IoT-Based Smart Cultivation Platform for Geisha Coffee with Artificial Light Integration

Korasut Fueangnoi[1]*, Kanokrak Pianngam[1], Thitika Wongchai[1]
Manatchanok Tamwong [1] and Satit Thamkhanta[1]
[1] *Princess Chulabhorn Science High School Chiang Rai, Rob wiang, Mueang, Chiang Rai, 57000 Thailand*
**e-mail: 05794korasut@pcccr.ac.th*

Abstract

The objectives of this project were to develop an intelligent platform to enhance the cultivation efficiency of Geisha coffee using IoT technology and artificial lighting, and to evaluate the performance of the developed intelligent platform in controlling environmental conditions and promoting the growth of Geisha coffee plants. The system was designed using the Design Thinking process, which included five steps: understanding the farmers' problems, defining the problem by considering context, cost, and the developer potential, generating ideas based on previous data and research, creating a prototype through analysis and design, and developing, testing, and improving the hardware and software. The results showed that the smart greenhouse system functioned effectively as designed and was powered by solar energy. The system consisted of a solar energy unit, an environmental sensing and control system for temperature, humidity and light intensity, and a real-time monitoring and control interface using Home Assistant. The system enabled convenient and timely monitoring and control of environmental conditions. In addition, it was able to maintain optimal conditions for the growth of Geisha coffee, increasing the potential for high-quality coffee production and reducing the risk of fungal infection. Therefore, the smart greenhouse system provides an effective alternative for coffee cultivation in a controlled environment.

Keywords: Smart Greenhouse, Geisha Coffee, Internet of Things (IoT), Artificial Lighting, Design Thinking

Introduction

Chiang Rai is one of Thailand's leading areas for Arabica coffee cultivation, particularly in the Doi Mae Mon area in Chiang Rai Province, where high-altitude conditions and mineral-rich soils with characteristics similar to volcanic soils provide a favorable environment for producing high-quality coffee [8].However, coffee cultivation in mountainous areas with complex terrain poses significant challenges for environmental monitoring and farm management, making resource utilization more difficult and costly. Furthermore, seasonal climate variations affect critical environmental factors, including temperature, humidity, and the occurrence of plant diseases, all of which directly influence coffee growth and productivity [2], [7].

Geisha coffee is a premium cultivar of *Coffea arabica*, internationally recognized for its exceptional aroma, complex flavor profile, and high commercial value [4].Because of its premium market value, Geisha coffee has the potential to generate higher economic returns per unit cultivation area than conventional Arabica coffee. However, its cultivation requires careful control of environmental conditions, particularly,soil quality temperature, humidity and mineral composition, to produce consistently high-quality beans [4].

Controlled environment agriculture, particularly greenhouse cultivation, provides an effective approach to mitigating the impacts of climate variability by maintaining optimal growing conditions throughout the production cycle. In this context, Internet of Things (IoT) technology and automated greenhouse systems play an important role in precision agriculture by enabling real-time monitoring and control of environmental parameters [1]. Furthermore, artificial lighting can supplement natural sunlight during periods of insufficient light, promoting plant growth and improving production efficiency, crop quality, and yield consistency [6].

However, the application of closed greenhouse systems integrated with IoT technology for Geisha coffee cultivation has received limited attention, particularly in Thailand. Therefore, this study proposes and develops a smart greenhouse system for Geisha coffee cultivation by integrating IoT technology, solar energy, and automated environmental control. The proposed system is designed to optimize growing conditions, improve resource-use efficiency, reduce production losses, and support the sustainable production of high-quality Geisha coffee.

Methodology

1). Research Design

This study employed a design and experimental research approach based on the Design Thinking framework, which consists of five stages: (1) problem identification,
(2) problem definition, (3) ideation,
(4) prototyping, and (5) testing and refinement. The objective was to develop an intelligent greenhouse system capable of real-time environmental monitoring, automated control, and remote data access. The experimental evaluation focused on assessing system stability, environmental control accuracy, and operational efficiency under controlled greenhouse conditions.

2). Materials and Equipment

2.1 Hardware Components

Table 1. Hardware Components Used in the Smart Greenhouse Prototype **:**

Component	Specification
ESP32 Microcontroller	Wi-Fi enabled
DHT11 sensor	Temperature & Humidity
Soil Moisture Sensor	Capacitive type
BH1750 Sensor	Digital light sensor
NPK Sensor	Soil nutrient sensor
Solar Panel	150 W photovoltaic
LED Grow Light	Full-spectrum LED
IoT Control Cabinet	Custom PCB
Voltage Regulator	NA505

2.2 Software Components

The software utilized in this study included:

1. Arduino IDE for embedded programming and firmware development.
2. Home Assistant platform for real-time monitoring, data logging, visualization, and automated system control.

3). System Architecture

The smart greenhouse system was developed based on Internet of Things (IoT) technology. Environmental sensors were installed inside the greenhouse to continuously measure temperature, relative humidity, soil moisture, soil NPK levels, light intensity, and system voltage.

The sensor data were processed by the ESP32 microcontroller and transmitted to the Home Assistant platform through a Wi-Fi network. Home Assistant provided real-time monitoring, historical data logging and remote access to the greenhouse system.

To maintain suitable growing conditions, the system compared the measured values with predefined threshold ranges. When any parameter exceeded the acceptable range, the corresponding device, such as the LED grow light or irrigation system, was activated automatically.

4. Experimental Procedure

The experimental procedure consisted of five stages.

Stage 1 : Preliminary Study and Environmental Assessment

A field survey was conducted in the Doi Mae Mon area, Chiang Rai Province, to examine the environmental conditions affecting Geisha coffee cultivation. Information on temperature, relative humidity, soil moisture, light intensity, and soil nutrient levels was collected through field observations and agricultural references. These findings were used to determine the environmental requirements for the greenhouse system.

Stage 2 : System Design and Development

A smart greenhouse prototype was designed by integrating environmental sensors, an ESP32 microcontroller, and IoT technology. A 150 W photovoltaic solar panel was selected as the primary power source to improve energy efficiency, while LED grow lights were installed to provide supplemental lighting when natural light was insufficient.

Stage 3 : Installation and Calibration

All sensors and electronic components were installed inside the greenhouse and calibrated before operation to ensure reliable measurements. The ESP32 microcontroller was programmed to collect environmental data at regular intervals and transmit the information to the Home Assistant platform.

Stage 4 : Dashboard Development and System Integration

A monitoring dashboard was developed using Home Assistant to display real-time environmental conditions, historical records, and system status. The platform also enabled remote monitoring and automatic control of greenhouse operations.

Stage 5 : System Testing and Evaluation

The prototype was tested at Princess Chulabhorn Science High School, Chiang Rai. The system performance was evaluated in terms of sensor accuracy, communication stability, data transmission, and automatic control before deployment in the target agricultural area.

Result and Discussion

1. Sensor Performance Evaluation

The performance of the developed IoT monitoring system was evaluated by comparing sensor measurements with reference instruments. Each parameter was measured five times, and the average values were used for comparison.

Table 2. Performance Evaluation of the IoT-Based Smart Greenhouse Monitoring System

Parameter	IoT System	Reference Instrument	Error (%)	Acceptable Range
Temperature (°C)	28.6	28.4	0.7	20–35
Relative Humidity (%)	49	50	2.0	40–70
Soil Moisture (%)	64	65	1.5	40–70
Light Intensity (lux)	60	58	3.4	Depends on crop
Nitrogen (mg/kg)	55	57	3.5	20–60
Phosphorus (mg/kg)	1542	1500	2.8	Depends on soil type
Potassium (mg/kg)	30	32	6.3	20–50
Soil pH	6.1	6.2	1.6	5.5–7.0

Note: *Values are presented as the average of five measurements. Error (%) was calculated by comparing the IoT sensor readings with the reference instrument.*

Table 2 shows that the measurements obtained from the IoT system were in good agreement with those from the reference instruments. The average measurement error remained low, indicating satisfactory sensor performance for greenhouse monitoring.

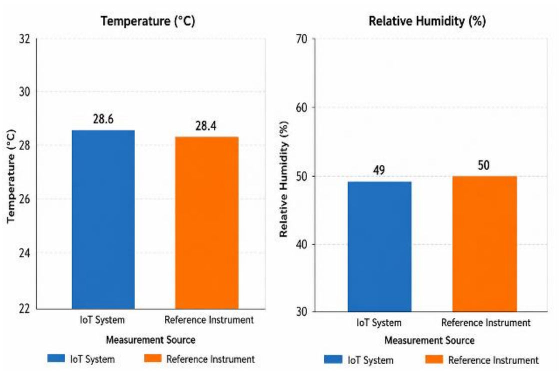

Fig. 1 compares the IoT sensor measurements with the reference instruments. The results showed good agreement.

2. Automated Environmental Control Performance

The developed control system responded automatically to changes in environmental conditions according to predefined threshold values. When soil moisture fell below the target level, the irrigation system was activated to restore suitable soil conditions. Likewise, the LED grow light was automatically switched on during periods of insufficient light intensity. These automated responses reduced the need for manual operation and helped maintain appropriate environmental conditions throughout the experimental period.

Real-time sensor data were continuously transmitted to the Home Assistant platform, allowing environmental conditions to be monitored remotely. During the experiment, the monitoring and control functions operated without communication failures or noticeable delays, indicating stable system performance.

3. System Stability and Technical Feasibility

The prototype operated continuously throughout the testing period with stable communication between the sensors, ESP32 microcontroller, and Home Assistant platform. The solar power subsystem provided sufficient energy for daily operation, supporting the use of renewable energy in greenhouse applications. These results demonstrate that the proposed system is technically feasible for continuous environmental monitoring and automated control in smart greenhouse systems.

4. Discussion

The results confirm that the proposed IoT-based smart greenhouse system can reliably monitor environmental conditions and perform automated control in real time. The low sensor measurement errors and stable system operation suggest that the developed prototype is suitable for precision greenhouse management.

These findings are consistent with previous studies that reported the benefits of IoT technology for environmental monitoring and automated control in precision agriculture [3], [9]. Although this study focused on prototype validation, the proposed system shows potential for supporting Geisha coffee cultivation under controlled environmental conditions. Future work should evaluate long-term crop growth, yield, and economic performance under practical cultivation conditions.

Conclusions

This study presented the design and development of an IoT-based smart greenhouse system for Geisha coffee cultivation, integrating artificial lighting and solar energy to improve environmental control and promote sustainable operation. The system was developed following the Design Thinking framework, which guided the processes of problem identification, system design, prototype development,and performance evaluation.

The experimental results showed that the prototype operated reliably under simulated greenhouse conditions. The integrated sensors continuously monitored key environmental parameters, including temperature, relative humidity, soil moisture, light intensity, and soil nutrients, while the ESP32 microcontroller transmitted real-time data to the Home Assistant platform. In addition, the automated control functions responded appropriately to predefined environmental thresholds, supporting stable greenhouse conditions throughout the experiment. The solar power subsystem also provided a consistent energy supply, highlighting the suitability of the proposed system for agricultural applications in remote areas.

Overall, the developed prototype offers a practical approach to smart greenhouse management by enabling continuous environmental monitoring, reducing manual operation, and improving the efficiency of resource utilization. Although the present study focused on engineering validation rather than biological crop performance, the findings confirm the technical feasibility of the proposed platform for controlled-environment agriculture.

Future research should include long-term cultivation experiments using Geisha coffee plants to evaluate growth performance, yield, and bean quality under practical conditions. The integration of artificial intelligence–based predictive control and advanced data analytics may further enhance system adaptability and support more efficient greenhouse management.

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