Asian Journal of Natural Sciences (AJNS)
Vol. 4, No.3, 2025: 197-208

Integration of IoT and Digital Technologies in Adaptive Lighting Systems to Optimize Microalgae Synthesis

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ARTICLEINFO

Keywords: Digital Technology, IoT, Adaptive Lighting, Microalgae Synthesis

Received : 05, July
Revised : 25, July
Accepted: 25, August

ABSTRACT

The integration of Internet of Things (IoT) with embedded microcontroller systems offers new opportunities for improving environmental control in bioprocess applications. This study presents the development and testing of an IoT-enabled adaptive lighting system designed to optimize the synthesis of microalgae in controlled aquatic environments. The system employs an ESP32 interfaced with a DS18B20 water temperature sensor and an analog pH sensor to monitor key environmental parameters in real time. Based on sensor feedback, the system dynamically adjusts the intensity of LED lighting to maintain optimal photosynthetic conditions for microalgae cultivation. The control logic is embedded in the microcontroller using threshold-based decision rules and pulse-width modulation for energy-efficient LED control. Field testing was conducted in a photobioreactor over several days, where the system demonstrated reliable performance in maintaining light conditions between 50 and 70 µmol $m^{-2} s^{-1}$, while responding adaptively to changes in water temperature and pH levels. The integration of IoT significantly enhanced user interaction, remote diagnostics, and process traceability. The results indicate that the proposed adaptive lighting system can improve the sustainability and productivity of synthesis. It also serves as a practical model for implementing low-cost, sensor-driven digital control systems in small-scale and biotechnology applications

DOI: https://doi.org/10.55927/ajns.v4i3.43
E-ISSN: 2986-2787
https://journal.formosapublisher.org/index.php/ajns

INTRODUCTION

The rapid growth of the global population has brought about significant challenges to food security. As the number of people continues to increase, the demand for nutritious, safe, and accessible food is also rising, placing intense pressure on existing food production systems. This population-driven demand exacerbates the competition for land use—between agricultural purposes and urban, industrial, or environmental needs—thus threatening the stability of food availability. In response, innovation in sustainable food sources has become imperative to ensure both the quantity and quality of food necessary for healthy and productive lives.

One such promising alternative lies in the use of microalgae. Microalgae are unicellular photosynthetic organisms with high biomass productivity and rich biochemical composition. They are increasingly recognized as a valuable resource in various sectors, including food, pharmaceuticals, cosmetics, biofuels, and environmental remediation (Anggreni, 2021; Azimatun, 2014). Their cultivation supports the goals of sustainable development by offering an efficient biological pathway for converting sunlight into biomass under controlled conditions. However, optimal microalgae cultivation is sensitive to several environmental parameters, notably light intensity, temperature, and pH, which must be precisely maintained to ensure effective photosynthesis and metabolite synthesis.

Traditionally, microalgae cultivation systems rely on static or manually controlled lighting, which lacks responsiveness to fluctuating environmental conditions. This often results in suboptimal energy usage and inconsistent biomass quality. To overcome these limitations, there is a growing need for intelligent, adaptive cultivation systems that can dynamically respond to real-time environmental data, thereby enhancing both energy efficiency and synthesis output.

Recent developments in embedded systems and the Internet of Things (IoT) present valuable tools for addressing these challenges. By integrating microcontrollers—such as the ESP32—with environmental sensors and remote monitoring platforms, it is now possible to implement real-time control systems for biological cultivation. These IoT-based adaptive systems can automate adjustments to lighting and other parameters based on continuous data feedback, offering a smart and cost-effective solution to optimize microalgae growth.

Despite the emergence of smart agriculture and aquaculture applications, limited studies have specifically focused on the integration of IoT-enabled adaptive lighting systems tailored for microalgae cultivation. Particularly lacking are systems that incorporate temperature and pH feedback in real-time to regulate light intensity dynamically.

This research addresses that gap by developing and testing an IoT-based adaptive lighting system using ESP32 microcontrollers, DS18B20 temperature sensors, and analog pH sensors. The system is designed to optimize microalgae synthesis efficiency through adaptive lighting control based on real-time environmental monitoring. The central question guiding this study is: Can a low-cost, sensor-driven adaptive control system improve the efficiency and sustainability of microalgae cultivation processes?

By providing an accessible, scalable, and intelligent control mechanism, this research contributes to the broader field of sustainable food innovation and smart environmental biotechnology. It also introduces a novel approach to microalgae cultivation that bridges the gap between biological needs and technological capabilities.

LITERATURE REVIEW

Adaptive Lighting in Controlled Environments

Adaptive lighting systems are designed to automatically adjust light output in response to environmental or biological feedback. In the context of plant and algae cultivation, such systems help maintain photosynthetically active radiation (PAR) within ideal thresholds, while reducing unnecessary energy expenditure. Pulse-width modulation (PWM) is a common method used to control LED brightness in such systems. Research has shown that adaptive lighting can significantly improve photosynthetic efficiency, though its application to microalgae cultivation—especially in aquatic systems—remains relatively underexplored.

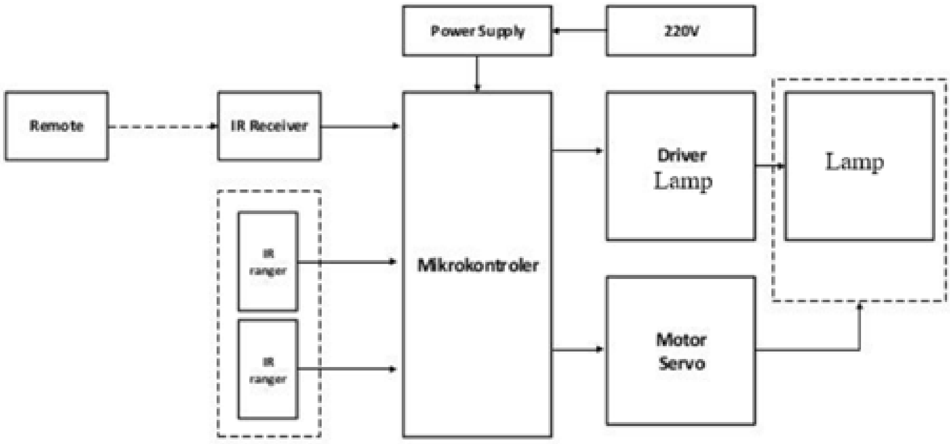

Figure 1. Scheme of Adaptive Lighting

IoT and Microcontroller-Based Control Systems

The term "Internet of Things" (IoT) was first used in 1999 by British technology pioneer Kevin Ashton to describe a system in which objects in the real world can be connected to the Internet with the help of sensors. Today IoT has become a popular term to describe scenarios where internet connectivity and computing capabilities can cover a wide variety of objects, devices, sensors and everyday items (Arta, 2022; Pranata, 2022).

IoT enables remote monitoring and control of physical systems via network-connected sensors and actuators. Microcontrollers such as the ESP32 offer built-in Wi-Fi/Bluetooth capabilities and GPIO pins to interface with multiple environmental sensors. When combined with platforms like MQTT, Node-RED, or Blynk, real-time data can be visualized and control decisions can be made remotely. This digital integration improves system responsiveness, enables data logging, and allows predictive control strategies.

Figure 2. Internet of Things

Environmental Sensing Technologies

The DS18B20 sensor is widely used for temperature and humidity measurements due to its low cost and accuracy. For water-based applications like microalgae photobioreactors, the DS18B20 can be adapted with waterproof casings or used in tandem with other aquatic sensors. pH-4502C sensors play a critical role in microalgae cultivation, as pH influences nutrient availability and photosynthetic activity. Integrating these sensors into a real-time control system provides a feedback loop essential for adaptive lighting logic.

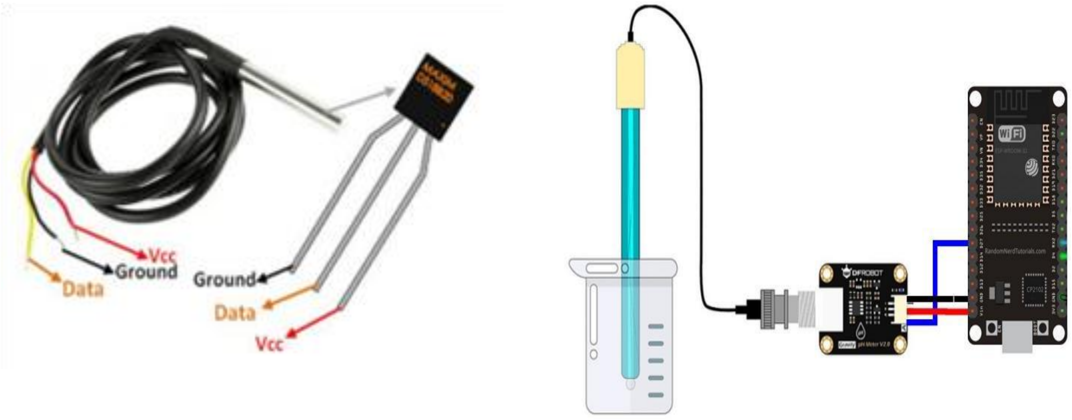

Figure 3. DS18B20 and pH-4502C Sensing

Integrating Digital Technology

The efforts for integrating digital technology within derive from the mythical idea that people will communicate what is in the digital. In fact (and perhaps unfortunately) this is not the case. Digital authorities' belief in the 'myth of the digitalize: the idea is that, once clearly stated in the system and in technology, learning objectives and contents become objects that are easy to learn or teach. This utilitarian view of the digitalize is often adopted by people while planning lessons and it becomes one of the many existing myths. Myths play a major role in people's lives. They help organize experiences even when they don't portray real problems or solutions. People often take myths to support and legitimate actions and decisions. However, as engineers or educators we must question and deconstruct myths inherent.

Figure 4. Integrating Digital Technology

The myth of the digital technology as driving force for learning is well established in teaching. In fact, objectives, contents and teaching methods that constitute the digital documents are mere rectification of teaching practices that shouldn't be taken as the source of learning. Most myths about the integration of digital technology in the digital results from unproblematic and oversimplified visions of digital technology in system of its forms and application strategies and from the ed-problematical of its use at large in society. In contrast, students bring meanings and practices from outside system which are diverse, powerful and one step ahead of the systems' view of digital technology in society. Those two rather different mindsets the system-rules

Research Gap

While studies on IoT in agriculture have increased in recent years, most implementations focus on soil moisture, irrigation, or greenhouse climate control. Very few have addressed aquatic biological processes like microalgae cultivation, especially with real-time sensor feedback linked to lighting control. This creates a gap in applied digital biotechnology for controlled aquatic environments, which this study aims to fill through an integrated, low-cost IoT lighting system for microalgae synthesis.

In research on the synthesis of micro-algae micro-samples using light sourced from solar panels (PLTS) technology, results were obtained on the design of PLTS so that it can supply lamps and aerator to supporting the synthesis in photosynthesis process in synthesis medium, as well as the results from the synthesis of micro-algae micro-samples.

METHODOLOGY

There are three methods in this research to solving the problem in manipulated of adaptive lighting in the microalgae synthesis.

1. Literature Study Method

In writing this thesis, the author studied references from various sources such as books, journals, articles related to the research that the author is researching. The various references used by the author to create this final assignment and other references related to the research.

2. Discussion or Interview Method

Collecting data by conducting direct discussions with expert

3. Observation Method

The author obtains data by coming directly to the field to observe and record the data needed to complete the thesis.

System Overview

This study implements a real-time adaptive lighting control system for microalgae synthesis using IoT technology. The system consists of an ESP32 microcontroller, a DS18B20 temperature sensor, an analog pH sensor, and an array of white LEDs. Data from environmental sensors are used as input to adjust the LED brightness dynamically using PWM control. An IoT dashboard is used for monitoring via MQTT communication protocol.

Hardware Configuration

ESP32: Functions as the central microcontroller unit (MCU), capable of processing sensor data and controlling LED output through PWM signals. Its built-in Wi-Fi module allows connectivity to the IoT dashboard.

DS18B20 Sensor: Measures water temperature (after waterproof encapsulation). This sensor has ±0.5°C accuracy and is sampled at 2-second intervals.

pH-4502C Sensor (Analog): Continuously measures the acidity of the culture medium. The voltage output is read via an analog input pin and calibrated using buffer solutions.

LED Lighting: The LED array is controlled through a MOSFET circuit driven by PWM from the ESP32, enabling fine-grained intensity control between 0% to 100%.

Software and IoT Integration

Arduino IDE is used for programming the ESP32 logic, including sensor reading, PWM modulation, and data transmission.

MQTT Broker (e.g., Mosquitto or Blynk Cloud): Enables bi-directional communication between the hardware and a mobile/web-based dashboard.

Dashboard: Displays real-time temperature and pH readings, light intensity status, and historical trends. It also allows manual override of the lighting system if needed.

Adaptive Control Logic

The control logic is based on threshold rules:

- If temperature < 22°C or pH < 6.5 → Increase light intensity
- If temperature > 30°C or pH > 8.5 → Decrease or shut off LEDs

- If both parameters are within range → Maintain LED at moderate level (~60% brightness)

These thresholds are based on literature for optimal microalgae photosynthesis conditions.

Testing Procedure

The system is deployed in a laboratory photobioreactor over a 5-day period. Temperature and pH are monitored continuously, and LED intensity adjustments are logged. Daily biomass measurements are recorded to assess microalgae growth.

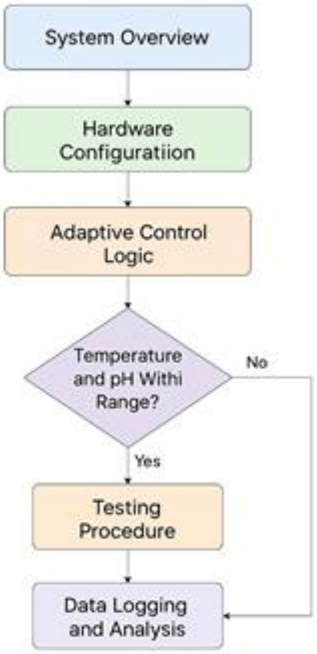

Figure 5. Flowchart of Adaptive Lighting Research

Data Logging and Analysis

Sensor data and system responses are logged to the cloud for post-analysis. Statistical evaluation is conducted to assess the correlation between environmental parameters, system responses, and biomass growth trends.

RESEARCH RESULT

Steps to test results

Technical design is a detailed design of technical aspects. In the context of adaptive lighting control, design to IoT technology, configuration, selection of equipment and components needed, and installation and interconnection plans. The technical design also includes in-depth calculations and simulations to ensure the adaptive lighting system works optimally according to local energy needs and environmental conditions.

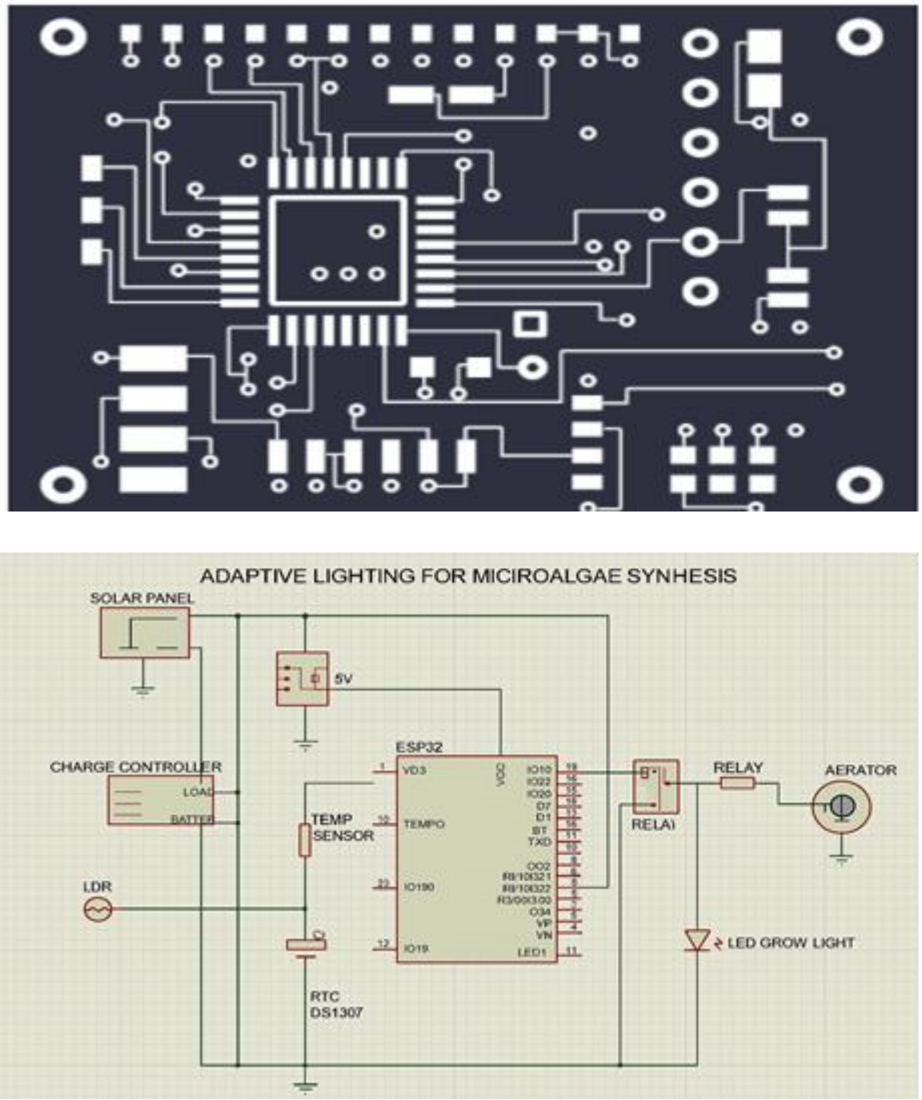

Figure 6. Adaptive Lighting for Microalgae Synthesis

In this study, adaptive lighting design uses components, namely smart lamp devices with microcontrollers, LDR sensors, LED drivers, and LEDs. This system adjusts the brightness level of LED lights based on environmental conditions, such as natural light and the presence of people. To test the sensor's capabilities, simulations with proteus simulations and matlab simulink simulations are also used to test the brightness of the room, (figure 6).

The light sensor (LDR) measures the intensity of natural light, if the natural light is bright enough, the lights will be dimmed or turned off. If the light is dim, the lights will be turned on or the brightness will be increased.

Based on the results of the simulation of the lighting system for the left media lane activity lab room (near the door and window) and the right media lane (on the dark wall side of the lab), the average lighting level for the left media lane activity lab room is higher than the right media lane. This difference is because the left lane is located near the entrance and window so that sunlight goes directly to the media while in the right lane the media only sticks to the inner lab wall. The highest average lighting level in the lab room occurred during the day at 13:00 when the synthesis measurements were carried out and during the dry season. At 19:00 both lines had a constant lighting level with an average of approximately 40-50 lux because the sun had set and the outdoor lights were on. This proves that both lanes fully utilize artificial lighting because there is no direct sunlight as shown in Table 1.

Table 1. Comparison lighting level to the media line in a day

Media	Comparison lighting level in a day (lux)				
Line	07:00	10:00	13:00	16:00	19:00
Left	150	520	1100	640	50
Right	58	96	124	90	40

In this study, IoT design uses components, namely the ESP 32 microcontroller, DS 18B20 temperature sensor, and pH-4502C sensor. To find the benefit of using adaptive lighting, research use 4 kinds of attitude to the media. They are (1) with adaptive lighting and aerator, (2) with adaptif lighting only, (3) with aerator only, and (4) without aerator adad adaptive lighting. From the results of these measurements, the results are obtained as in the following figure.

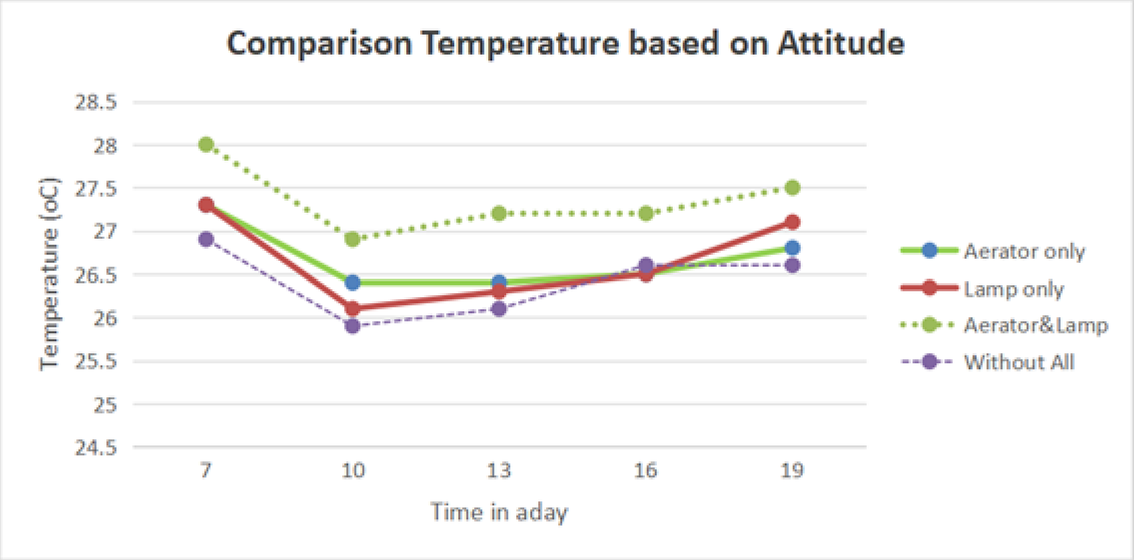

Figure 7. Comparison measurement temperature with different attitude

DISCUSSION

These microalgae contain nutrients, including protein, omega-3, essential fatty acids, and carotenoids, making them a richer source of nutrients compared to traditional feeds such as millet, gram, or other small fish commonly used in fisheries. In addition, microalgae also contain compounds such as antioxidants, antimicrobials, and disease-preventing molecules, which have the potential to extend the lifespan of humans and fish in aquatic ecosystems.

Thus, microalgae have an important role in maintaining food security and supporting fisheries ecosystems and the aquatic environment as a whole.

Microalgae growth is influenced by the type of media or nutritional factors. Different types of media will have different media nutrient compositions, which can affect the concentration of fat produced. Regulation of nutritional factors such as nitrogen and phosphorus concentrations can be used as regulators to increase lipid synthesis. Nitrogen nutrient sources can come from KNO3, NH4+ and urea, but NO3- obtained from KNO 3 provides the highest algae growth rate. Phosphorus sources can come from the use of KH2PO4. [9] Nannochloropsis was made as much as 1 liter each with a ratio of sea water and starter of 70:30. Furthermore, Walne media was added as much as 1 ml/l, Agriculture media as much as 1 ml/l, and for MQ media, solution A was added as much as 2 ml/l, solution B as much as 1 ml/l and klewat as much as 3 ml/l. Optimization of nutritional factors was carried out on selected types of media by modifying ammonium (NH4) and phosphate (PO4) compounds with concentrations according to treatment.

In the synthesis of microalgae microsamples, the Sustainability Theory was used to meet current needs without sacrificing future generations, which is in line with the application of solar panels in microalgae synthesis and the Green Tourism Theory, namely the use of renewable energy and microalgae-based biomaterials can support sustainable tourism. Microalgae can be used for natural cosmetics, functional foods, and ecotourism. The technology used in microalgae synthesis supports the principle of carbon emission reduction and energy efficiency in green tourism. Microalgae can also be used to absorb CO2 and process liquid waste, supporting the principle of zero-waste in green tourism. From the literature review and theory above, this research has a strong foundation in solar energy conversion for adaptive lighting in microalgae synthesis, IoT system with automatic sensors for monitoring microalgae growth, application of intelligent algorithms in IoT-based lighting regulation, and the relationship between microalgae and green industry in supporting sustainable tourism.

Based on the results of the study above, there are several suggestions that can be given to improve the sustainability and effectiveness of this research and provide further contributions to the development of blue technology and green technology. The following are suggestions from researchers. It is better to be more careful in manual calculations when calculating and selecting components so that they are more optimal and can increase the selling value of the synthesis. In order to be more accurate in designing, it is better to use a comparison of software that supports design in the future.

CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis and discussion of Integration of IoT and Digital Technologies in Adaptive Lighting Systems to Optimize Microalgae Synthesis several conclusions can be drawn as follows:

The integration of Internet of Things (IoT) with embedded microcontroller systems offers new opportunities for improving environmental control in bioprocess applications. This study presents the development and testing of an IoT-enabled adaptive lighting system designed to optimize the synthesis of microalgae in controlled aquatic environments. The system employs an ESP32 interfaced with a DS18B20 water temperature sensor and an analog pH sensor to monitor key environmental parameters in real time. Based on sensor feedback, the system dynamically adjusts the intensity of LED lighting to maintain optimal photosynthetic conditions for microalgae cultivation. The control logic is embedded in the microcontroller using threshold-based decision rules and pulse-width modulation for energy-efficient LED control. Field testing was conducted in a photobioreactor over several days, where the system demonstrated reliable performance in maintaining light conditions between 50 and 70 µmol $m^{-2} s^{-1}$, while responding adaptively to changes in water temperature and pH levels. The integration of IoT significantly enhanced user interaction, remote diagnostics, and process traceability. The results indicate that the proposed adaptive lighting system can improve the sustainability and productivity of synthesis. It also serves as a practical model for implementing low-cost, sensor-driven digital control systems in small-scale and biotechnology applications.

ADVANCED RESEARCH

Each study has limitations; thus, we can describe about development of this research to integration with digital communication technology, smart system, and sustainable tourism based on local wisdom for further research.

ACKNOWLEDGMENT

This section gives us the opportunity to thank our colleagues who provided suggestions for our paper: Electrical Department in Politeknik Negeri Bali, Engineering in Ganesha Indonesia, founders in Cita Widya Suhita, and Communication Studies in UHN IGB Sugriwa Denpasar.

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