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Design and Implementation of an IoT-Based Real-Time Monitoring System for Optimizing the Growth of Chili Plants (Capsicum annuum L.)

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Abstract

Background: Chili (Capsicum annuum L.) is an economically important horticultural commodity whose production is constrained by fluctuating environmental conditions and suboptimal crop management. **Objective:** This study aimed to design, implement, and test an Internet of Things (IoT)-based real-time monitoring system for essential growth parameters of chili plants. **Methods:** The system integrated sensors for soil moisture, air temperature, air humidity, and light intensity with an ESP32-based controller, wireless data transmission, MySQL storage, and a web dashboard for real-time visualization. **Results:** Testing showed that the system acquired, transmitted, stored, and visualized environmental data with low latency and supported threshold-based pump control for irrigation management. **Conclusion:** The developed system provides actionable monitoring information for precision chili cultivation and can support data-driven decisions on water use and environmental management.

Keywords: Chili; Internet of Things (IoT); precision agriculture; monitoring system; smart farming

Cite This Article

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INTRODUCTION

Chili pepper (*Capsicum annuum L.*) stands as one of the most significant horticultural commodities globally, valued for its culinary uses, nutritional content, and economic contribution to agricultural sectors, particularly in developing nations [1]. However, optimizing chili production remains a complex challenge. Unlike staple crops, chili growth is highly sensitive to external factors, demanding precise control and consistent environmental conditions [2]. Traditional farming practices, which often rely on subjective assessments and scheduled interventions, are inherently inefficient and frequently lead to resource wastage and suboptimal yields due to a reactive, rather than proactive, approach to crop management [3].

The productivity and quality of *Capsicum annuum L.* are critically dependent on maintaining optimal parameters for growth, including soil moisture content, ambient temperature, air humidity, and light intensity [4]. Deviations outside these narrow optimal ranges, such as severe drought stress from insufficient soil moisture or disease proliferation caused by high humidity and temperature swings, can severely compromise plant health, delay fruiting, and drastically reduce the commercial value of the harvest. Therefore, the ability to continuously monitor and immediately respond to changes in these microclimatic conditions is paramount for maximizing the genetic potential of the chili plant.

To address the limitations of conventional farming and meet the rising global demand for efficient food production, the agricultural industry is undergoing a paradigm shift towards precision agriculture. The Internet of Things (IoT) serves as the core technological enabler for this revolution [5]. By integrating sensor networks, microcontrollers, and wireless communication protocols, IoT allows high-resolution spatial and temporal data to be collected from the field. This capability moves decision-making away from intuition and towards empirical evidence, offering a pathway to highly targeted and efficient resource utilization for sustainable agriculture.

Although general IoT applications already exist in agriculture, dedicated, cost-effective, and user-friendly systems tailored to the specific physiological requirements of crops such as chili are still needed [6]. Existing solutions are often proprietary, expensive, or lack the real-time data visualization needed for immediate management adjustments. This study therefore aimed to bridge this gap by designing a robust real-time monitoring system focused on the critical variables of chili growth and providing continuous, reliable data streams directly relevant to chili growers in variable environments [7].

The proposed system addresses these requirements through an integrated hardware and software architecture. The system is centered on the ESP32-CAM and ESP32 Dev V4 modules, which function as the control unit, data processor, and network gateway [8]. The module interfaces with the DHT22 sensor for air temperature and humidity, the Soil Moisture Sensor M2 for soil moisture detection, and the Light Dependent Resistor (LDR) for light intensity monitoring. Data acquired by the ESP32 are transmitted wirelessly to a server using PHP and MySQL for storage and management. The information is displayed in real time on a web-based dashboard, enabling remote monitoring and functioning as an early warning system for suboptimal temperature, humidity, soil moisture, and light conditions.

The primary objective of this study was to design, implement, and test the functionality and reliability of an IoT-based real-time monitoring system for *Capsicum annuum L.* The successful implementation and validation of this system are expected to contribute to horticultural management by providing accurate and low-latency environmental data,

supporting precise data-driven decisions, optimizing water and fertilizer use, reducing operational costs, and improving the yield and quality of chili production [9].

METHODS

Research Design

This study employed a systematic development process based on the ADDIE model, which consists of Analysis, Design, Development, Implementation, and Evaluation, to create, deploy, and validate the IoT-based real-time monitoring system [10]. This framework guided the project lifecycle and ensured that the system addressed the environmental requirements for optimizing the growth of *Capsicum annuum L.* The ADDIE framework was chosen because it provides a flexible yet rigorous structure to manage complex steps, including sensor integration, firmware coding, database implementation, and application interface creation. Each phase functioned as a quality gate so that project development progressed based on validated outputs from the previous phase.

Development Target and Research Subject

The primary target of this research was the engineered product itself, namely the IoT-based real-time monitoring system designed to optimize *Capsicum annuum L.* growth. The main development focus was on the successful integration, functionality, and stability of the hardware and software components. The experimental subject used to test system implementation was chili plant (*Capsicum annuum L.*), specifically the *Bird's Eye Chili* variety.

Hardware Functionality

The hardware functionality assessment focused on the operation and integration of the control unit and sensors. The ESP32-CAM and ESP32 Dev V4 modules served as the central processor, data collector, and Wi-Fi communication gateway. The DHT22 sensor was used to measure air temperature and humidity, the Soil Moisture Sensor M2 was used to measure soil moisture, and the LDR sensor was used to monitor light intensity in the plant environment.

Software Infrastructure

The software infrastructure consisted of a MySQL database running on a Local Host server for storing and retrieving time-series sensor data, together with a web application for real-time data display, historical visualization, and threshold-based alert activation. The database and dashboard were designed to support continuous monitoring and allow users to evaluate the environmental status of the chili plant remotely.

Research Procedure

The study followed the five ADDIE phases. The Analysis phase defined the critical optimal environmental thresholds and technical requirements. The Design phase established the system architecture, component specifications, and MySQL database schema. The Development phase included hardware assembly, sensor calibration, ESP32 Dev V4 firmware programming, and Local Host backend configuration for MySQL data insertion. During the Implementation phase, the system was deployed and continuous real-time data collection was initiated, automatically recording sensor readings into the MySQL database at fixed intervals. The Evaluation phase assessed the capability of the system to acquire, transmit, store, display, and respond to environmental data.

Instruments and Data Collection Techniques

The technical instruments consisted of the ESP32-CAM module, ESP32 Dev V4 controller, DHT22 sensor, Soil Moisture Sensor M2, LDR sensor, relay module, 12 VDC brushless pump, 12 V 5 A power supply, LM2596 step-down converter, Local Host server, and MySQL database. The primary data collection technique was automated real-time data acquisition. Environmental data were sampled by the ESP32 Dev V4 at fixed intervals and transmitted wirelessly for logging into the MySQL database, generating continuous time-series data.

Data Analysis Technique

The environmental data were analyzed to demonstrate the capability of the system to monitor whether the growing environment remained within predetermined optimal ranges. Data interpretation was performed through graphical time-series visualization, in which daily and weekly sensor data plots were displayed alongside upper and lower thresholds. Recorded values within optimal thresholds indicated that the IoT system provided stable and accurate data input for maintaining ideal growing conditions, whereas significant fluctuations outside the thresholds indicated the need for troubleshooting, sensor placement adjustment, or recalibration.

RESULTS

The Analysis phase translated the biological and agronomic requirements of *Capsicum annuum L.* cultivation into quantifiable engineering specifications. Based on a review of chili pepper physiology and local farming practices, specific target ranges were established for air temperature, relative humidity, soil moisture, and light intensity, as shown in Table 1. These optimal thresholds served as the foundation for the automated alert mechanism and central data interpretation logic, ensuring that the monitored environment remained conducive to plant growth and development [11-14].

This agronomic requirement directly informed the technical system requirements. To capture dynamic environmental fluctuations, the system was engineered to sample data from the DHT22, Soil Moisture M2, and LDR sensors at a minimum interval of five minutes. This sampling frequency balances timely data capture with power efficiency. For data integrity and archival purposes, all sensor readings were transmitted and stored within the MySQL database hosted on the Local Host server with timestamps. The system was also designed to trigger immediate visual or notification alerts whenever a monitored parameter deviated from its established optimal threshold.

Table 1. Optimal environmental thresholds for chili plant monitoring.

Parameter	Optimal Range Established	Significance
Air Temperature (Tair)	24°C-32°C	Directly impacts photosynthesis and respiration rates. Temperatures outside this range inhibit growth and fruit setting.
Air Humidity (RH)	60%-80%	Affects transpiration rates and susceptibility to fungal diseases. Low humidity leads to wilting, while high humidity encourages mold.

Soil Moisture Content (θ)	40%-65% (field capacity)	Essential for nutrient uptake. This range avoids drought stress and root rot.
Light Intensity (IL)	20%-40%	Defines the necessary light exposure for maximizing photosynthetic efficiency.

The system installation was executed based on the wiring diagram to ensure operational efficiency and accurate microclimate sensing for *Capsicum annuum L.* The ESP32 Dev V4 served as the central processing unit, managing data flow from the sensors and controlling the irrigation actuator. The DHT22 sensor was placed near the chili plant canopy to capture the immediate microclimate, while the capacitive soil moisture sensor was inserted into the active root zone. The LDR sensor was positioned above the plant to monitor light intensity. The system was powered by a 12 V 5 A power supply, which supplied the pump via the relay module and was regulated down by the LM2596 converter to power the ESP32 and sensors. This sensor placement and integrated control circuit ensured that the collected data were relevant for real-time environmental management.

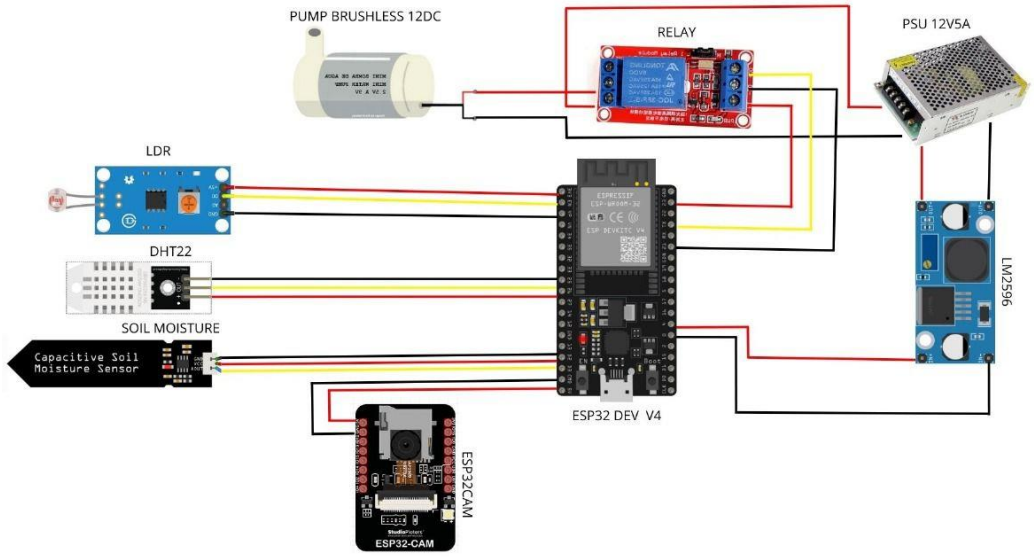

Figure 1. Schematic diagram of the ESP32-based IoT chili plant monitoring system.

The IoT data repository was designed in MySQL using two tables, namely data_sensor and gambar. The data_sensor table served as the primary repository for time-series data from the monitoring system and recorded sensor readings together with pump actuator status. This design is suitable for a technical research project because it logs both raw sensor data, such as soil_volt and soil_adc, and processed data, such as kelembapan_tanah. This dual logging approach supports debugging and future recalibration. Logging the actuator status through pump_status and pump_reason also ensures traceability of the system control logic. The gambar table stores metadata for images or photos related to the monitoring project, particularly images captured by the ESP32-CAM, allowing organized retrieval of visual documentation.

Table 2. Explanation of the data_sensor table structure.

Column (Field)	Data Type	Description / Function
id	INT(11)	Primary key used as the unique identifier for each data row and set to AUTO_INCREMENT.
waktu	TIMESTAMP	Records the time and date the data were logged using current_timestamp().
soil_volt	FLOAT	Raw voltage value read from the soil moisture sensor.
soil_adc	INT(11)	Raw ADC value read from the soil moisture sensor pin.
kelembapan_tanah	FLOAT	Processed soil moisture value, generally expressed as a percentage.
intensitas_cahaya	FLOAT	Light intensity value after conversion from the raw LDR reading.
suhu	FLOAT	Air temperature value read from the DHT22 sensor.
kelembapan_udara	FLOAT	Air humidity value read from the DHT22 sensor.
pump_status	VARCHAR(10)	Status of the pump actuator when the data were recorded.
pump_reason	VARCHAR(50)	Justification for the pump status, such as below threshold or manual mode.
soil_condition	VARCHAR(10)	Interpreted soil condition based on kelembapan_tanah, such as dry, optimal, or wet.

Table 3. Explanation of the gambar table structure.

Column (Field)	Data Type	Description / Function
id	INT(11)	Primary key used as a unique identifier for each image entry and set to AUTO_INCREMENT.
label	VARCHAR(50)	Short label or description to identify the image content, such as Plant_Day_15 or Sensor_Setup.
filename	VARCHAR(100)	Actual file name of the image and reference to the physical image file on the server.
waktu	TIMESTAMP	Records the exact time and date the image was captured or uploaded to the server.

The Development phase successfully transitioned the system design into a functional, integrated hardware and software prototype, which was subsequently deployed during the Implementation phase. Hardware assembly was completed by connecting the DHT22, LDR, and capacitive soil moisture sensor to the ESP32 Dev V4. The ESP32 Dev V4 firmware was finalized to acquire sensor data, execute control logic, and transmit data via Wi-Fi. Sensor calibration was especially important for the soil moisture sensor. Although the gravimetric method was initially planned, internal consistency checks were performed to establish the relationship between raw ADC values and processed moisture values. The Local Host backend was configured with the MySQL database and server script for receiving data packets and inserting them into the data_sensor table.

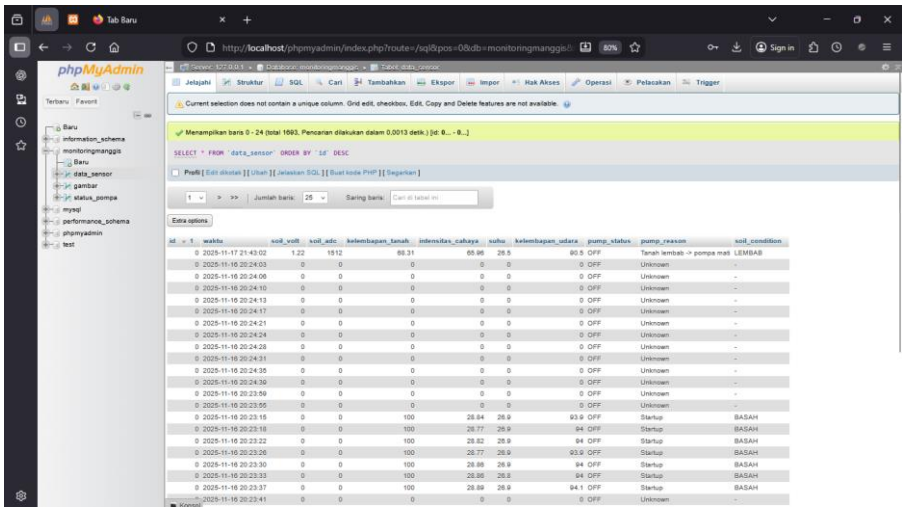

Figure 2. The data_sensor table in phpMyAdmin.

During the Implementation phase, the integrated system was physically deployed in the experimental environment, as shown in Figure 3. This deployment confirmed the strategic placement of the monitoring unit near the chili plant subject (*Capsicum annuum L.*). The successful deployment was validated by the populated data_sensor table, which showed continuous logging of environmental variables.

Figure 3. Integrated IoT monitoring system in operation.

The monitoring dashboard application served as the Human-Machine Interface (HMI), allowing users to remotely monitor the environment, view system status, and validate

the control logic executed by the ESP32 Dev V4. The dashboard confirmed the successful integration of firmware and Local Host backend, validating the primary functionality of the system. The interface displayed synchronized sensor metrics, including air temperature, air humidity, soil moisture, and light intensity, demonstrating that the DHT22, capacitive soil moisture sensor, and LDR were correctly integrated and transmitting data with low latency.

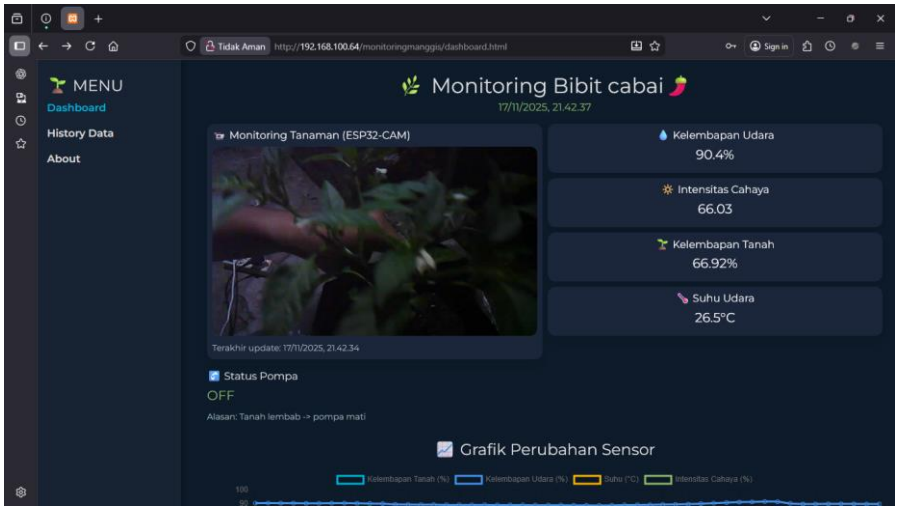

Figure 4. Implementation of the monitoring dashboard application.

The historical data table provided empirical validation of the successful implementation and functionality of the system firmware and backend logic. Continuous logging, evidenced by time-stamped entries, confirmed that the ESP32 Dev V4 actively transmitted data and that the Local Host server successfully inserted records into the MySQL database. Most readings reflected normal operating conditions, with relatively stable humidity, temperature, soil moisture, and light intensity values. The consistent OFF status of the pump indicated that soil moisture was above the irrigation threshold and that the control logic was correctly preventing overwatering. Row 11 showed the ON pump status when the soil moisture value dropped to 0%, validating the control loop from trigger condition to relay signal and action recording.

History Data

No	Waktu	Tanah (%)	Udara (%)	Suhu (°C)	Cahaya	Pump
1	2025-11-17 21:43:02	68.31	90.5	26.5	65.96	OFF
2	2025-11-17 21:42:59	67.85	90.5	26.5	65.37	OFF
3	2025-11-17 21:42:55	68.23	90.5	26.5	65.86	OFF
4	2025-11-17 21:42:51	67.38	90.5	26.5	66.23	OFF
5	2025-11-17 21:42:48	67.08	90.5	26.5	66.13	OFF
6	2025-11-17 21:42:44	67.08	90.5	26.5	65.74	OFF
7	2025-11-17 21:42:40	67.08	90.5	26.5	66.06	OFF
8	2025-11-17 21:42:37	67.31	90.4	26.5	66.15	OFF
9	2025-11-17 21:42:33	66.92	90.4	26.5	66.03	OFF
10	2025-11-17 21:42:29	70.69	90.5	26.5	66.91	OFF
11	2025-11-17 21:42:23	0	90.4	26.6	37.7	ON
12	2025-11-17 21:42:14	68.69	90.4	26.6	56.26	OFF

Figure 5. Historical data displayed in the monitoring dashboard.

DISCUSSION

The implemented IoT monitoring system demonstrates that low-cost sensor integration can support precision management of chili cultivation. The ability to continuously record air temperature, air humidity, soil moisture, and light intensity provides a technical basis for early detection of environmental deviations. In practical farming contexts, such a system can reduce dependence on subjective observation and improve the timing of irrigation or environmental intervention.

The combined use of raw and processed sensor values in the database also strengthens system traceability. Raw values are useful for recalibration and debugging, whereas processed values are more accessible for end users through the dashboard. This two-level data strategy is important in agricultural IoT systems because sensor drift, environmental noise, and changes in sensor placement can affect field readings over time.

The system also showed effective threshold-based actuation through pump control. The pump remained OFF when soil moisture was adequate and activated when the monitored value indicated extreme dryness. This result supports the use of simple rule-based control as an initial automation strategy for small-scale chili cultivation. However, future development should include longer field testing, calibration against independent reference instruments, protection of electronic components under outdoor conditions, and integration of predictive models for irrigation scheduling.

CONCLUSIONS

This study successfully implemented and validated an IoT-based real-time monitoring system for automated management of *Capsicum annuum L.* cultivation. The ESP32-based controller, DHT22 sensor, soil moisture sensor, LDR sensor, relay, and pump actuator were functionally integrated into a complete monitoring and control architecture. The system demonstrated reliable data acquisition, continuous low-latency logging into a MySQL database, and effective threshold-based pump control. The web dashboard provided a usable Human-Machine Interface for real-time visualization and status confirmation. Overall, the developed system achieved its objective of delivering accurate and actionable environmental information for proactive agricultural management, with future improvements recommended in long-term field validation, sensor calibration, and predictive decision-support features.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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