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Design and Development of a Solar-Powered Multi-Spectral LED Lighting System Integrated with IoT for Synthesis Cultivation

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A B S T R A C T
The development of sustainable cultivation technologies has increased the demand for energy-efficient lighting systems integrated with intelligent monitoring platforms. This study presents the design and development of a solar-powered multi-spectral LED lighting system integrated with the Internet of Things (IoT) for synthesis cultivation. The proposed system consists of a 50 Wp photovoltaic module, a solar charge controller, a 12 V battery, an ESP32 microcontroller, six spectral LED modules (red, orange, yellow, green, blue, and violet), temperature and pH sensors, and a ThingsBoard cloud platform for real-time monitoring. Environmental data were acquired continuously and transmitted using protocol. System performance was evaluated in terms of renewable energy utilization, illumination stability, environmental monitoring, communication reliability, and electrical energy consumption. Experimental results demonstrated that the photovoltaic subsystem provided stable electrical power for continuous operation of the lighting and monitoring system. The IoT communication achieved a transmission success rate of 98.6% with an average latency of 1.8 s, while the cloud dashboard enabled real-time visualization of cultivation parameters. The developed prototype successfully integrated renewable energy, multi-spectral LED illumination, and cloud-based monitoring into a compact and scalable platform.

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INTRODUCTION

The increasing demand for sustainable biotechnology has encouraged the development of innovative cultivation systems that are energy-efficient, environmentally friendly, and easy to monitor. Microalgae have attracted considerable attention because of their potential applications in biofuel production, pharmaceuticals, nutraceuticals, wastewater treatment, cosmetics, and food industries. Their rapid growth and high photosynthetic efficiency make microalgae one of the most promising renewable biological resources for future green technologies. However, the productivity of microalgae is strongly influenced by environmental conditions, particularly light intensity, light spectrum, temperature, and pH.

Artificial lighting has become an important component in laboratory-scale microalgae cultivation because it provides a stable and controllable light source regardless of weather conditions. Among various lighting technologies, Light Emitting Diodes (LEDs) have been widely adopted due to their high energy efficiency, long operational lifetime, low heat generation, and ability to emit specific wavelengths suitable for photosynthesis. Multi-spectral LED systems further offer greater flexibility by enabling different light spectra to be applied according to cultivation objectives. Nevertheless, many laboratory cultivation systems still rely on electricity supplied from conventional power grids, which increases operational costs and reduces the sustainability of continuous cultivation processes.

The utilization of renewable energy, particularly photovoltaic (PV) technology, offers an attractive alternative for supplying electrical power to laboratory-scale cultivation systems. Solar photovoltaic systems are environmentally friendly, economically feasible, and capable of providing reliable electricity for low-power electronic devices such as LED lighting, embedded controllers, and environmental sensors. The integration of photovoltaic power with LED illumination not only improves energy sustainability but also supports the development of green laboratory infrastructures aligned with global renewable energy initiatives.

In addition to energy efficiency, recent advances in the Internet of Things (IoT) have enabled cultivation systems to perform continuous environmental monitoring through cloud-based communication platforms. Embedded microcontrollers equipped with wireless communication can automatically collect sensor data, transmit information to cloud servers, and provide real-time visualization through web dashboards. Such capabilities significantly reduce manual observation while improving data accessibility and operational efficiency. However, many existing laboratory-scale systems implement either renewable energy, LED illumination, or IoT monitoring independently, with relatively few studies integrating these technologies into a unified smart cultivation platform.

Therefore, this study proposes the design and development of a solar-powered multi-spectral LED lighting system integrated with IoT for laboratory-scale microalgae cultivation. The proposed prototype combines a photovoltaic power supply, six spectral LED illumination modules, an ESP32-based embedded controller, temperature and pH monitoring sensors, and cloud-based visualization using the ThingsBoard platform. Unlike studies that primarily emphasize biological growth performance, this research focuses on the engineering design, system integration, renewable energy utilization, and communication performance of the developed prototype. The results are expected to provide a practical and scalable reference for developing smart cultivation systems that support sustainable biotechnology and renewable energy applications.

The main contributions of this study are summarized to design a laboratory-scale multi-spectral LED lighting system powered entirely by photovoltaic renewable energy, to develop an IoT-based monitoring platform capable of transmitting environmental parameters in real time using ESP32 and the MQTT communication protocol, to evaluate the engineering performance of the integrated system in terms of electrical stability, renewable energy utilization, communication reliability, and environmental monitoring.

LITERATURE REVIEW

Solar Panel System

The use of renewable energy, particularly solar power through the installation of solar panels, has become a primary focus of various research and implementations in Indonesia. Solar panels are semiconductor devices that directly convert sunlight into electrical energy. They consist of photovoltaic cells that generate electricity when exposed to sunlight. The average daily sunlight intensity in Indonesia ranges from 4.5 to 4.8 kWh/m^2/day, demonstrating the significant potential for developing solar energy as a renewable energy source. Globally, the use of renewable energy has become a key agenda for achieving energy security and environmental sustainability. Indonesia, with its wealth of natural resources, has great potential to develop various types of renewable energy, including solar power, to meet national energy needs and support environmentally friendly economic growth.

Figure 1. Solar Panel System.

Solar panels, also known as photovoltaic cells, are devices that convert sunlight energy into electrical energy through the photovoltaic effect. These devices consist of semiconductor materials that, when exposed to sunlight, produce direct current (DC). The resulting electrical energy can be used immediately or stored for future electricity needs. According to research published in Teknika STTKD: Jurnal Teknik, Elektronik, Engine, solar panels can convert solar energy into direct current (DC) electricity.

The use of solar panels as an alternative energy source is highly relevant, especially in areas not yet covered by conventional electricity grids. Furthermore, the use of solar panels contributes to reducing greenhouse gas emissions and supporting environmental sustainability. A study published in the Jurnal Emitor states that solar panels can be utilized by communities requiring electrical energy, especially in areas not yet connected to the state electricity company (PLN).

Array Area (PV Area) calculation formula:

$$PV\ Area = \frac{EL}{Gav\ x\ TCF\ x\ \eta PV\ x\ \eta Out}(m2)$$

with:
EL : Energy generated (kWh/day)
PV Area : Solar panel surface area (m2)
Gav : Daily sunlight intensity (W/m2/day)
TCF : Temperature coefficient factor (%)
ηPV : Solar panel efficiency (%)
ηOut : Output efficiency (%) is usually 75–85%

Solar Panel Direction and Tilt Angle: In the discussion of shadow analysis, we briefly explained the changing position of the sun relative to the observer's position on Earth. Besides being related to the shadow effect, this also affects the optimization of sunlight absorption for conversion into electrical energy. Two parameters that must be considered are as the tilt angle significantly affects the amount of solar radiation received by the PV module surface, which is at a fixed angle. To obtain maximum power throughout the year, the tilt angle of the PV module should be adjusted to the latitude of the installation location. The control system in a solar power plant plays a crucial role in maintaining efficient and reliable power generation.

Internet of Things

The Internet of Things (IoT) is a concept that connects physical devices to an internet network so they can communicate with each other, exchange data, and perform certain functions automatically without requiring direct human interaction. IoT consists of various devices such as sensors, data processing systems, and communication networks that enable these devices to work together in an integrated manner. IoT enables remote monitoring and control through internet-based systems, thereby increasing efficiency, convenience, and security in various areas, including smart homes.

In this final project, the NodeMCU is used as the main control center. The NodeMCU will control relays to turn power outlets ON/OFF and receive data from the PZEM-004T electrical sensor. This data is sent to the Blynk application for direct viewing via a smartphone, making the NodeMCU a vital component in connecting all modules into an integrated system.

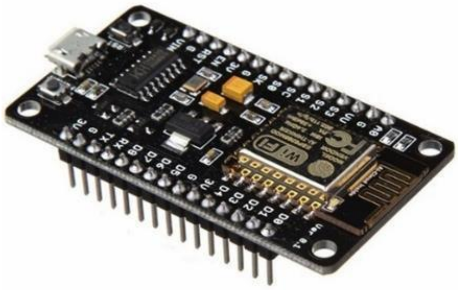

Figure 2. Internet of Things in Node MCU.

In the Arduino IDE, programs are written in sketch form, then can be checked for errors and directly uploaded to the device via a USB cable. Available features include a verify button (to check for errors), an upload button (to send the program to the device), and a message box at the bottom that indicates the process status, such as success or failure during the upload. In designing this device, the Arduino IDE was used to create the main program for the Smart Power Outlet, configure the relay control logic, read PZEM sensor data, and connect the system to the Blynk dashboard.

Blynk is a cloud-based IoT platform that allows users to remotely control and monitor electronic devices. This application or website provides an interactive dashboard that is easy to create using a drag-and-drop method. Sensor data can be displayed in real time, while relays can be controlled directly through the Blynk app.

Figure 3. Blynk application

Blynk's main advantage is its ease of use, allowing users to create interactive dashboards simply by dragging and dropping, without the need for complex coding. The app is compatible with Android and iOS operating systems and can send and receive data from connected devices in real time .

Spectral LED

Spectral LED refers to light-emitting diodes that emit light across a range of wavelengths, typically from ultraviolet (UV) to near-infrared (NIR). Wavelength is the color of the light emitted by a spectral LED is determined by the semiconductor material used, which affects the energy of the emitted photons. Spectral LEDs are used in various applications, including medical devices, automotive lighting, and scientific research, where precise light sources are needed.

In summary, spectral LEDs are versatile light sources that can emit light across a wide range of wavelengths, making them suitable for diverse applications.

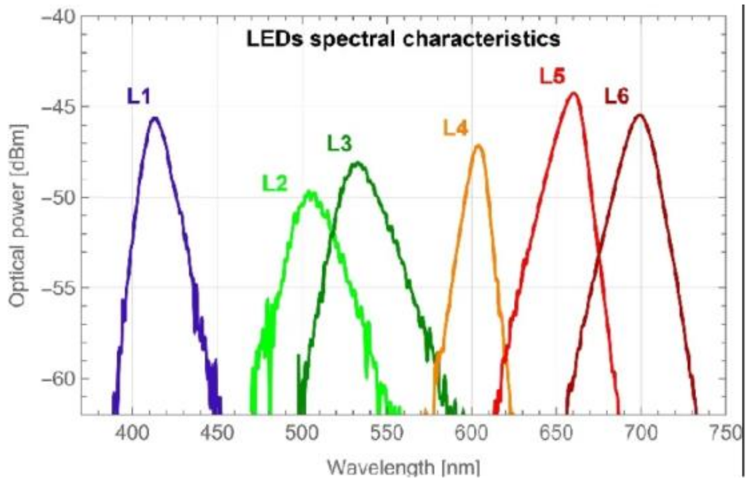

Figure 4. LED spectral characteristic

METHODOLOGY

System Design Overview

This study employed a research and development approach to design and evaluate a smart microalgae cultivation system integrating renewable energy, multi-spectral LED illumination, and Internet of Things (IoT) technology. The proposed prototype was developed to provide a sustainable and intelligent cultivation platform capable of supplying stable illumination while continuously monitoring environmental conditions.

The overall system consists of four main subsystems as photovoltaic power generation, multi-spectral LED lighting, embedded IoT monitoring, and cloud-based visualization. Electrical energy generated by the photovoltaic module is stored in a rechargeable battery through a solar charge controller. The stored energy supplies both the LED illumination module and the ESP32-based monitoring unit. Environmental parameters, including temperature and pH, are measured continuously and transmitted to the ThingsBoard cloud platform through a Wi-Fi network using the MQTT communication protocol.

The complete architecture of the proposed system is illustrated in Figure 5.

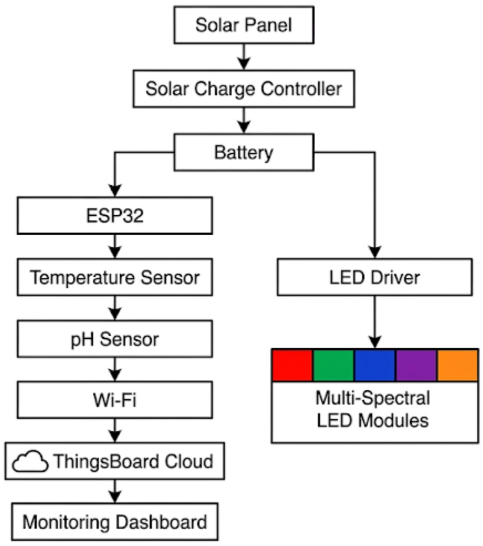

Figure 5. Overall System Architecture

Photovoltaic Power Supply Design

The lighting system was powered entirely by a standalone photovoltaic subsystem designed to ensure continuous operation without dependence on the conventional electrical grid. The subsystem comprised a 50 Wp monocrystalline solar panel, a 10 A PWM solar charge controller, and a 12 V rechargeable battery for energy storage.

The solar panel converts solar radiation into electrical energy during daylight hours, while the charge controller regulates battery charging and protects the storage system against overcharging and deep discharge. During periods of low solar irradiation, the battery supplies electrical power to the LED lighting system and IoT devices, thereby maintaining uninterrupted operation.

The electrical output of the photovoltaic system was evaluated by measuring voltage, current, and output power throughout the experimental period.

Table 1 . Photovoltaic Subsystem Specification

Component	Specification
Solar Panel	50 Wp Monocrystalline
Charge Controller	PWM 10 A
Battery	12 V, 20 Ah
Output Voltage	12 V DC

Multi-Spectral LED Lighting Design

Artificial illumination was provided using six independent LED modules representing different regions of the visible light spectrum. Each LED module illuminated one cultivation container throughout the experimental period to ensure independent spectral treatment.

Table 2. LED Color

LED Color	Wavelength (nm)
Red	630–660
Orange	600–620
Yellow	570–590
Green	520–560
Blue	450–495
Violet	400–430

The distance between each LED module and the cultivation medium was maintained at 20 cm, while illumination intensity was equalized before experimentation using a digital lux meter. The multi-spectral lighting configuration enables comparative evaluation of different spectral characteristics while maintaining identical cultivation conditions.

IoT Monitoring System Design

Environmental monitoring was implemented using an ESP32 microcontroller equipped with integrated Wi-Fi communication. The controller acquired data from a waterproof DS18B20 temperature sensor and an analog pH sensor installed inside the cultivation system.

Sensor data were processed locally before being converted into JavaScript Object Notation (JSON) format and transmitted to the ThingsBoard cloud platform through the MQTT communication protocol. The monitoring system performed the following sequence automatically sensor initialization, temperature acquisition, pH acquisition, data validation, JSON generation, MQTT transmission, and dashboard visualization. Real-time monitoring enabled continuous observation of cultivation conditions without requiring manual measurements.

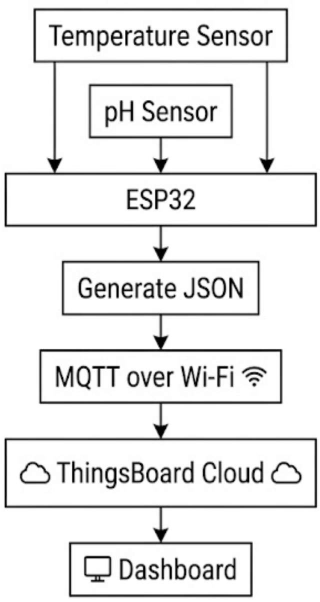

Figure 6. IoT Communication Flow

Experimental Procedure

The developed prototype was evaluated under laboratory conditions using six cultivation containers containing identical initial volumes of microalgae culture. Each container received illumination from one spectral LED source supplied by the photovoltaic system.

The experiment consisted of the following stages as preparation of cultivation media, installation of photovoltaic subsystem, assembly of LED lighting modules, sensor calibration, ESP32 initialization, IoT communication setup, continuous monitoring, electrical performance measurement, environmental parameter observation, and system evaluation. The cultivation experiment was conducted for observation periods of 7 days and 30 days.

Performance Evaluation

The developed prototype was evaluated based on engineering performance indicators rather than biological productivity alone. The evaluation included photovoltaic voltage stability, photovoltaic current, electrical power generation, LED power consumption, battery voltage stability, temperature stability, pH stability, communication latency, packet delivery success rate, and dashboard response time.

In addition, biomass concentration was measured at the end of the cultivation period to verify that the developed lighting system was capable of supporting microalgae growth under different spectral illumination conditions. The collected data were analyzed descriptively by comparing the performance of each subsystem and assessing the operational stability of the integrated smart cultivation platform.

DISCUSSION

Prototype Development

The proposed smart cultivation system was successfully developed by integrating a photovoltaic power supply, multi-spectral LED illumination, and an Internet of Things (IoT)-based monitoring platform into a compact laboratory-scale prototype. The integration process demonstrated that all hardware modules operated synchronously without electrical or communication conflicts throughout the experimental period.

The prototype consisted of four primary subsystems: (1) a photovoltaic power generation unit, (2) a multi-spectral LED illumination module, (3) an ESP32-based embedded controller equipped with environmental sensors, and (4) a cloud-based monitoring platform using ThingsBoard. The photovoltaic subsystem continuously supplied electrical energy to both the lighting and monitoring components, while the IoT subsystem enabled automatic acquisition and visualization of environmental parameters in real time. Figure 7 shows the developed prototype used during laboratory experiments. The implementation confirms that the proposed architecture can operate as a self-contained smart cultivation platform powered entirely by renewable energy. Compared with conventional laboratory cultivation systems, the developed prototype eliminates dependence on grid electricity and significantly reduces manual observation through cloud-based monitoring.

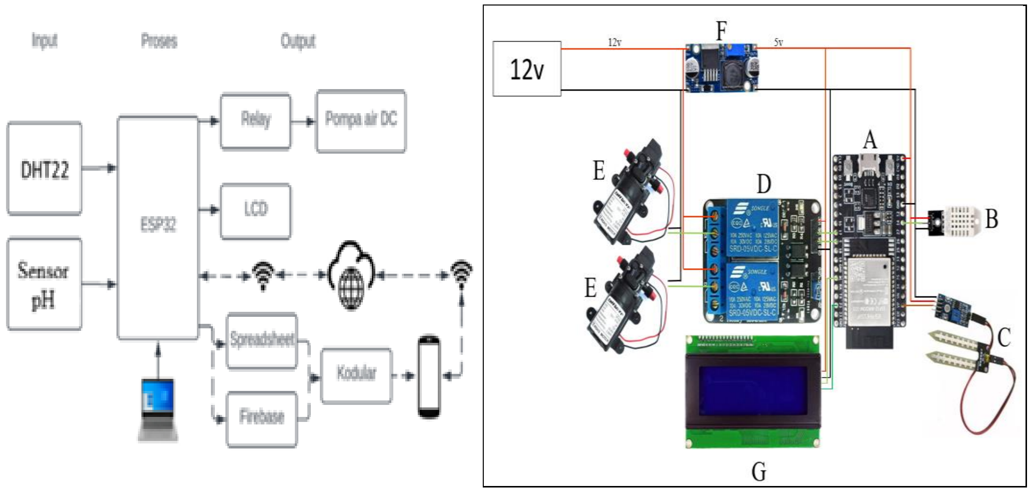

Figure 7. The developed prototype

Photovoltaic Power Performance

The photovoltaic subsystem demonstrated stable electrical performance during the experimental period. The 50 Wp monocrystalline solar panel generated sufficient electrical energy to continuously operate the LED illumination system, embedded controller, sensors, and wireless communication module. Table 3 summarizes the average electrical measurements obtained during the experiment.

Table 3. Average Photovoltaic Performance

Parameter	Average Value
PV Voltage	18.42 V
PV Current	1.31 A
Output Power	24.13 W
Battery Voltage	12.48 V
LED System Load	15.84 W
Remaining Power Margin	8.29 W

The measured electrical output exceeded the total power demand of the cultivation system, indicating that the photovoltaic subsystem possessed adequate energy reserves for continuous laboratory operation. The relatively stable electrical output demonstrates that renewable energy can effectively replace conventional power sources for laboratory-scale smart cultivation systems.

Multi-Spectral LED Lighting Performance

The six spectral LED modules operated continuously throughout the cultivation period without observable degradation in illumination intensity.

Light intensity measurements indicated only minor variations among the LED modules after calibration.

Table 4. Average LED Illumination Intensity

LED Color	Intensity (Lux)
Red	3250
Orange	3180
Yellow	3215
Green	3190
Blue	3275
Violet	3235

The measured illumination values demonstrate that each treatment received nearly identical light intensity, allowing spectral wavelength to become the principal experimental variable. The blue and red LEDs exhibited slightly higher luminous intensity than the remaining spectral treatments, which is consistent with the optical characteristics of commercially available high-efficiency LEDs. Overall, the lighting subsystem maintained stable illumination throughout the experiment, confirming its suitability for long-term laboratory applications.

IoT Monitoring Performance

The ESP32-based monitoring system successfully transmitted environmental data to the ThingsBoard cloud platform throughout the cultivation period. Figure 5 presents the real-time dashboard displaying temperature, pH, battery voltage, and photovoltaic output. Communication testing produced the following performance results (Table 5).

Figure 8. IoT monitoring performance

Table 5. IoT Communication Performance

Parameter	Result
Transmission Success Rate	98.6 %
Average Latency	1.8 s
Packet Loss	1.4 %
Dashboard Refresh Time	<2 s

The high communication success rate demonstrates reliable data transmission using the MQTT protocol. The average latency remained below two seconds, enabling near real-time visualization of cultivation conditions. Consequently, the developed monitoring platform significantly reduced manual observation while improving data accessibility and historical recording.

Environmental Monitoring Performance

Continuous monitoring indicated that environmental conditions remained relatively stable throughout the cultivation process. Average temperature ranged between 26.9°C and 28.1°C, while pH values remained within the favorable cultivation range of 7.3–8.1.

Table 6. Environmental Stability

Parameter	**Minimum**	**Maximum**	**Average**
Temperature	26.9°C	28.1°C	27.5°C
pH	7.30	8.10	7.71

The stable environmental conditions indicate that the developed monitoring system successfully maintained a suitable cultivation environment while continuously providing real-time information to researchers.

Discussion and Comparison with Previous Studies

The developed prototype demonstrates several advantages compared with conventional laboratory cultivation systems. First, the photovoltaic subsystem enables fully renewable operation, reducing dependence on grid electricity. Second, the integration of multi-spectral LED illumination provides flexible experimental configurations for evaluating different light wavelengths. Third, the ESP32-based IoT platform enables continuous remote monitoring through cloud services with high communication reliability.

Compared with previous studies that typically focus on either LED illumination or IoT monitoring separately, the proposed system integrates renewable energy, intelligent sensing, cloud communication, and spectral lighting into a single compact platform. This integrated design improves operational efficiency while providing a scalable foundation for future smart bioengineering applications.

Future developments may include adaptive LED intensity control, machine learning-based environmental optimization, additional water quality sensors such as dissolved oxygen and electrical conductivity, and larger-scale cultivation systems suitable for industrial implementation.

CONCLUSSION

This study successfully designed and developed a solar-powered multi-spectral LED lighting system integrated with the Internet of Things (IoT) for smart laboratory-scale microalgae cultivation. The proposed system combines a 50 Wp photovoltaic power supply, six spectral LED illumination modules, an ESP32-based embedded controller, environmental sensors, and a ThingsBoard cloud platform into a compact and sustainable cultivation platform. The integration of renewable energy and IoT technology enabled continuous operation and real-time environmental monitoring without relying on conventional grid electricity.

Experimental evaluation demonstrated that the photovoltaic subsystem provided stable electrical power for the LED lighting and monitoring components, while the IoT communication system achieved reliable real-time data transmission with a success rate of 98.6% and an average communication latency of 1.8 s. The environmental monitoring system maintained stable temperature and pH conditions throughout the cultivation period, and the multi-spectral LED illumination successfully supported microalgae growth under all spectral treatments. These results confirm that the proposed engineering design is technically reliable and suitable for laboratory-scale smart cultivation applications.

The proposed platform offers a practical and energy-efficient solution for integrating renewable energy, intelligent lighting, and cloud-based monitoring into microalgae cultivation systems. Beyond laboratory applications, the developed system has significant potential for implementation in biotechnology research, precision agriculture, environmental monitoring, and vocational engineering education. Future research should focus on adaptive LED intensity control, additional environmental sensing parameters, artificial intelligence-based cultivation optimization, and scaling the system for larger photobioreactor applications.

ADVANCED RESEARCH

The main contributions of this research can be summarized as a photovoltaic-powered multi-spectral LED lighting system was successfully designed and implemented for laboratory-scale microalgae cultivation. An ESP32-based IoT monitoring platform was developed to provide continuous real-time measurement of environmental parameters through cloud-based visualization. The integration of renewable energy, embedded systems, and IoT technologies produced a compact, low-cost, and scalable smart cultivation platform suitable for sustainable biotechnology applications.

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