 06:00 to 18:00. The scheduling was performed using the keypad interface on the control box, and the reference time was provided by the DS3231 RTC module integrated with the ESP32 microcontroller. During the testing period, the light intensity, represented by the Photosynthetic Photon Flux Density (PPFD), was continuously measured using a BH1750 light sensor and recorded to verify the system's response to the predefined schedule. The measurement data were used to ensure that the system could accurately switch the lighting on and off at the appropriate time and maintain a stable intensity during the lighting period. The success of the test was determined based on the conformity of the on/off timing with the programmed schedule and the stability of the PPFD values during the active cycle.

2.3.2 Light Distribution

Light distribution evaluation was conducted to determine the intensity distribution of the LED lighting in the indoor hydroponic system. Measurements were performed at three different lamp heights: 15 cm, 20 cm, and 25 cm above the NFT hydroponic channel, covering a measurement area of 130 cm × 60 cm (Figure 6).

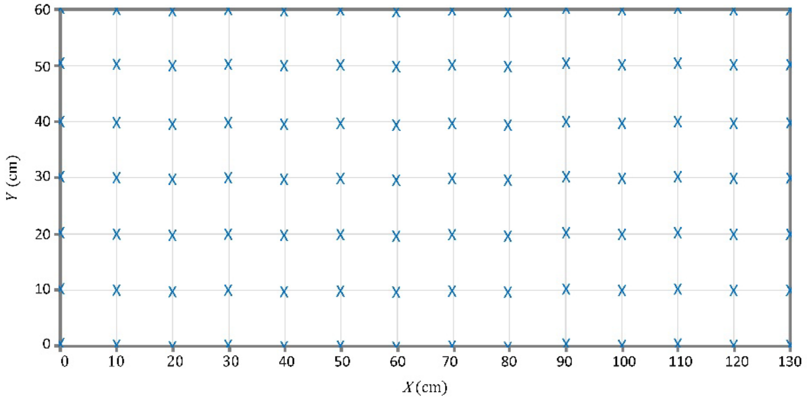


Figure 6. Measurement point locations for evaluating the light distribution over a 130 × 60 cm area. The '×' symbols indicate the measurement points used in the interpolation process.

A total of 98 measurement points were systematically assigned and evenly distributed across the area to obtain an accurate representation of the light distribution. The light intensity at each point was measured in PPFD units (μmol/m²/s). The intensity values were processed using cubic interpolation to generate a contour map of the light distribution.

The interpolation grid was generated at a resolution of 100 × 100 points, with 1 cm intervals along the X- and Y-axes based on the measurement area dimensions. The interpolation results were visualized as contour maps with 30 color gradient levels (levels = 30). This study employed the SciPy library in the Python environment to perform a two-dimensional cubic interpolation on the measured data. The resulting visualizations revealed varying light distribution patterns depending on lamp height, which were used to determine the optimal lighting configuration for the indoor hydroponic system.

2.3.3 Power Consumption

Power consumption testing was conducted to determine the total electrical energy requirements of the system during operation. Measurements were taken using a digital clamp meter (Hioki 3286-20, Japan) by clamping the device onto the main power cable while the system was operating in the automatic scheduling mode. The current (I) and voltage (V) values obtained during the operating period (t) were used to calculate the total power consumption (W) of the LED grow light system (Equation 3).

$$W = V \times I \times t \tag{3}$$

3. Results and Discussion

3.1 Prototype of the Automatic LED Lighting System

The prototype of the automatic lighting system developed in this study was designed to support plant growth in an indoor vertical hydroponic system. The system integrates RGB LED lights with an automatic control unit based on an ESP32 microcontroller, which enables real-time lighting scheduling. The physical structure consisted of a two-tier planting rack, each equipped with two LED array units installed above the plants. The LED lights were configured with a spectral composition of 70% red, 10% green, and 20% blue. This ratio is based on the study reported by Ahmed et al. (2020), who demonstrated that plant pigments absorb red light (610–760 nm) and play a significant role in photosynthesis, flowering, and budding. Blue light (450–500 nm) promotes chlorophyll formation and stimulates early photomorphogenic responses. Although green light (500–570 nm) is less absorbed, it can penetrate deeper into the lower leaf layers and aid in the growth of the inner canopy layers.

Table 1. Technical specifications of the automatic LED grow light array system.

No.	Component	Specification
1	Microcontroller	ESP32, dual-core, WiFi + Bluetooth
2	Light sensor	BH1750
3	Real-time clock (RTC)	DS3231
4	LED chip type	SMD 5730 RGB
5	Spectrum composition	R:G:B (70:10:20)
6	Number of lamps per rack	2 units per rack (total of 4 units for two levels)
7	Lamp input power	± 12V DC
8	Lighting schedule	Input via keypad: start time, duration, and active days
9	Monitoring	16×4 LCD display
10	Reflector	Aluminum
11	Heatsink	Aluminum fin block

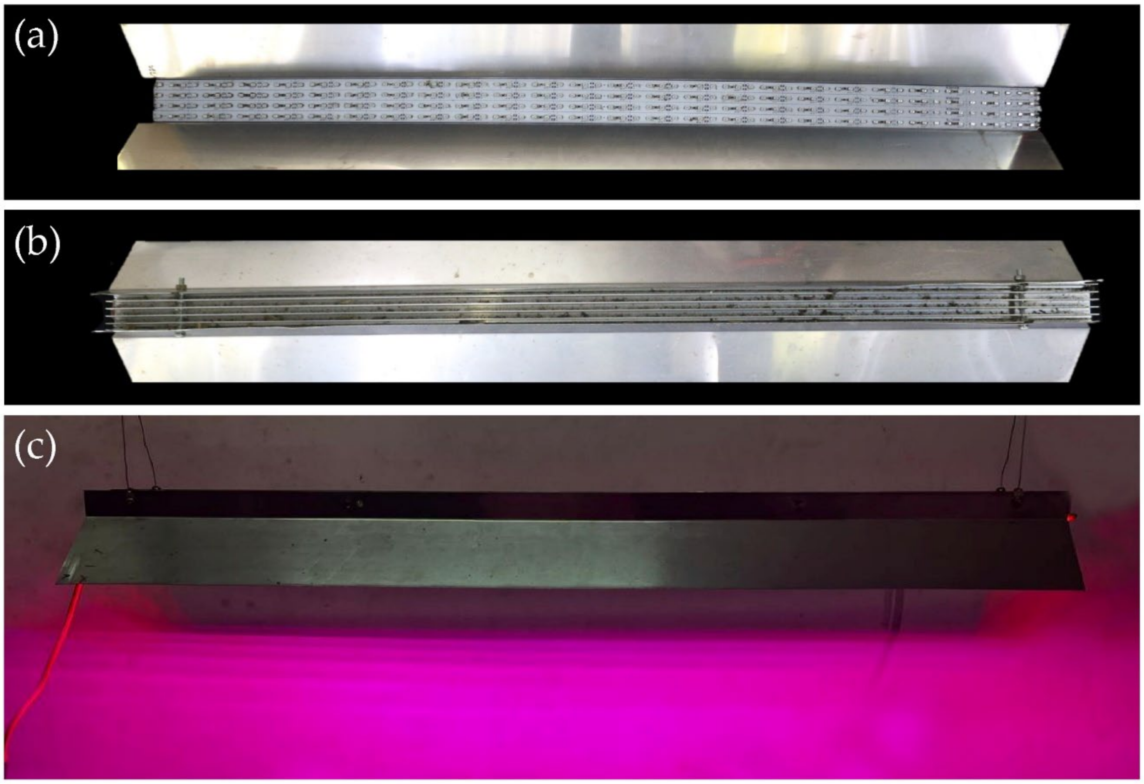


Figure 7. Prototype of the LED lighting system: (a) bottom view of the LED array, (b) top view of the aluminum heatsink, and (c) light visualization from the RGB spectral combination.

The lighting system was designed to meet the light intensity requirements of the plants and ensure energy efficiency and uniform light distribution. The use of red-blue LED lights has proven effective in supporting these objectives, as demonstrated by Pennisi et al. (2020), who reported that a red-blue LED configuration could optimize energy efficiency and crop yield in indoor cultivation. Each LED unit was mounted on a PCB equipped with a heatsink and reflector, dissipating heat and focusing the light distribution onto the plant area. The lighting is controlled automatically through an RTC module and light sensor, with a user interface consisting of a keypad and an LCD. From the control perspective, the use of an ESP32 microcontroller enables the system to operate modularly, energy efficiently, and at a low cost. Singh et al. (2015) also emphasized that smart LED-based lighting control systems can reduce energy consumption by up to 40–50% compared to conventional greenhouse lighting systems. A prototype visualization of the lighting system is shown in Figure 7, with a dominant magenta light emission.

3.2 Lighting Schedule Testing

Lighting schedule testing was conducted to evaluate the accuracy of the system in automatically controlling the on/off timing of the lights based on parameters input by the user. The system utilizes the DS3231 RTC module as a real-time clock reference, whereas the ESP32 microcontroller executes the scheduling logic. Figure 8 illustrates the performance of the automatic lighting system over two consecutive days.

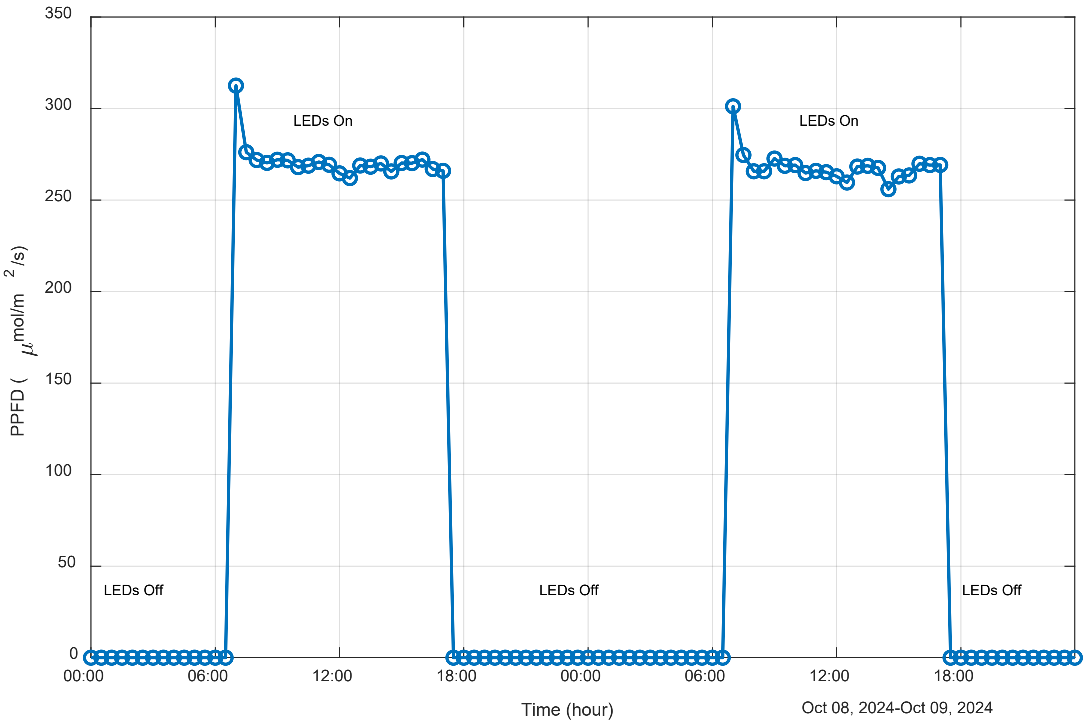


Figure 8. The performance graph of the automatic lighting system over two days of testing shows the LED on/off pattern scheduled from 06:00 to 18:00 WIB daily. PPFD values increased when the lights were on and returned to zero when the lights were off, indicating an accurate and consistent response of the system to the set timing.

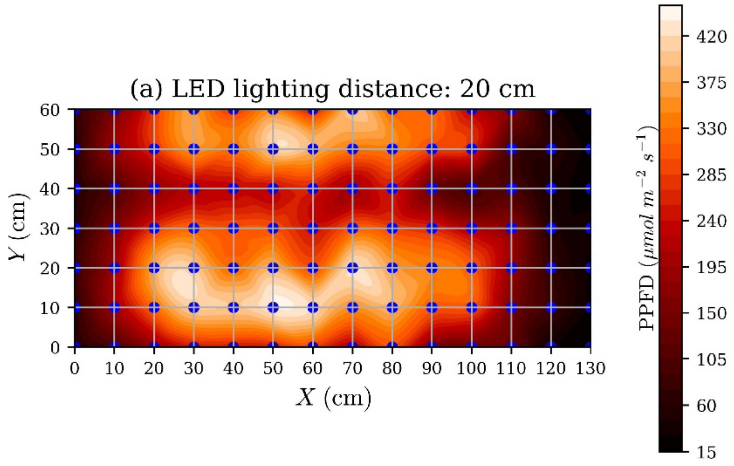
Performance testing showed that the system could turn the LED lights on precisely at 06:00 and off at 18:00 each day, providing a consistent 12-hour photoperiod. During the LEDs On phase, the PPFD remained stable within the 260 to 275 μmol/m²/s range, with a brief spike exceeding 300 μmol/m²/s at the initial activation before stabilizing. The system completely ceased light emission in the LEDs Off phase (18:00 to 06:00). The PPFD values dropped to zero, indicating that the relay effectively cut off the power without leakage or switching delay. Analysis showed that the deviation in lamp activation and deactivation times was within 1 to 2 seconds of the scheduled time, demonstrating high system accuracy. The system's performance exhibited time consistency and stable light output during the active period, reflecting the optimal functioning of all components, including the RTC module, programmed scheduling logic, and relay control. These results confirm that the developed automatic scheduling system can precisely replicate the natural light cycle in an indoor cultivation environment.

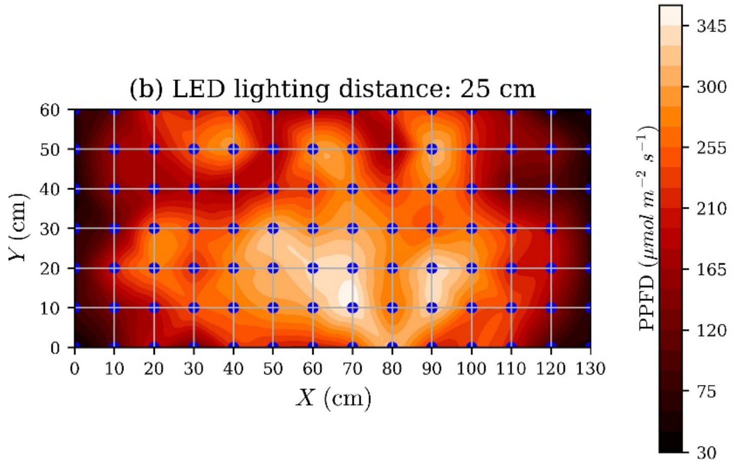
3.3 Light Distribution Testing

The results of the light distribution test indicated that lamp height significantly affected the light intensity distribution across the plant area. Figure 9 shows the PPFD distribution from the LED lighting system at three different heights: (a) 20 cm, (b) 25 cm, and (c) 30 cm. Brighter colors indicate higher light intensities, whereas darker colors represent areas with lower intensities. At a height of 20 cm (Figure 9a), the light distribution pattern appeared highly concentrated at several points directly beneath the LEDs, particularly in the center of the measurement area. Points with PPFD values exceeding 400 μmol/m²/s appeared only locally and decreased rapidly toward the edges, indicating an uneven distribution. This suggests that the lamps were too close to the plant surface, resulting in only the area directly under the lamps receiving high intensity, while peripheral areas were under-illuminated. Conversely, at a height of 25 cm (Figure 9b), the light distribution improved. Bright spots are more widely spread, and the color gradient indicates a smoother intensity transition from the center to the edge. The maximum PPFD value decreased to approximately 330 μmol/m²/s, but the area covered by moderate PPFD values (210–300 μmol/m²/s) became broader. This pattern indicates a more proportional lighting across the entire planting area. The most uniform distribution was achieved at a height of 30 cm (Figure 9c). The maximum intensity further decreased to approximately 320 μmol/m²/s, but the light distribution across the entire surface became more homogeneous. Areas with moderate and low intensities were evenly distributed, indicating that there were no excessively bright or dark spots. This pattern is ideal for hydroponic systems, as each plant receives a relatively equal light intensity, resulting in more uniform plant growth. Overall, increasing lamp height decreased peak PPFD values but improved light distribution uniformity. Pennisi et al. (2020) indicated that a PPFD of 250 μmol/m²/s is the optimal light intensity level to maximize energy and water use efficiency, as well as to enhance the yield and physiological quality of lettuce and basil in indoor cultivation systems using red-blue LED lighting. This highlights the importance of precise lighting design in closed hydroponic systems.

3.4 Power Consumption Testing

A power consumption test was conducted to determine the daily energy requirements of the entire automatic lighting system. Calculations were performed by considering all system components, including the electronic circuitry in the control box and the four LED light units used in the indoor vertical hydroponic system. Based on measurements using a digital clamp meter, the total current (amperes) drawn by the system was recorded at 0.96 A with an operating voltage of 230 V. With a lighting duration of 12 hours per day, the total energy consumption of the system was approximately 2.65 kWh/day. This value reflects the energy efficiency of the microcontroller-based LED lighting system, which generally remains within acceptable limits for small- to medium-scale indoor plant cultivation applications.


(a) LED lighting distance: 20 cm


(b) LED lighting distance: 25 cm

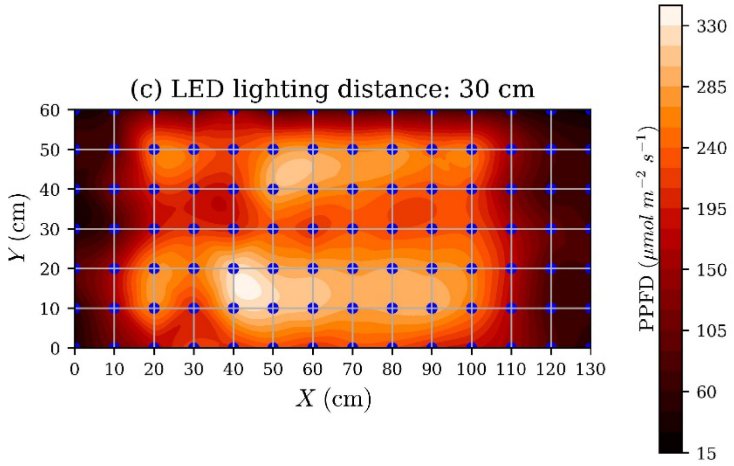

(c) LED lighting distance: 30 cm

Figure 9. Light intensity distribution (PPFD) from the LED lighting system at three different heights: (a) 20 cm, (b) 25 cm, and (c) 30 cm.

4. Conclusion

In this study, we successfully developed and evaluated an automatic LED lighting system for indoor vertical hydroponic cultivation. The system integrates programmable scheduling, real-time light monitoring, and LED arrays configured with red (70%), blue (20%), and green (10%) spectral compositions. Performance testing showed that the system accurately executed the scheduled light cycles, switching on at 06:00 and off at 18:00, with a consistent photoperiod of 12 h per day. The measured PPFD during the active lighting phase remained within the optimal range of 260–275 μmol/m²/s, which was sufficient to meet a daily light integral (DLI) of approximately 12 mol/m²/day, which aligns with the recommended light requirements for leafy vegetables. Light distribution testing indicated that a lamp height of 30 cm provided the most uniform illumination across the plant area, thereby minimizing hotspots and shadows. Despite slightly lower peak PPFD values at this height (~320 μmol/m²/s), the even distribution enhanced uniform plant growth. The total daily power consumption of the system was 2.65 kWh, which included four LED arrays and an integrated control unit. These findings confirm the effectiveness of the developed system in delivering energy-efficient, consistent, and uniform lighting that is suitable for precision indoor farming applications.

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