

Development of an IoT-Based Smart Farming System Powered by Solar Energy with Supplemental LED Lighting for Green Cos Lettuce Cultivation

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Abstract

This paper presents the design and implementation of a smart farming system for Green Cos lettuce cultivation using solar energy as the primary power source. The objective is to optimize resource usage and enhance plant growth through an automated control system based on the ESP8266 microcontroller. The system monitors and controls environmental factors, including soil moisture, ambient temperature, and light intensity, accessible via a web application. Additionally, LED grow lights were employed to extend the photoperiod by 2 hours daily. The experimental results compared the growth of Green Cos lettuce between the proposed smart farm system and a conventional method over 35 days. The results revealed that the smart farm system significantly improved growth rates; the average height of lettuce in the smart farm was 51 cm, compared to 41.5 cm in the conventional method. Furthermore, the smart farm system reduced the harvest time from 42 days to 35 days. These findings demonstrate the efficiency of integrating IoT and renewable energy in precision agriculture.

Keywords: Smart Farming, Internet of Things (IoT), Solar Energy

1. Introduction

In the strategic era of Thailand 4.0, the agricultural sector is undergoing a transformative paradigm shift toward technology-driven methodologies. Traditional open-field agriculture is increasingly threatened by inherent vulnerabilities, particularly climate volatility, erratic weather patterns, and rising global temperatures. These unpredictable environmental factors, coupled with severe labor shortages and inefficient water resource management, significantly hinder crop productivity and quality. To mitigate these challenges, Smart Farming, or precision agriculture, has emerged as a crucial innovation. By integrating the Internet of Things (IoT), wireless sensor networks, and cloud-based analytics, farmers can transition from manual, experience-based observations to data-driven decision-making. This technological integration allows for high-precision control over agricultural microclimates, facilitating real-time monitoring and enabling automated, rapid responses to environmental fluctuations. Such an advanced approach is essential for ensuring optimal growing conditions, especially for high-value

commercial crops that are highly sensitive to abiotic stressors.

Green Cos lettuce (*Lactuca sativa*) is one such commercially significant crop, widely cultivated for its nutritional value and high market demand. However, achieving its maximum yield potential requires stringent environmental management. The physiological development and morphological characteristics of Green Cos lettuce are primarily governed by soil moisture consistency, photoperiod, and light intensity. These parameters directly dictate the plant's photosynthetic efficiency, nutrient uptake capacity, and overall vegetative growth rates. In conventional farming, exclusive reliance on natural sunlight and manual irrigation often subjects the plants to suboptimal conditions. Overcast skies during the rainy season or excessive heat during the dry season lead to inconsistent cultivation cycles, stunted growth, and unpredictable crop yields. Consequently, an engineered environment is required to stabilize these variables.

While modern smart greenhouses can successfully manipulate microclimates, they often introduce a new critical challenge: high energy consumption. Implementing automated irrigation pumps, ventilation, and artificial lighting systems typically relies heavily on the conventional power grid. This reliance significantly increases the operational costs for farmers and contributes to a larger carbon footprint. Furthermore, the expansion of smart farming into remote or rural areas is frequently hindered by the lack of reliable grid infrastructure. Therefore, the integration of decentralized renewable energy sources is paramount to making precision agriculture economically viable and environmentally sustainable.

To address these multifaceted limitations, this research proposes the development and performance evaluation of an autonomous smart farm prototype powered entirely by a standalone Photovoltaic (PV) system. The adoption of solar energy ensures the system's sustainability, zero-emission operation, and functional viability in off-grid remote areas. The core engineering architecture utilizes a NodeMCU ESP8266 microcontroller to orchestrate a closed-loop control system for automated irrigation and supplemental lighting. By employing specialized LED Grow Lights—

specifically tuned to emit the red and blue spectrums critical for Chlorophyll A and B absorption—the system artificially extends the daily light integral (DLI) to accelerate the growth rate of the Green Cos lettuce. Ultimately, the primary objectives of this study are to design a reliable solar-powered IoT control system, to optimize water and energy resource efficiency, and to empirically demonstrate that this technological integration can significantly reduce the cultivation period and improve crop yields compared to conventional farming methods.

2. System Design

The proposed smart farming system is architected to operate autonomously using renewable energy. The design is categorized into three subsystems: the photovoltaic power supply, the IoT-based control hardware, and the software control logic.

2.1 Photovoltaic Power Supply System

To ensure continuous operation in off-grid conditions, the power system was sized based on the daily energy consumption of the actuators (water pumps, mist pumps, and LED grow lights). The total estimated daily energy demand is approximately 850 Wh. The generation unit consists of two 260 W polycrystalline silicon solar panels connected in parallel to maximize current. A 30 A MPPT (Maximum Power Point Tracking) charge controller is utilized to optimize energy harvesting efficiency. Energy is stored in a 12 V, 120 Ah deep-cycle battery, providing sufficient autonomy for system operation during cloudy days or nighttime. The electrical configuration is designed as a DC microgrid, supplying 12 VDC directly to all loads to eliminate DC-AC inversion losses. The single-line diagram of the electrical system is illustrated in Fig. 1.

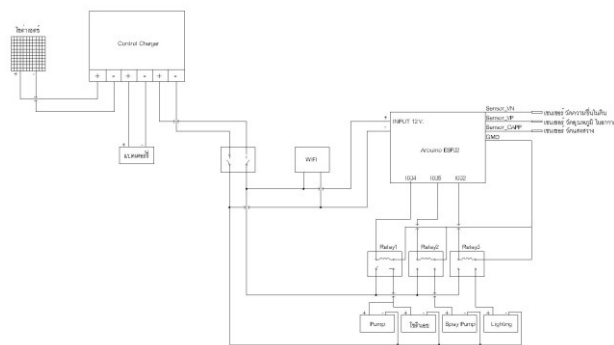


Fig. 1: Power System Single Line Diagram of the proposed smart farm

2.2 IoT Hardware Architecture

The hardware architecture of the proposed smart farming system is centered around the NodeMCU ESP8266, a versatile microcontroller selected for its integrated Wi-Fi capabilities, low power consumption, and cost-effectiveness, while remaining scalable to an ESP32 for more intensive processing requirements. This central processing unit facilitates a robust Internet of Things framework by interfacing with a specialized

sensor array designed for comprehensive environmental monitoring. Ambient temperature is captured using the DS18B20 digital sensor, which employs a waterproof casing and the OneWire communication protocol to ensure precise and reliable data acquisition even in high-humidity greenhouse conditions. To manage the irrigation cycle, an analog resistive soil moisture sensor is utilized to determine the exact hydration needs of the substrate. Furthermore, a Light Dependent Resistor (LDR) module monitors ambient light intensity, serving as the primary trigger for the supplemental lighting subsystem. The execution of control commands is handled by high-performance actuators, including a submersible water pump for irrigation, a misting pump for humidity regulation, and specialized LED grow lights for photosynthetic support. These actuators are interfaced through a 4-channel relay module featuring optocoupler isolation. This design choice is critical for engineering reliability, as it provides an electrical barrier that protects the sensitive microcontroller circuitry from back electromotive force (EMF) and transient voltage spikes during switching operations, thereby ensuring long-term system stability and operational safety in an autonomous agricultural environment.

2.3 Software Implementation and Control Logic

The software framework for the proposed smart farming system was developed utilizing the Arduino Integrated Development Environment (IDE), structured around a robust finite state-machine architecture to ensure deterministic behavior and system reliability. This software design accommodates two distinct operational paradigms: Automatic and Manual modes, which provide a balance between autonomous precision and human intervention. In the Automatic Mode, the system functions as a sophisticated closed-loop control mechanism, where environmental parameters are continuously sampled through the sensor array. The control logic evaluates real-time data against predefined setpoints, specifically maintaining soil moisture levels above a 50% threshold and activating supplemental lighting when ambient light intensity drops below 500 Lux. A critical feature of this implementation is the integration of hysteresis logic within the decision-making algorithm; by establishing upper and lower operational bounds, the software effectively prevents "chattering"—the rapid and repetitive switching of relay contacts—thereby extending the lifespan of mechanical actuators and ensuring electrical stability. Complementing this is the Manual Mode, which allows users to override the autonomous logic via a dedicated web-based dashboard or mobile application, enabling direct control over specific relays for maintenance or localized irrigation tasks. For data management, the system utilizes a lightweight communication protocol where sensor values are serialized into JavaScript Object Notation (JSON) format. These data packets are transmitted asynchronously to a cloud-based MySQL database through RESTful HTTP POST requests. This

approach is highly advantageous for remote agricultural deployments, as JSON minimizes data overhead and reduces latency in areas with constrained network bandwidth. As illustrated in the comprehensive control flow in Fig. 2, the operational sequence begins with a critical initialization phase, where the ESP8266 establishes a secure connection to the local Wi-Fi network and calibrates the connected peripherals. Once connectivity is verified, the system enters a continuous execution loop, performing high-frequency data acquisition, local logic processing, and remote synchronization. This integrated software architecture ensures that the microclimate remains optimal for Green Cos lettuce growth while providing a scalable data infrastructure for long-term environmental analysis and performance monitoring.

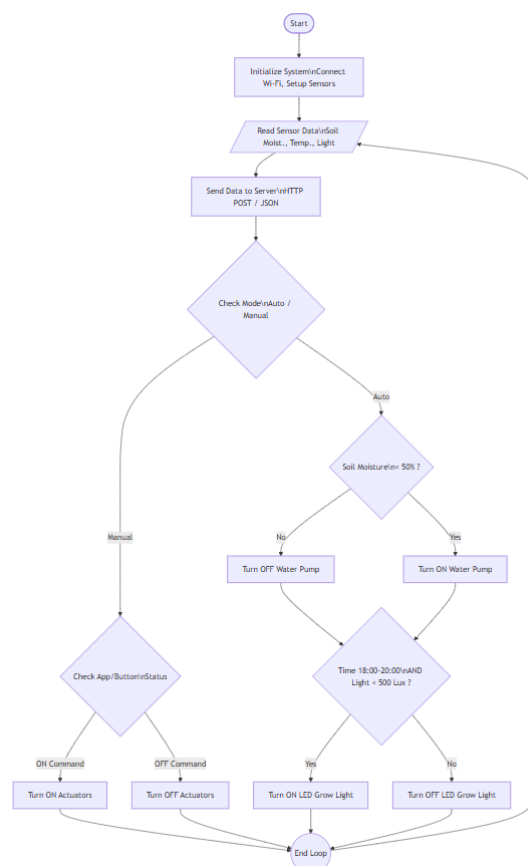


Fig. 2: Control logic flowchart of the proposed smart farming system

The operational thresholds for the automated control logic were established based on both agricultural literature and empirical calibration. The soil moisture threshold was set at 50% to maintain optimal volumetric water content for *Lactuca Sativa*, preventing both drought stress and root hypoxia (waterlogging). Furthermore, the light intensity threshold was defined at 500 Lux. This value was determined through experimental calibration to represent twilight or overcast conditions, ensuring that the supplemental LED grow lights are only activated when natural photosynthetic

active radiation (PAR) is insufficient, thereby optimizing the system's energy efficiency. Due to the physical constraints of the prototype greenhouse, the experiment was conducted for 1 cultivation cycle with 15 plants per group. However, environmental variables were strictly monitored and logged continuously to ensure data reliability.

3. Results and Discussion

The performance of the proposed IoT-based smart farming system was evaluated in two aspects: the reliability of the electrical/control system and the biological impact on Green Cos lettuce growth.

3.1 System Operation Verification

The system was tested continuously over a 35-day cultivation cycle. The solar power supply system, consisting of 2x260 W panels and a 120 Ah battery, successfully maintained a stable 12 VDC bus voltage without interruption, proving its capability to support the load (pumps, sensors, and LEDs) even during cloudy periods. The ESP8266-based controller accurately acquired environmental data and executed control logic as programmed.

Soil Moisture Control: The system maintained soil moisture levels above 50% by automatically triggering the water pump when the threshold was breached.

Lighting Control: The LDR sensor successfully detected sunset, and the system automatically activated the LED grow lights from 18:00 to 20:00, extending the photoperiod by 2 hours daily.

3.2 Growth Comparison Results

The growth rate of Green Cos lettuce in the smart farm (Experimental Group) was compared with that of a conventional outdoor plot (Control Group). The height of the plants was recorded weekly, as summarized in Table 1.

Table 1 Comparison of Green Cos lettuce height between conventional and smart farm methods over 5 weeks.

Week	Green Cos lettuce height (cm)		Diff.
	Conventional Method	Smart Farm System	
1	4.8	6.5	1.7
2	8.5	9.4	0.9
3	10	11.5	1.5
4	35	40.5	5.5
5	41.5	51	9.5

Significant differences in growth rates were observed between the two groups starting from the second week of the experiment. During the initial stage (Week 1), both groups exhibited comparable heights of approximately 4.8 cm. However, during the rapid growth stage (Weeks 3-4), the smart farm plants demonstrated a markedly accelerated growth rate; by Week 4, they reached a height of 40.5 cm, outperforming the conventional group which stood at 35 cm. At the final

harvest stage (Week 5), the smart farm plants achieved a maximum average height of 51 cm, whereas the conventional plants reached only 41.5 cm. Furthermore, the implementation of the smart farm system effectively reduced the cultivation period, with the lettuce reaching market-ready maturity in just 35 days, significantly faster than the 42–45 days typically required by conventional methods.

3.3 Discussion

The superior growth performance observed in the smart farm system can be attributed to two primary engineering interventions: the extension of the photoperiod via supplemental LED lighting and the maintenance of microclimate stability. By providing specific red (630–660 nm) and blue (430–460 nm) spectrums between 18:00 and 20:00, the system effectively increased the Daily Light Integral (DLI) and stimulated Chlorophyll A and B absorption, which promoted faster cell division and stem elongation.

Furthermore, the precise control of soil moisture ensured microclimate stability, preventing water stress and facilitating continuous nutrient uptake; in contrast, the conventional method's reliance on manual irrigation and natural sunlight resulted in environmental fluctuations that negatively impacted the plants' metabolic rates.

4. Conclusion

This research successfully developed a standalone smart farming system powered by a 520 Wp solar PV system and controlled by an ESP8266-based IoT controller. The system effectively managed microclimate conditions, specifically soil moisture and supplemental lighting, ensuring stable operation without reliance on the main grid. Experimental results demonstrated that the integration of 2-hour supplemental LED lighting (Red/Blue spectrum) and precise irrigation control significantly enhanced the growth of Green Cos lettuce. The plants in the smart farm reached an average height of 51 cm, surpassing the conventional method (41.5 cm) by approximately 22.8%. Furthermore, the cultivation cycle was reduced to 35 days. These findings validate the potential of integrating renewable energy and precision agriculture technologies to increase crop yield and optimize resource efficiency. Future work will focus on implementing machine learning algorithms for predictive environmental control and scaling the system for commercial greenhouse applications.

5. References

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