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Development of an IoT-Based Real-Time Monitoring System for Light Intensity, Temperature, and Humidity in Dragon Fruit Farms

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ABSTRACT

The rapid advancement of smart agriculture under the Industry 4.0 paradigm has accelerated the integration of digital and IoT technologies into modern farming systems, aiming to enhance productivity, optimize resource utilization, and promote environmental sustainability. Meanwhile, dragon fruit is a major export fruit of Vietnam, grown mostly in Binh Thuan, Long An, and Tien Giang provinces. Following the above trend, this study presents the design and implementation of an Internet of Things (IoT)-based climate monitoring system that allows real-time observation and recording of light intensity, temperature, and humidity parameters at dragon fruit farms. The system integrates an ESP32 microcontroller, a DFRobot SEN0390 light sensor, and a digital temperature and humidity sensor SHT30. Data is transmitted via Wi-Fi to a cloud platform for real-time display, IoT MQTT (Message Queuing Telemetry Transport) Panel application, web interface and automatically stored in Google Sheets for long-term analysis. A key improvement of this study lies in the integration of wide-range light sensors compared to previous greenhouse IoT system studies. Experimental validation demonstrates stable system performance, with average data latency under two seconds and high measurement accuracy, confirming the reliability and scalability. The system provides an agricultural environmental monitoring solution for farmers, setting a basis for big data analytics and future automation in Vietnam.

Keywords: IoT; Smart Agriculture; Environmental Monitoring; ESP32; Dragon Fruit; MQTT

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1. Introduction

1.1. Scientific Context

The Internet of Things (IoT) has emerged as a transformative technology in agriculture, enabling real-time sensing, wireless communication, and data analytics for process automation. IoT-based monitoring systems can connect environmental sensors, cloud platforms, and mobile applications to form an integrated smart farming ecosystem [1,2].

Recent advancements in microcontroller technology—especially the ESP32, known for its dual-core processing, integrated Wi-Fi/Bluetooth connectivity, and low power consumption—have facilitated the development of affordable monitoring devices for agriculture. By combining ESP32 with digital sensors such as SHT30 (for temperature and humidity) and DFRobot light sensors, data can be continuously collected and visualized through cloud services like Blynk or Google Sheets [1,3,4].

1.2. Research Gap

Vietnam's agricultural sector plays a critical role in national food security and export development, contributing over 14% to GDP. Among its high-value crops, dragon fruit represents a major export commodity, particularly in the southern provinces such as Binh Thuan, Long An, and Tien Giang. Dragon fruit plants thrive best in temperatures between 25–35 °C and require strong sunlight for more than 12 h per day to stimulate flowering. Additionally, air humidity plays a crucial role in fruit set [5,6].

Despite significant progress in IoT-based agricultural applications, most existing systems focus on greenhouse crops or irrigation scheduling, with limited research addressing outdoor fruit farms that require exposure to natural lighting conditions. For dragon fruit cultivation, environmental monitoring must operate in open-field conditions with variable weather, requiring robust communication, sensor calibration, and reliable data storage.

1.3. Objectives

This research aims to develop an IoT-based system for real-time monitoring and data logging of environmental parameters in dragon fruit farms. The specific objectives are to:

- Design and assemble a low-cost hardware system integrating ESP32, SHT30, and light sensors for continuous data acquisition.
- Develop software to visualize real-time parameters via web and mobile interfaces and log data automatically to Google Sheets.
- Evaluate system stability, latency, and reliability under outdoor conditions.

1.4. Related Researches

The integration of IoT technologies into agriculture has significantly evolved in the past decade, particularly in the areas of environmental monitoring, irrigation management, and precision farming. Numerous studies have demonstrated the feasibility of using low-cost sensors and wireless networks to improve data-driven decision-making in crop management.

Recent studies from Vietnam provide empirical evidence of the suitability of IoT technology for agricultural environmental monitoring and semi-automatic climate control. Dung et al. (2018) [7] developed a wireless sensor network system for mushroom cultivation that is capable of continuously measuring temperature, humidity, and light intensity at multiple locations, demonstrating the feasibility of low-cost multi-point microclimate monitoring. Additionally, Tin et al. (2020) [8] implemented an IoT-based monitoring and control system for rice fields using Alternate Wetting and Drying (AWD) irrigation, allowing remote monitoring of environmental and soil-water conditions and validating the stability of pump control through microcontroller-relay integration. In 2022, Ton That et al. [9] fabricated a device integrating sensors, microcontrollers, and IoT (Internet of Things) technology, including sensor modules connected to a central module via Wi-Fi to monitor microclimates such as temperature, humidity, and light in the greenhouse. In 2023, Vu and Nguyen [10] designed a local area network architecture of a controller that collects data from environmental sensors and cameras used to measure, monitor, and record environmental parameters such as temperature and humidity as well as images of coffee leaves damaged by diseases. These studies are the basis for the fabrication of practical systems and confirm the ability to apply IoT to practical agriculture.

In 2024, Do [11] presented the design and implementation of an IoT agricultural monitoring and control system. The system combines various components such as NodeMCU ESP32, soil moisture sensor, light sensor, pH sensor, DHT22, and Blynk IoT cloud. The completed system collects farm environmental data from sensors and transmits it to mobile devices for easy monitoring and performing automated tasks such as remote irrigation. Building on these advances, Anh et al. (2025)[12] designed a semi-automatic oyster mushroom cultivation model using IoT sensing combined with LoRa/Modbus communication, achieving reliable closed-loop regulation of temperature and humidity.

Internationally, research on IoT for smart agriculture has advanced toward multi-sensor data fusion and automated actuation. Rahmaniar et al. (2023)[13] introduced an ESP32-based compost monitoring system that utilized Android integration for real-time visualization. Although limited to monitoring functions, it highlighted the importance of low-latency data transmission in biological processes. Kalpana et al. (2024)[14] proposed a smart irrigation system combining soil moisture and temperature sensing with mobile-based monitoring to optimize water use, demonstrating the potential of feedback-based control in open-field farming. Furthermore, Hu et al. (2022)[15] deployed a LoRa-based IoT network for orchard management, integrating light and humidity sensors for autonomous irrigation and lighting control.

Several practical implementations indicate that farmers have already adopted IoT solutions in orchard management. In northern Spain, an IoT-based smart system was employed in vineyards to monitor environmental conditions and support irrigation control[16]. In Indonesia, a recent study developed an IoT-based system integrated with an expert system for real-time monitoring and disease diagnosis in cocoa cultivation, in which environmental data are continuously collected via sensors and processed by an ESP32 microcontroller to support precision agriculture and more efficient crop management[17]. A pilot study developed an IoT-based smart monitoring and management system for apple orchards, integrating multi-layer architecture and wireless environmental sensing to support disease and pest forecasting, as well as irrigation and fertilization management. The system enabled data-driven decision-making through predictive models and threshold-based control, resulting in reduced pesticide and fungicide use, optimized water and fertilizer consumption, and improved yield and fruit quality[18]. Building on these successful applications, research efforts and the adoption of IoT technologies in orchard management have continued to expand in recent years[19–21].

To better illustrate the novelty and technical advantages of the proposed IoT architecture, **Table 1** provides a detailed comparison between this study and representative recent agricultural monitoring systems reported in the literature.

Table 1. Comparison between the proposed IoT system and recent agricultural monitoring studies.

Study	Platform	Sensors Used	Application Field	Unique Features	Limitations
Dung et al. (2018)[7]	Arduino + Wi-Fi	Temp., Humidity, Light	Mushroom greenhouse	Multi-node network	Indoor only
Tin et al. (2020)[8]	NodeMCU	Soil moisture, Temp.	Rice field	Irrigation automation	No light sensing
Ton That et al. (2023)[9]	ESP8266	Temp., Humidity	Greenhouse	Semi-auto climate control	Limited scalability
Hu et al. (2022)[15]	STM32	Light, Humidity	Orchard	Long-range wireless	No real-time mobile dashboard
Rahmaniar et al. (2023)[13]	ESP32	Temp., Humidity	Compost monitoring	Android visualization	Indoor-only
Pranoto et al. (2025)[17]	ESP32	Temp., Humidity	Cocoa disease monitoring	AI-assisted	High cost
This study (2025) (authors' proposal)	ESP32 DevKit V1	SHT30, DFRobot SEN0390 (Temp., Humidity, Light)	Outdoor dragon fruit farm	MQTT + HyperText Transfer Protocol (HTTP); Dual dashboard (mobile + web), Google Sheets integration, low latency.	Currently passive monitoring; future work includes solar power and AI prediction

The novelty of this research lies in its integration of a wide-range ambient light sensor (DFRobot SEN0390) with the ESP32 platform to support accurate real-time monitoring under outdoor open-field conditions, which is rarely addressed in existing IoT studies that typically focus on greenhouses. More specifically, the approach uses a dedicated broadband light sensor (required for dragon fruit) that previous studies often omit or use narrowband sensors (for greenhouses). In contrast to previous works, the present system uniquely combines continuous monitoring of temperature, humidity, and light intensity with automatic data logging through Google Sheets and dual visualization interfaces (mobile MQTT dashboard and web-based Chart.js application). This dual-layer design enhances accessibility and transparency of farm data while ensuring low-cost deployment and scalability for open-field fruit cultivation.

2. Materials and Methods

2.1. System Overview

The proposed environmental monitoring system was developed based on Internet of Things (IoT) architecture, integrating low-cost sensors, a microcontroller, and a cloud-based data visualization platform. The system was designed to continuously collect and transmit environmental parameters—specifically temperature, humidity, and light intensity—to a remote server for real-time monitoring and data archiving.

The overall architecture follows a three-layer structure consisting of:

1. Sensing Layer—Responsible for data acquisition from the environmental;
2. Network & Processing Layer—Responsible for signal processing, data transmission, and cloud synchronization;
3. Application Layer—Providing real-time visualization and user access via mobile and web interfaces.

2.2. Hardware Components

All hardware components were selected based on cost efficiency, compatibility, and reliability for continuous monitoring applications. All sensors were calibrated prior to installation to ensure measurement accuracy (**Table 2**).

2.3. Documents and Software

To ensure reliable data acquisition, communication, visualization, and storage, various software tools and libraries were employed; these components and their respective functions are detailed in **Table 3**.

Table 2. Hardware components utilized in the IoT monitoring system.

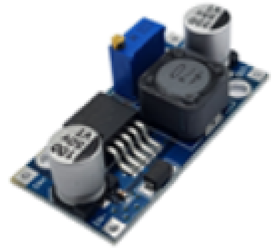
Components	Code/Model—Specifications	Function
 Microcontroller Unit (MCU)	Model: ESP32 DevKit V1 (ESP-WROOM-32) Operating voltage: 3.3–5 V Current consumption: 15 mA Power rating: 75 mW Communication interfaces: I^2C (Inter-Integrated Circuit), Serial Peripheral Interface (SPI), Universal Asynchronous Receiver–Transmitter (UART)/Universal Synchronous/Asynchronous Receiver–Transmitter (USART), and Universal Serial Bus (USB)	Serves as the central processing unit, responsible for sensor data acquisition and wireless data transmission via Wi-Fi.
 Power Module	Model: LM2596 DC–DC (Direct Current–Direct Current) Converter Input voltage: 3–30 V Adjustable output voltage: 1.5–30 V Maximum output current: 3 A Efficiency: ~92% Power rating: 15 W Dimensions: 45 × 20 × 14 mm	Provides a regulated power supply for the microcontroller and all connected sensors.

Table 2. *Cont.*

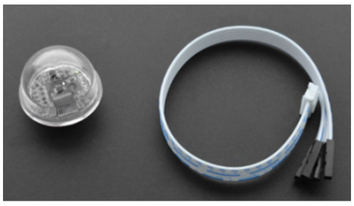
Components	Code/Model—Specifications	Function
 Ambient Temperature and Humidity Sensor	Model: SHT30 Operating voltage: 2.4–5.5 V DC Temperature range: −40 °C to 125 °C Humidity range: 0–100% RH Temperature accuracy: ±0.3 °C Humidity accuracy: ±3% RH Power consumption: 4.8 µW Communication interface: I^2C Weight: 65 g	Measures ambient air temperature and relative humidity in the orchard environment.
 Ambient Light Intensity Sensor	Model: DFRobot Ambient Light Sensor (0–200 klx), SKU: SEN0390 Supply voltage: 2.7–6 V Operating current: 0.7 mA Measurement range: 0–200 klx Accuracy: 0.054 lx Communication interface: I^2C Operating temperature: −40 °C to +85 °C	Measures solar radiation intensity throughout the day.
 Power Adapter	Model: 1230 Input: 100–240 V AC, 50/60 Hz Output: 12 V DC, 3 A	Supplies stable power to the IoT system through the electrical enclosure.

Table 3. Software components utilized in the IoT monitoring system.

Component	Software/Version—Specifications	Function
Microcontroller Programming Environment	Arduino Integrated Development Environment (IDE) • Programming language: C/C++ • Integrated tool for uploading firmware to ESP32 • Includes Serial Monitor for real-time sensor data inspection	Programming, compiling, and uploading control firmware for the ESP32 microcontroller.
ESP32 Software Libraries (Arduino Framework)	• WiFi.h (Wi-Fi connectivity) • PubSubClient (MQTT communication) • Wire.h (I^2C communication) • Adafruit_SHT31 (SHT30 sensor driver) • DFRobot_B_LUX_V30B.h (light sensor driver)	Sensor control, data acquisition, and transmission via MQTT/Webhook.
Mobile Application	IoT MQTT Panel (Android/iOS) • Real-time dashboard for temperature, humidity, and light visualization • Supports MQTT and WebSocket protocols	Real-time visualization of sensor data on mobile devices.
MQTT Broker	• Mosquitto MQTT Broker (local or cloud deployment) • Alternative: HiveMQ Public Broker • Ports: 1883 (MQTT TCP), 8884 (MQTT WebSocket)	Acts as the data exchange hub between ESP32, Google Sheets, the mobile application, and the web interface.
Web-based Monitoring Interface	HyperText Markup Language (HTML5) + Cascading Style Sheets (CSS3) + JavaScript • MQTT WebSocket Client (Eclipse Paho JS) • Data visualization using Chart.js	Real-time IoT dashboard for web-based monitoring of environmental parameters.

Table 3. *Cont.*

Component	Software/Version—Specifications	Function
Online Data Storage Platform	Google Sheets + Google Apps Script • Receives data from ESP32 via HyperText Transfer Protocol (HTTP) POST method/Webhook or via MQTT →Application Programming Interface (API) Gateway → Sheets • Automatically logs structured data (timestamp–temperature–humidity–light intensity) • Supports real-time synchronization	Cloud-based storage of IoT data for statistical analysis and reporting.
Data Analysis Tools	• Google Sheets (charting, filtering, and pivot tables) • Microsoft Excel (offline analysis) • Python (Pandas, Matplotlib)	Processing and analyzing sensor datasets acquired from the IoT system.
Testing and Debugging Tools	• Serial Monitor (Arduino IDE) • MQTT Explorer	Monitoring MQTT packets and validating the correctness of transmitted data formats.

2.4. System Implementation and Sensor Integration

The core of the system is the ESP32 DevKit V1 microcontroller, which manages data acquisition, processing, and wireless transmission. To ensure stable operation in outdoor agricultural environments, the power supply unit utilizes an LM2596 DC–DC buck converter to step down the external 12 V input (from a standard adapter) to a regulated 5V output for the microcontroller and sensors.

Sensor integration is achieved through standard communication protocols to optimize wiring and signal integrity. Both the SHT30 temperature-humidity sensor and the DFRobot Ambient Light Sensor (SEN0390) utilize the I^2C interface, connected to the ESP32 via GPIO21 (Serial Data Line, SDA) and GPIO22 (Serial Clock Line, SCL). The SHT30 sensor operates at 3.3 V, providing high-precision digital output, while the SEN0390 sensor is capable of measuring illuminance up to 200 klx, making it suitable for monitoring intense sunlight in open fields.

All electronic components are housed in an electrical cabinet to protect against dust, moisture and physical impact. Circuit Breaker (CB) is integrated to ensure electrical safety and circuit protection.

2.5. Software Architecture and Communication Protocol

The software for ESP32 is developed using Arduino IDE in C++ language, using a modular architecture for efficient multitasking. The software logic avoids blocking functions (such as delay()) by using non-blocking timer mechanisms (e.g., millis()), allowing sensor readings, MQTT communication and HTTP requests to be performed simultaneously.

The communication architecture uses a hybrid approach, supporting both real-time monitoring and historical data logging:

1. Real-time visualization (Web Dashboard): A custom web interface has been developed using HTML, CSS and JavaScript. This combination of Web technologies ensures a lightweight, responsive (responsive) interface that can be accessed on any modern browser, meeting the requirements for convenient remote monitoring. This interface uses the Paho MQTT JavaScript client library to directly subscribe to data topics published by the ESP32 node. Upon receiving a data packet (in JavaScript Object Notation (JSON) format), the client updates the interface immediately. Data visualization uses the Chart.js library to dynamically display:
    - Parameter values: Display instantaneous numerical values of Temperature, Humidity and Light Intensity.
    - Dynamic charts: Line and column charts can show the fluctuation trends of parameters over short periods of time (e.g., the last hour).
    - Reconstructing historical graphs: Historical data are retrieved directly from Google Sheets using the Google Sheets API (via RESTful HTTP requests in JSON-format). The web client sends a query specifying the target sheet and range, and the API returns the corresponding dataset, which is parsed and fed into Chart.js for rendering. The web interface has an option to reconstruct histor-

ical graphs based on typical time options, such as Last 12 h, Last 24 h, Last 3 days, Last 7 days, Last 1 month, Last 1 year…

2. MQTT protocol (for streaming): ESP32 acts as a client that publishes JSON formatted sensor data (temperature, humidity, light) to a public MQTT broker (HiveMQ) on specific topics. This lightweight protocol ensures low latency (less than 2 s) and minimal bandwidth usage.

HTTP/HTTPS protocol (for logging): The system periodically sends HTTP GET requests containing sensor values as parameters to a Google Apps Script URL. This script acts as a webhook to directly append timestamped data to Google Sheets, providing a cost-effective, long-term database solution.

3. Results

3.1. Design, Fabrication, and Installation of the IoT Hardware System

Following the research procedure described earlier, the IoT-based climate monitoring system for the dragon fruit orchard was successfully designed, fabricated, and assembled. The hardware architecture was developed based on three main functional layers: (1) The sensor layer, (2) The processing and communication layer, and (3) The application and visualization layer. **Figure 1** shows the assembled internal components of the control unit.

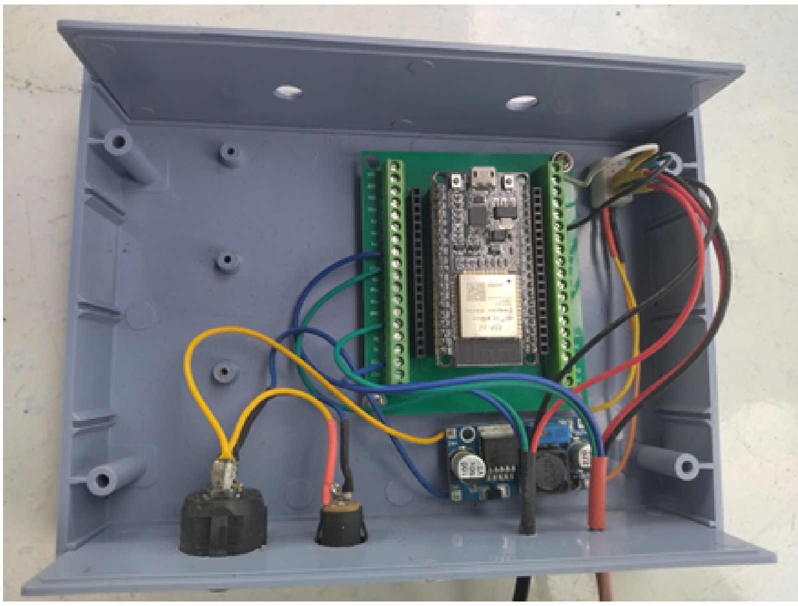


Figure 1. Connected hardware components.

1. **Sensor Layer**

The system employs an SHT30 sensor to measure air temperature and humidity, together with a DFRobot SEN0390 sensor to measure ambient light intensity. Both sensors communicate with the microcontroller via the I^2C protocol, reducing the number of required connection pins while improving data transmission stability. Sensor signals are sampled every 2 s, ensuring that environmental fluctuations in the dragon fruit cultivation area are accurately captured.

2. **Processing and Communication Layer**

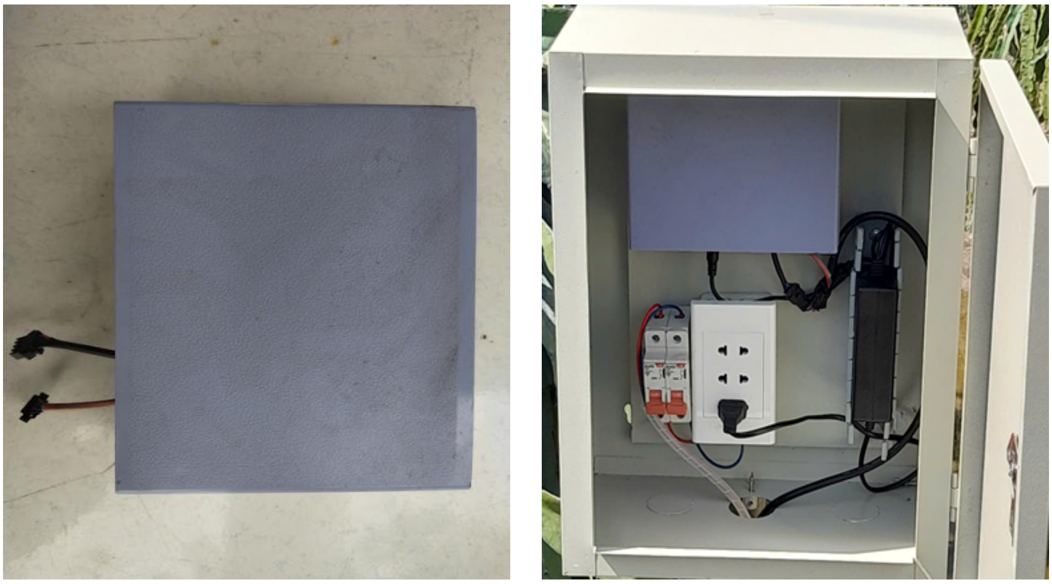
The central processing unit is an ESP32 DevKit V1, responsible for acquiring, processing, and transmitting sensor data through its integrated Wi-Fi module. The microcontroller is programmed using the Arduino IDE with C/C++, incorporating the following supporting libraries: Wire.h, Adafruit_SHT31.h, DFRobot_B_LUX_V30B.h, WiFi.h, PubSubClient.h, and HTTPClient.h.

The ESP32 performs two tasks simultaneously: (1) Transmitting sensor data via the MQTT protocol to the MQTT Dashboard mobile application and a Web Monitoring interface, and (2) Uploading real-time data logs to Google Sheets through the Google Apps Script API. Real-time synchronization is managed using NTP (Network Time Protocol), ensuring accurate timestamping of each recorded data packet.

3. Visualization and Application Layer

Visual monitoring and data access are provided through two interfaces: (1) a smartphone application and (2) a web-based dashboard. These functions are supported using a smartphone, a laptop, and a local Wi-Fi network infrastructure.

All hardware components were neatly integrated into a single technical enclosure, which was installed inside an electrical cabinet to protect the circuitry from moisture, sunlight, and rain. The sensor cables were securely and safely connected, and the system was powered via an adapter connected to an internal power outlet within the cabinet (**Figure 2**).



(**a**) Microcontroller housing. (**b**) Electrical cabinet.

Figure 2. Hardware assembly.

Laboratory testing confirmed that all system components operated stably under controlled conditions. The power supply remained constant, with an average current consumption of 165 mA. The sensors exhibited acceptable accuracy, with mean deviations of ±0.5 °C for temperature, ±3% RH for humidity, and ±100 lux for light intensity when compared with calibrated reference instruments. The average data transmission latency from the sensors to the dashboard was approximately 1.8 s, ensuring real-time capability for environmental monitoring.

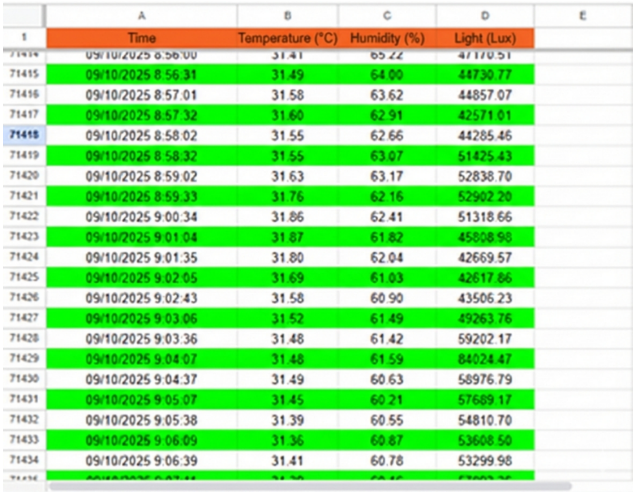
3.2. Software Compilation and Integration with the Application Dashboard and Web Interface

The control program was developed using the Arduino IDE in C/C++, incorporating specialized libraries to support system functionalities. The WiFi.h library was employed for wireless network connectivity, while PubSubClient.h facilitated MQTT-based communication. Sensor data acquisition was implemented using Adafruit_SHT31.h for the SHT30 temperature–humidity sensor and DFRobot_B_LUX_V30B.h for the ambient light sensor. In addition, real-time synchronization was enabled through time-handling libraries that obtain timestamp information from an NTP server.

After programming, the source code was successfully compiled and uploaded to the ESP32 DevKit V1 microcontroller via the Micro-USB interface at a baud rate of 115,200 bps. The compilation process produced no syntax errors, and the device initialized correctly according to the defined startup sequence. Output from the Serial Monitor confirmed that the ESP32:

- Established a stable connection with the preconfigured Wi-Fi network;
- Synchronized real-time clock data with the NTP server;
- Successfully connected to the MQTT broker (CloudMQTT Server).

The collected data were automatically logged to Google Sheets (**Figure 3**) via Google Apps Script, enabling long-term storage and supporting subsequent large-scale data analysis. Users were able to access and visualize the data through two monitoring interfaces:



	Time	Temperature (°C)	Humidity (%)	Light (Lux)
71414	09/10/2025 8:56:00	31.41	65.22	47170.51
71415	09/10/2025 8:56:31	31.49	64.00	44730.77
71416	09/10/2025 8:57:01	31.58	63.62	44857.07
71417	09/10/2025 8:57:32	31.60	62.91	42571.01
71418	09/10/2025 8:58:02	31.55	62.66	44285.46
71419	09/10/2025 8:58:32	31.55	63.07	51425.43
71420	09/10/2025 8:59:02	31.63	63.17	52838.70
71421	09/10/2025 8:59:33	31.76	62.16	52902.20
71422	09/10/2025 9:00:34	31.86	62.41	51318.66
71423	09/10/2025 9:01:04	31.87	61.82	45808.98
71424	09/10/2025 9:01:35	31.80	62.04	42669.57
71425	09/10/2025 9:02:05	31.69	61.03	42617.86
71426	09/10/2025 9:02:43	31.58	60.90	43506.23
71427	09/10/2025 9:03:06	31.52	61.49	49263.76
71428	09/10/2025 9:03:36	31.48	61.42	59202.17
71429	09/10/2025 9:04:07	31.48	61.59	84024.47
71430	09/10/2025 9:04:37	31.49	60.63	58976.79
71431	09/10/2025 9:05:07	31.45	60.21	57689.17
71432	09/10/2025 9:05:38	31.39	60.55	54810.70
71433	09/10/2025 9:06:09	31.36	60.87	53608.50
71434	09/10/2025 9:06:39	31.41	60.78	53299.98

Figure 3. Data is sent continuously to Google Sheets.

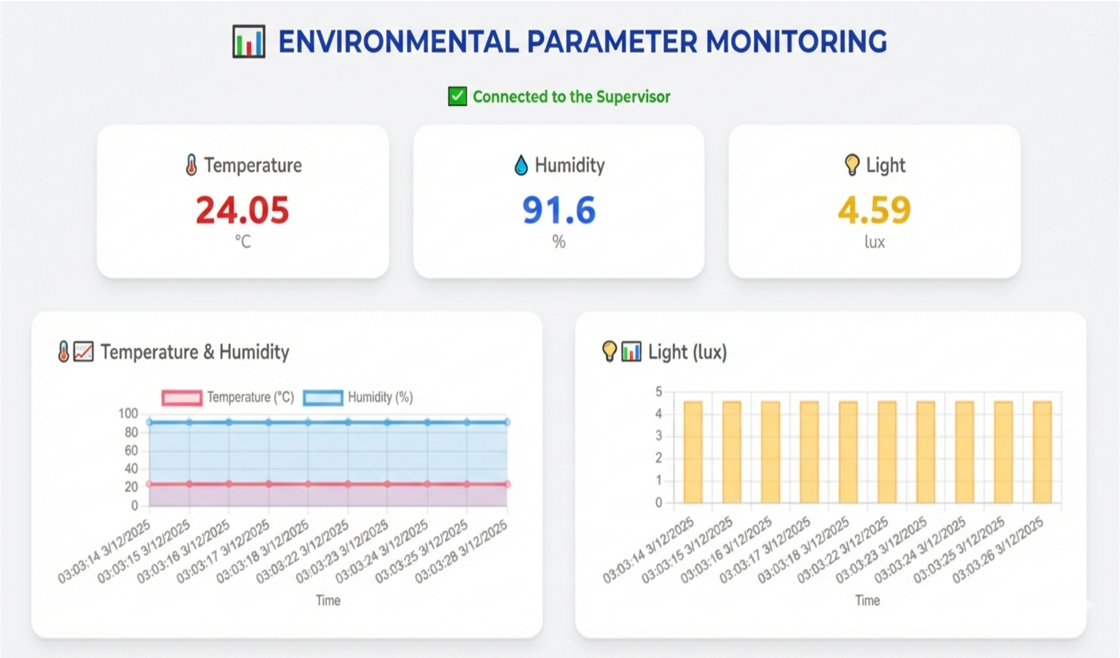
1. Smartphone Application (IoT MQTT Panel)

Sensor data (including temperature (°C), relative humidity (%), and light intensity (lux)) were transmitted at 2-second intervals and displayed simultaneously on the IoT MQTT Panel dashboard installed on Android/iOS smartphones. The application provided real-time visualization of each data channel (Topic), trend plots for environmental variables, and a system activity log for tracking operational status.

2. Access Using a Web Browser on Any Device

A web interface developed using HTML and JavaScript (with Chart.js) served as an integrated monitoring platform. It supported both real-time visualization via MQTT and the rendering of historical datasets retrieved from Google Sheets. The interface displayed time-series plots, bar charts, and other aggregated graphical representations. Through this dashboard, users could inspect live sensor readings, retrieve historical datasets, and reconstruct environmental trends at different temporal scales (daily, monthly, or annually) to support climate variability assessment in dragon fruit farms (**Figures 4** and **5**).

The results indicate that the entire data transmission pipeline operated reliably, exhibiting an average latency of less than 2 s with no packet loss during continuous operation. These findings demonstrate the robustness of the MQTT protocol and confirm the capability of the ESP32 to handle concurrent processing tasks effectively in environmental monitoring applications.



ENVIRONMENTAL PARAMETER MONITORING

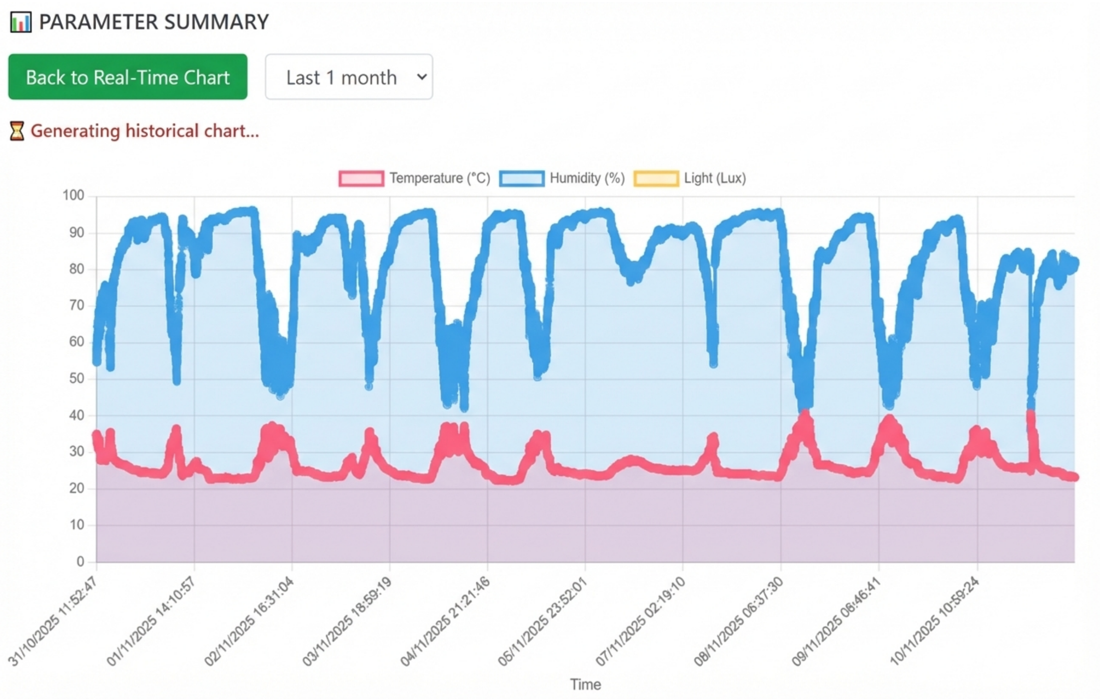
☑ Connected to the Supervisor

Temperature: 24.05 °C

Humidity: 91.6 %

Light: 4.59 lux

Figure 4. Real-time monitoring web interface.



📊 PARAMETER SUMMARY

⌛ Generating historical chart...

Figure 5. Web interface when viewing historical charts.

3.3. Deployment and Field Testing in a Dragon Fruit Farm

The IoT system was deployed and installed in a dragon fruit farm owned by Mr. Ho Tai Linh (address: 444 Thuan Loi Hamlet, Thuan My Commune, Tan Tru District, former Long An Province) (**Figure 6**) to evaluate its operational performance under real outdoor conditions. The system was configured to monitor key microclimatic parameters in the orchard, including air temperature, relative humidity, and light intensity. This field installation enabled continuous environmental data collection to support climatic assessment and environmental analysis of dragon fruit cultivation areas.

Figure 6. The farmer's dragon fruit farm, where the IoT system is tested.

In the field deployment configuration, the SHT30 sensor was installed inside a custom-built radiation shield at a height of 1.2–1.8 m above ground level, corresponding to the canopy zone of the dragon fruit plants (**Figure 7**). This arrangement ensured accurate measurement of the surrounding air temperature and humidity. The DFRobot SEN0390 light sensor was mounted in an upward-facing orientation, positioned to avoid shading from the plant canopy so that incident solar radiation could be measured reliably throughout the day.

(**a**) Sensors installed in the dragon fruit farm. (**b**) Light intensity sensor. (**c**) Temperature and humidity sensor.

Figure 7. Some pictures of the electrical cabinet and sensors installed in the field.

The control cabinet housing the IoT hardware was installed indoors or under a protective roof to prevent exposure to moisture and direct sunlight (**Figure 8**). A 30-m signal cable connected the cabinet to the field-mounted sensors. The system was powered through an adapter placed inside the control cabinet, providing stable power delivery and maintaining continuous Wi-Fi connectivity throughout the monitoring period.

Figure 8. An electrical cabinet containing the microprocessor of the IoT system.

The field results demonstrate that the system initialized and operated stably, acquiring sensor data continuously and transmitting it to the MQTT Broker at 2-s intervals without any communication interruptions. All parameters were simultaneously visualized on both the MQTT Dashboard mobile application and the customized web interface (HTML/JavaScript/Chart.js), clearly confirming the robustness and synchronization capability of the implemented communication architecture.

During continuous operation, the system recorded a total of 152,429 data entries, automatically logged to Google Sheets in real-time format (timestamp–temperature–humidity–light intensity). These data were subsequently visualized through the web-based interface (HTML/JavaScript/Chart.js), enabling users to track temporal variation patterns of temperature, humidity, and light intensity on an hourly, daily, and monthly basis.

In **Figure 9**, the chart illustrates the variation of sunlight intensity recorded in the dragon fruit orchard throughout December 2025. The data exhibit a distinct daily cycle, with light intensity increasing rapidly after sunrise, peaking around midday, and decreasing to nearly zero during nighttime. The maximum intensity reaches approximately 180,000 lux under clear sky conditions, while lower peaks on certain days (around 100,000–120,000 lux) suggest the presence of clouds or overcast weather. The repeated, consistent waveform indicates that the sensing and data logging system operated with high stability and accuracy. Overall, the light intensity pattern corresponds well with the typical climatic characteristics of the Mekong Delta, where high solar radiation during daytime provides favorable conditions for dragon fruit growth and flowering.

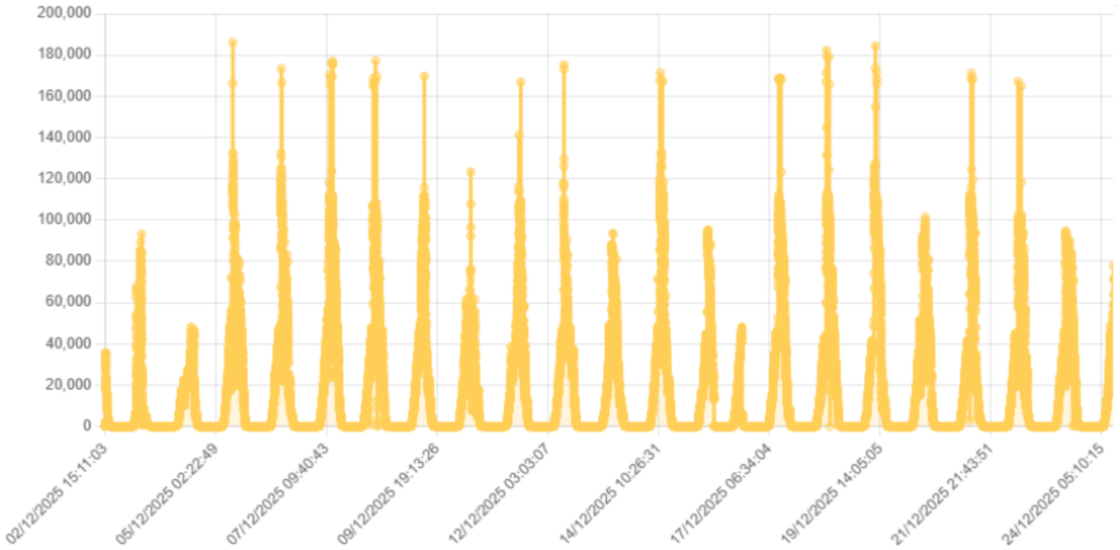


Figure 9. The chart shows the variation in sunlight intensity recorded at the dragon fruit farm.

The collected dataset exhibited high accuracy and strong consistency with reference measurements obtained from a calibrated psychrometer. The research team used a Lutron LM-8010 handheld microclimate meter (**Figure 10**) to verify and compare the measurements. Specifically, the average deviation between the SHT30 sensor and the reference instrument was ±0.4 °C for temperature and ±2.1% RH for humidity, which is within the acceptable tolerance range of the sensor specifications. Light intensity values showed clear diurnal variation between 06:00 and 18:00, ranging from approximately 1000 lux at early morning to over 100,000 lux at midday under direct sunlight—consistent with the ecological characteristics of the Mekong Delta region.

Figure 10. The Lutron LM-8010 handheld microclimate meter.

The system maintained high operational stability under harsh environmental conditions (ambient temperature up to 38 °C and humidity exceeding 85%). No connection loss or system freezing events were observed throughout the entire testing period. These findings confirm the feasibility and reliability of the IoT model for environmental monitoring in dragon fruit orchards and highlight its potential for extension to more advanced smart-farming applications, such as soil nutrient monitoring, soil moisture sensing, or automated irrigation control in future studies.

4. Discussion

The installation and pilot operation of the IoT-based monitoring system in the dragon fruit orchard demonstrated stable performance, continuous data acquisition, and high reliability under real outdoor environmental conditions. Compared with domestic and international studies on IoT-based agricultural environmental monitoring[9–14], the proposed model offers a notable advantage by integrating three sensor groups (temperature, humidity, and sunlight intensity) together with a dual monitoring platform comprising the MQTT Dashboard mobile application and a web-based visualization interface (HTML/JavaScript). This configuration ensures both real-time observation and long-term trend analysis, thereby meeting the practical requirements of precision-oriented dragon fruit cultivation.

To further assess the consistency of the collected environmental data, basic statistical analysis was performed on the temperature, humidity, and light intensity datasets. Over a continuous 15-day observation period, the average temperature was 31.2 ± 1.8 °C, with a variance of 3.24 $°C^2$, while relative humidity exhibited a mean of 74.6 ± 4.3% RH (variance = 18.5 $(RH)^2$). Light intensity data showed a mean daily peak of 145,000 ± 22,000 lux, reflecting typical tropical radiation patterns. The low standard deviation across successive days confirmed high repeatability of the measurements. These statistical results validate the stability and accuracy of the IoT sensing system under varying weather conditions.

In addition, the adoption of the MQTT (Message Queuing Telemetry Transport) communication protocol, instead of conventional platforms such as HTTP or Firebase, provides benefits in terms of low latency (<2 s), stable transmission efficiency, and optimized energy consumption for continuous outdoor monitoring applications. The integration of automated data logging via Google Sheets further enhances data transparency and establishes a foundation for advanced data analytics using tools such as Python, Excel, or AI-based forecasting in future work.

Compared with indoor or livestock-related environmental monitoring systems[7,9–13,22], the system developed in this study operates entirely outdoors, thus being directly exposed to sunlight, rainfall, and large thermal fluctuations. Despite these challenges, it maintained high operational stability throughout the experimental period. This indicates that the hardware integration, protective enclosure design, wiring layout, and environmental sealing have been appropriately selected to ensure mechanical durability and measurement reliability.

However, the current system remains at the passive monitoring stage and has not yet incorporated automatic feedback control mechanisms for irrigation, lighting, or microclimate regulation. Moreover, the operational duration was relatively short, limiting the ability to assess seasonal variations or long-term sensor drift over multiple cropping cycles. Therefore, future research should focus on implementing closed-loop control systems, integrating additional soil-related sensors (soil moisture, EC, and pH), and applying artificial intelligence or machine learning techniques to analyze large datasets and predict microclimatic conditions, thereby enhancing precision decision-making in crop management.

Overall, the findings of this study establish a solid technical foundation for deploying intelligent IoT monitoring systems in dragon fruit cultivation, contributing to the digital transformation of agriculture in Viet Nam. The system is low-cost, simple, and easily scalable, yet capable of providing highly effective continuous monitoring of environmental parameters that directly influence fruit yield and quality.

Despite its technical success, the current system presents several limitations. First, sensor drift may occur over prolonged exposure, requiring periodic calibration. Second, system operation depends on stable Wi-Fi connectivity, which may be unreliable in remote farms. Third, seasonal variation in solar radiation and ambient humidity was not fully analyzed due to the limited monitoring period. Future development will address these challenges by integrating solar power modules for autonomous operation, adopting LoRa/NB-IoT communication for long-range data transfer, and extending observation over multiple crop cycles. Moreover, advanced data analytics and AI/ML-based prediction models will be explored to support adaptive irrigation and precision control in smart farming systems.

5. Conclusions

This study has successfully designed and implemented an IoT-based environmental monitoring system for dragon fruit cultivation, using the ESP32 DevKit V1 microcontroller, SHT30 and DFRobot SEN0390 sensors, and the MQTT communication protocol. The system allows real-time monitoring of temperature, humidity, and light intensity through the MQTT Dashboard mobile application and HTML/JavaScript web interface, and automatically logs data to Google Sheets.

The field implementation has demonstrated high stability and accuracy under outdoor conditions, with transmission latency and measurement errors within acceptable limits. The results have confirmed the reliability of the proposed low-cost IoT architecture for agro-climate monitoring and its potential for data-driven analysis and decision-making in precision agriculture.

Future work should focus on extending the system towards closed-loop control by integrating earth sensors and actuators, applying artificial intelligence/machine learning (AI/ML) techniques for predictive analytics, and implementing solar-powered LoRa or NB-IoT communication for large-scale, sustainable agricultural applications.

Author Contributions

Conceptualization, A.-T.T. and H.T.T.; methodology, A.-T.T.; software, N.Q.P.; validation, H.T.T., N.Q.P. and T.T.H.; formal analysis, A.-T.T.; investigation, T.H.N.; resources, T.H.N.; data curation, N.Q.P.; writing—original draft preparation, A.-T.T.; writing—review and editing, H.T.T.; visualization, T.T.H.; supervision, H.T.T.; project administration, A.-T.T.; funding acquisition, A.-T.T. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The raw, time-series sensor data generated and analyzed during this study, along with the source code for the custom web visualization dashboard, are available in a publicly archived repository.

The data supporting the reported results—including real-time display and historical trends—can be accessed via the following link, which directs to the HTML/JavaScript code of the monitoring dashboard [HTML/Web Visualization Code]: https://drive.google.com/file/d/1935Ynyh_-LFlItes1B7PcaDSA6_wb5RC/view.

This file contains the complete client-side code, including the Chart.js configuration and the JavaScript logic used to process and display both the real-time MQTT streams and the historical data queried from the underlying Google Sheets database.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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