

Design and Implementation of an Internet of Things (IoT)-Based Smart Farming System for Chili Plants in Parit 4, Tembilahan Hulu

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Abstract

Efficient irrigation management is essential for improving chili cultivation productivity while reducing excessive water consumption. This study aimed to design and implement an Internet of Things (IoT)-based smart farming system capable of performing automatic irrigation and real-time environmental monitoring. The proposed system employed an ESP32 microcontroller integrated with a capacitive soil moisture sensor, a DHT22 sensor, a relay module, and a DC water pump. Environmental data were transmitted through a Wi-Fi network to a MySQL database and visualized using a web-based dashboard, allowing users to monitor soil moisture, air temperature, and relative humidity while controlling irrigation remotely. The developed system was evaluated through Black Box Testing to verify hardware and software functionality, communication reliability, and automatic irrigation performance. The implementation results demonstrated that all system components operated successfully, enabling stable real-time monitoring, automatic irrigation based on predefined soil moisture thresholds, and remote manual control through the web interface. The communication process between the ESP32 and the web server achieved response times below three seconds, while the usability evaluation obtained a feasibility score of 88.8%, indicating that the system is highly suitable for practical application. The proposed IoT-based smart farming system effectively improves irrigation efficiency, optimizes water utilization, and supports sustainable chili cultivation through integrated environmental monitoring and automated irrigation management.

Keywords: Automatic irrigation; ESP32; Internet of Things (IoT); Smart farming; Soil moisture monitoring

1. Introduction

Agriculture remains one of the most important sectors supporting food security and economic development, particularly in developing countries where horticultural commodities contribute significantly to local income and national agricultural production. Among these commodities, chili (*Capsicum annum* L.) is widely cultivated because of its high commercial value and continuous market demand. However, successful chili cultivation depends heavily on appropriate irrigation management. Maintaining optimal soil moisture is essential because insufficient water can inhibit nutrient absorption, reduce plant growth, and lower crop productivity, whereas excessive irrigation may increase the risk of root diseases and unnecessary water consumption [1], [2]. Therefore, efficient irrigation management has become one of the major challenges in modern agricultural practices.

In many agricultural areas, including chili plantations in Parit 4, Tembilahan Hulu, irrigation activities are still performed manually and rely heavily on farmers' experience and rainfall availability. During the dry season, soil moisture frequently drops below the level required for optimal plant growth, causing water stress and reducing crop yield. On the other hand, manual irrigation is often carried out without considering the actual moisture condition of the soil, resulting in inefficient water utilization and increased labor requirements. These limitations demonstrate the necessity of developing an intelligent irrigation system capable of monitoring environmental conditions continuously and automatically supplying water according to the actual needs of the plants.

Recent advances in the Internet of Things (IoT) have significantly transformed conventional agricultural practices into smart farming systems. IoT enables physical devices equipped with sensors, microcontrollers, communication modules, and cloud-based applications to exchange data through the Internet without continuous human intervention [3]. In agriculture, IoT technology facilitates real-time monitoring of environmental parameters such as soil moisture, temperature, and air humidity while simultaneously controlling irrigation equipment automatically. Consequently, farmers are able to monitor crop conditions remotely, reduce water consumption, improve irrigation efficiency, and minimize operational costs through data-driven decision making [4].

Numerous studies have explored the implementation of automatic irrigation systems using different hardware platforms and control approaches. Orlando and Irawan developed an Arduino Uno-based automatic watering system utilizing a soil moisture sensor, LCD, buzzer,

and servo motor to regulate irrigation according to soil conditions [6]. Jusmi et al. introduced an automatic irrigation device employing Arduino Uno and soil moisture sensing technology to assist ornamental plant growers in maintaining proper watering schedules [7]. Setiadi et al. proposed an IoT-based smart irrigation system capable of automatically regulating irrigation gates while supporting remote monitoring functions [8]. Meanwhile, Andrianto implemented an IoT-enabled indoor plant monitoring system integrating soil moisture sensors, light sensors, fuzzy logic, and a web interface to automate irrigation decisions [9]. Other studies incorporated DHT22 sensors, NodeMCU, Android-based applications, or fuzzy inference methods to improve irrigation accuracy and environmental monitoring capabilities [10].

Although previous studies have demonstrated that IoT technologies can improve irrigation efficiency, several limitations remain. Many systems rely solely on Arduino-based architectures with limited processing capability and communication performance. Some studies focus only on soil moisture monitoring without simultaneously considering ambient temperature and humidity, while others employ mobile applications such as Blynk that provide limited flexibility for comprehensive web-based data visualization and management. Furthermore, several irrigation systems apply fixed threshold values or scheduling mechanisms that are difficult to adapt to different cultivation environments. These limitations indicate that a more integrated smart farming platform capable of combining environmental monitoring, automatic irrigation, real-time web visualization, and remote manual control is still required, particularly for chili cultivation.

To overcome these limitations, this research proposes the design and implementation of an Internet of Things (IoT)-based smart farming system for chili plants using the ESP32 microcontroller as the primary processing unit. The proposed system integrates a capacitive soil moisture sensor and a DHT22 sensor to continuously monitor soil moisture, air temperature, and humidity. Sensor data are transmitted to a web server through the Internet, allowing farmers to observe field conditions in real time using a web-based dashboard. In addition, the system automatically activates the water pump whenever soil moisture falls below a predefined threshold while also providing manual control through the web interface when necessary.

The proposed system was implemented and evaluated in a chili cultivation area located in Parit 4, Tembilahan Hulu, Indonesia. The main contribution of this study is the development of an integrated smart farming platform that combines automatic irrigation, environmental monitoring, Internet-based communication, and web-enabled remote management using ESP32 technology. The proposed system is expected to improve irrigation efficiency, optimize water utilization, reduce dependence on manual irrigation practices, and support sustainable agricultural management through real-time monitoring and intelligent decision-making.

To validate the effectiveness of the proposed system, a prototype was developed by integrating hardware and software components into a unified IoT platform. The hardware consisted of an ESP32 microcontroller, a capacitive soil moisture sensor, a DHT22 sensor, a relay module, and a DC water pump, while the software included a web-based monitoring dashboard and a MySQL database for data storage. The developed prototype was evaluated through functional testing and usability assessment to verify communication reliability, automatic irrigation performance, real-time environmental monitoring, and remotecontrol capabilities under actual field conditions.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods, including the research framework, system architecture, hardware and software components, automatic irrigation mechanism, and testing procedures. Section 3 presents the implementation results, system performance, environmental monitoring, web-based dashboard, and system evaluation. Finally, Section 4 summarizes the conclusions of the study and highlights the practical contributions of the proposed IoT-based smart farming system for sustainable chili cultivation.

2. Materials and Methods

2.1. Research Framework

This study adopted a systematic research framework to guide the design, implementation, and evaluation of the proposed Internet of Things (IoT)-based smart farming system for chili cultivation. As illustrated in Figure 1, the research consisted of six sequential stages: problem identification, data collection, data processing and analysis, material preparation, system implementation, and system testing. The framework ensured that each stage was conducted systematically, beginning with identifying the irrigation problems experienced by farmers and ending with evaluating the performance of the developed system.

The research was initiated by identifying the challenges associated with conventional irrigation practices in chili cultivation at Parit 4, Tembilahan Hulu. Data were subsequently collected through field observations, interviews with farmers, and literature review to obtain both technical and practical requirements for the proposed system. The collected information was then analyzed to determine the hardware and software specifications before assembling and programming the IoT-based irrigation system. Finally, the completed system was evaluated using Black Box Testing to verify the functionality of each hardware and software component, including environmental sensing, automatic irrigation, real-time data transmission, and web-based monitoring.

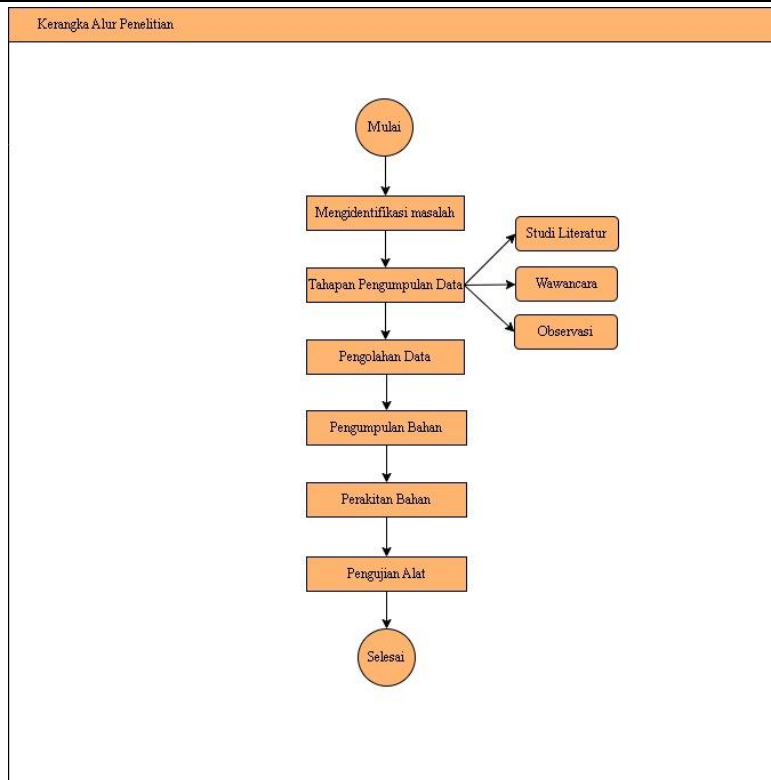


Fig 1: Research framework of the proposed IoT-based smart farming system.

2.2. System Architecture

The proposed smart farming system was designed using the Internet of Things (IoT) architecture to enable automatic irrigation and real-time environmental monitoring. The ESP32 microcontroller served as the central processing unit responsible for collecting sensor readings, executing irrigation decisions, and transmitting data to the web server via a wireless Internet connection.

The sensing unit consisted of a capacitive soil moisture sensor for measuring soil moisture and a DHT sensor for monitoring ambient temperature and relative humidity. Based on the predefined soil moisture threshold, the ESP32 automatically activated or deactivated the relay module connected to the water pump. Simultaneously, all environmental parameters were transmitted to a MySQL database and displayed through a web-based monitoring dashboard, enabling farmers to remotely observe field conditions and manually control the irrigation system when necessary.

2.3. Hardware and Software Components

The hardware components included an ESP32 microcontroller, a soil moisture sensor, a DHT sensor, a relay module, a DC water pump, power supply, water hoses, jumper wires, and supporting electronic components. The ESP32 functioned as the primary controller responsible for sensor acquisition, data processing, Internet communication, and irrigation control.

The software environment consisted of Arduino IDE for ESP32 programming, Visual Studio Code for web application development, XAMPP as the local web server, MySQL for data storage, and a web browser for accessing the monitoring dashboard. These software tools collectively enabled real-time data acquisition, storage, visualization, and remote system management.

2.4. Automatic Irrigation Mechanism

The developed system continuously monitored soil moisture, air temperature, and humidity through the connected sensors. Sensor readings were processed by the ESP32 to determine whether irrigation was required. When the measured soil moisture value fell below the predefined threshold, the ESP32 activated the relay module to switch on the water pump automatically. Once the soil moisture reached the desired level, the relay was deactivated, and irrigation stopped.

In addition to automatic operation, the system provided a web-based dashboard allowing users to monitor environmental conditions in real time and manually activate or deactivate the irrigation system through an Internet connection. This dual operating mode increased system flexibility while ensuring efficient water utilization.

2.5. System Testing

The developed smart farming system was evaluated using Black Box Testing to verify the functionality of each hardware and software component. The evaluation focused on ensuring that every system function operated according to the specified requirements without examining the internal program structure.

The testing procedure included verification of the soil moisture sensor, DHT sensor, ESP32 communication module, relay operation, water pump activation, database communication, and web dashboard functionality. The performance of automatic irrigation was evaluated by observing the system response under different soil moisture conditions, while real-time monitoring was assessed by verifying successful data transmission from the ESP32 to the web dashboard. A function was considered successful when the observed system output matched the expected operational behavior defined during system design.

3. Results and Discussion

3.1. System Design

The proposed IoT-based smart farming system was designed to automate irrigation and provide real-time environmental monitoring for chili cultivation. The system integrates sensing, processing, communication, and irrigation control into a single platform capable of operating automatically while allowing remote monitoring through a web-based dashboard.

Figure 3 illustrates the overall architecture of the developed system. The architecture consists of three main layers: the input layer, the processing layer, and the output layer. The input layer includes a DHT22 sensor for measuring air temperature and relative humidity, and a capacitive soil moisture sensor for monitoring soil moisture conditions. Both sensors continuously acquire environmental data and transmit the measurements to the ESP32 microcontroller.

The ESP32 functions as the central processing unit responsible for collecting sensor readings, executing the irrigation algorithm, and transmitting environmental data to the web server through a Wi-Fi connection. The received data are stored in a MySQL database and visualized through a web-based monitoring dashboard, enabling users to observe environmental conditions in real time and access historical records.

The output layer consists of a relay module connected to a DC water pump. The irrigation process is controlled automatically according to predefined soil moisture threshold values. When the measured soil moisture falls below the threshold, the ESP32 activates the relay to switch on the water pump. Once sufficient soil moisture has been achieved, the relay is deactivated and irrigation is stopped automatically. In addition, users may manually control the irrigation process through the web dashboard whenever necessary.

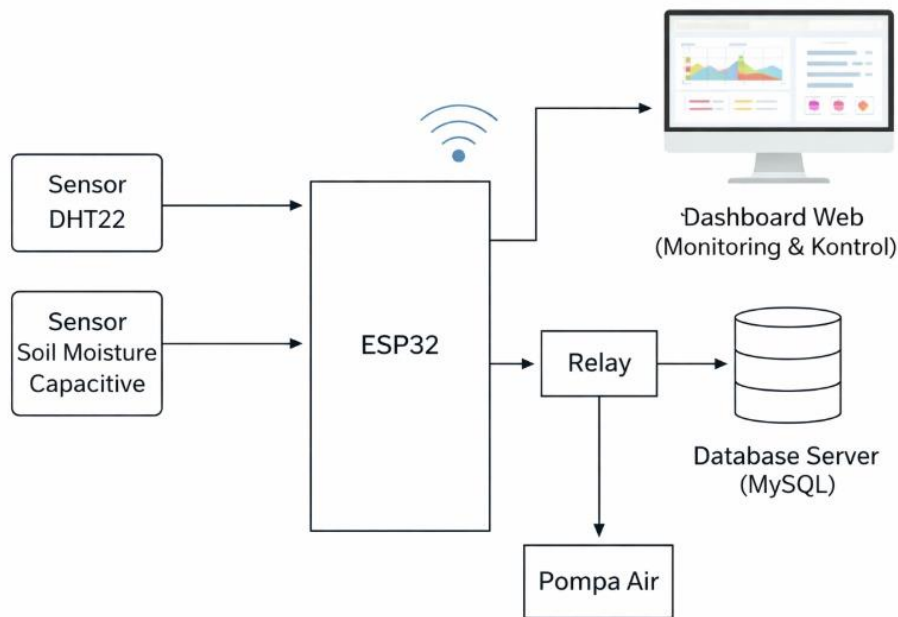


Fig. 2: Overall architecture of the proposed IoT-based smart farming system.

Figure 3 presents the hardware block diagram of the developed system. The diagram illustrates the interaction among the sensing devices, ESP32 microcontroller, wireless communication module, relay, and irrigation pump. Environmental data collected by the sensors are processed by the ESP32 before being transmitted to the server, while irrigation commands are executed through the relay module to control the water pump.

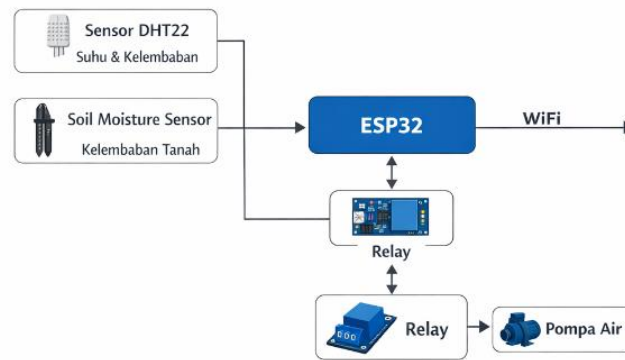


Fig. 3: Hardware block diagram of the proposed system.

The complete hardware implementation is shown in Figure 5. The prototype was assembled using an ESP32 DevKit V1, a capacitive soil moisture sensor connected to GPIO34, a DHT22 sensor connected to GPIO4, a single-channel relay module connected to GPIO18, and a DC water pump powered by an external 5 V power supply. The hardware components were interconnected using jumper wires to ensure reliable communication and stable system operation. The implemented prototype successfully integrated sensing, wireless communication, automatic irrigation, and web-based monitoring into a compact IoT platform.

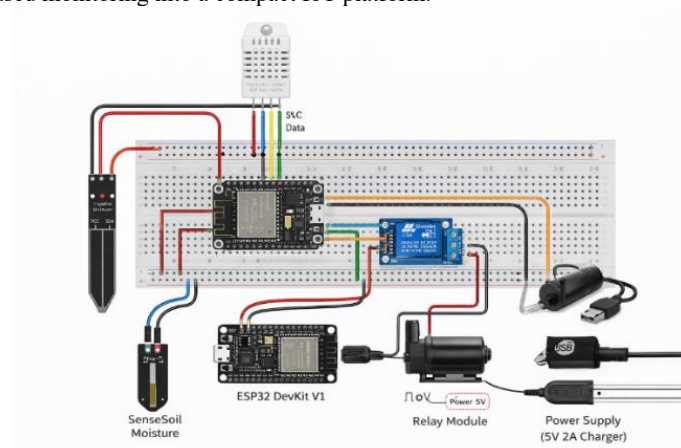


Fig. 5: Hardware schematic of the developed smart farming prototype.

3.2. Prototype Implementation



Fig. 6: Implemented prototype of the IoT-based smart farming system.

After completing the system design, the proposed smart farming system was implemented by integrating the ESP32 microcontroller, DHT22 sensor, capacitive soil moisture sensor, relay module, and DC water pump into a single embedded platform, as shown in Figure 6. The prototype was developed to validate the automatic irrigation mechanism and real-time monitoring functions before field deployment.

The ESP32 acted as the main controller by collecting environmental data from the connected sensors, processing the acquired information, and transmitting the data to the web server through a Wi-Fi connection. Based on the predefined soil moisture threshold, the ESP32 automatically controlled the relay module to activate or deactivate the irrigation pump. The developed prototype successfully integrated sensing, communication, automatic irrigation, and remote monitoring into one IoT-based smart farming platform.

Throughout the implementation stage, the prototype operated continuously without communication failures between the sensing unit, controller, and monitoring server. The successful integration of hardware and software components demonstrates the feasibility of the proposed architecture for supporting efficient irrigation management in chili cultivation.

3.3. Environmental Monitoring Performance

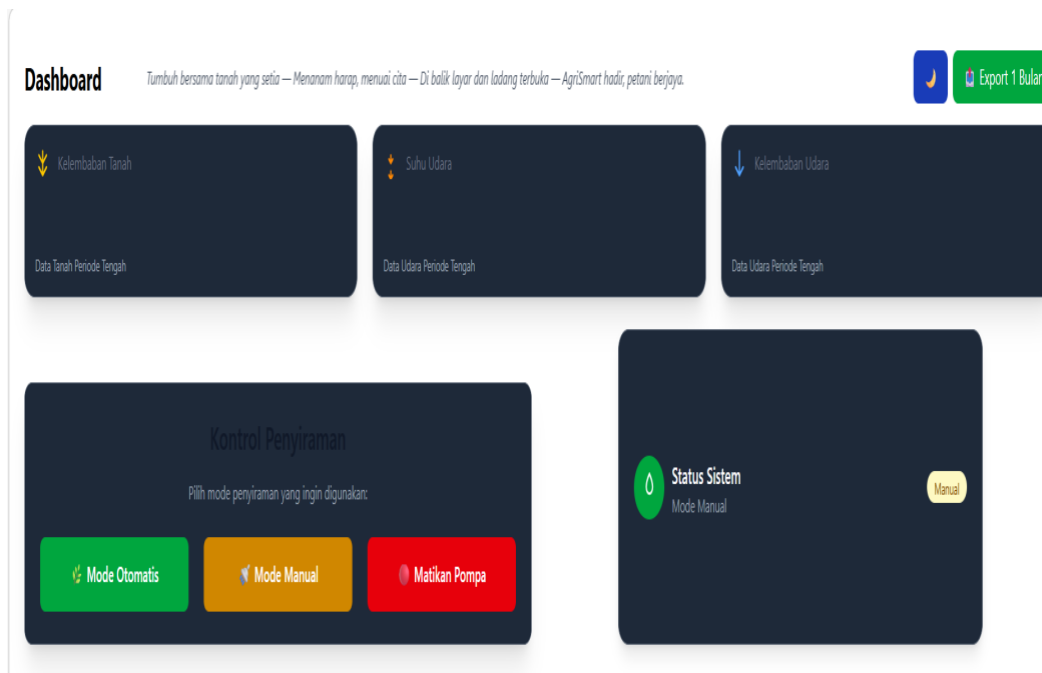


Fig. 7: Main interface of the web-based monitoring dashboard.

The developed web-based dashboard provides real-time monitoring of environmental conditions measured by the IoT system. As shown in Figure 7, the dashboard displays three primary parameters, namely soil moisture, air temperature, and relative humidity, collected by the ESP32 from the connected sensors. In addition, the interface provides automatic and manual irrigation controls, allowing users to remotely operate the water pump through an Internet connection. The system status panel also indicates the current irrigation mode, enabling users to verify whether the system is operating automatically or manually.

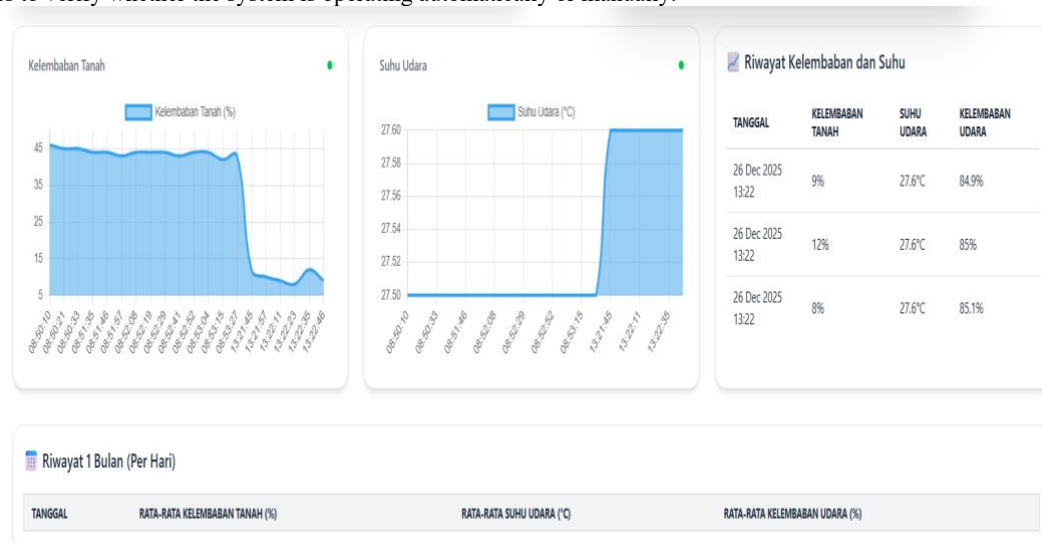


Fig. 8: Historical monitoring dashboard showing environmental trends and recorded data.

Figure 8 presents the historical monitoring interface of the developed system. The dashboard visualizes soil moisture and air temperature trends using line graphs while simultaneously displaying historical sensor records stored in the MySQL database. These historical data allow users to evaluate environmental changes over time and analyze irrigation performance based on previous measurements. The availability of graphical visualization and data history supports better decision-making for irrigation management and improves long-term monitoring of chili cultivation.

3.4. System Testing and Discussion

The developed IoT-based smart farming system was evaluated using the Black Box Testing method to verify that all hardware and software components operated according to the specified functional requirements. The evaluation focused on communication reliability, dashboard functionality, irrigation control performance, and overall system usability.

Table 1 summarizes the communication testing results between the ESP32 and the web server. The ESP32 successfully established a Wi-Fi connection, transmitted environmental data to the server, and received irrigation control commands from the web application. All communication scenarios were completed successfully, indicating stable data exchange between the embedded device and the monitoring platform.

Table 1: Communication testing results between the ESP32 and the web server.

No	Skenario Pengujian	Hasil yang Diharapkan	Hasil Aktual	Status
1	ESP32 dinyalakan	Perangkat terhubung ke WiFi	Terhubung ke WiFi	Berhasil
2	ESP32 mengirim data ke server	Data diterima server	Data tersimpan di database	Berhasil
3	Server mengirim perintah ke ESP32	ESP32 menerima perintah	Relay merespon sesuai perintah	Berhasil

The functionality of the monitoring dashboard was subsequently evaluated, and the results are presented in Table 2. The dashboard successfully displayed real-time environmental parameters, system status, historical records, and graphical visualizations without functional errors. Compatibility testing also confirmed that the application operated correctly across multiple web browsers, including Google Chrome, Microsoft Edge, and Mozilla Firefox.

Table 2: Functional testing results of the web-based monitoring dashboard.

No	Fitur yang Diuji	Hasil yang Diharapkan	Hasil Aktual	Status
1	Tampilan status sistem	Mode ditampilkan sesuai kondisi	Status sesuai alat	Berhasil
2	Grafik histori data	Grafik muncul tanpa error	Grafik tampil normal	Berhasil
3	Tabel riwayat data	Data tersimpan dan tampil	Data tampil lengkap	Berhasil
4	Akses multi-browser	Berjalan di Chrome, Edge, Firefox	Berjalan normal	Berhasil

The automatic and manual irrigation mechanisms were further verified through irrigation control testing. As summarized in Table 3, manual activation and deactivation of the water pump through the dashboard were completed successfully with response times of less than three seconds. During automatic operation, the ESP32 continuously compared the measured soil moisture with the predefined threshold and activated the irrigation pump whenever the soil moisture dropped below the specified value. The pump was automatically turned off after the desired moisture level had been reached, demonstrating reliable implementation of the automatic irrigation algorithm.

Table 3: Automatic and manual irrigation control testing results.

No	Mode Pengujian	Aksi	Respon Sistem	Waktu Respon	Status
1	Mode Manual	Tombol ON ditekan	Pompa menyala	< 3 detik	Berhasil
2	Mode Manual	Tombol OFF ditekan	Pompa mati	< 3 detik	Berhasil
3	Mode Otomatis	Sistem aktif	Pompa bekerja sesuai logika sistem	< 3 detik	Berhasil

To evaluate the practicality of the developed system, usability testing was conducted using a Likert-scale questionnaire completed by ten respondents. The evaluation considered dashboard readability, ease of irrigation control, clarity of system information, response speed, and overall user satisfaction. The summarized results are presented in Table 4.

Table 4: Usability evaluation results.

No	Pernyataan	Total Skor	Skor Maksimal	Persentase
1	Tampilan dashboard mudah dipahami	44	50	88%
2	Menu kontrol penyiraman mudah digunakan	46	50	92%
3	Status sistem (otomatis/manual) jelas ditampilkan	43	50	86%
4	Respon sistem saat tombol ditekan cepat	45	50	90%
5	Informasi yang ditampilkan pada dashboard sudah lengkap	42	50	84%
Total		220	250	88%

The usability assessment produced an overall score of 88.8%, which falls within the "Very Feasible" category. This result indicates that users considered the developed monitoring dashboard easy to understand, responsive, and practical for supporting irrigation management. The highest evaluation score was obtained for the irrigation control feature, while the remaining assessment criteria also achieved consistently high scores, demonstrating good acceptance of the proposed system.

Overall, the experimental results demonstrate that the proposed IoT-based smart farming system successfully integrates environmental sensing, automatic irrigation, wireless communication, database management, and web-based monitoring into a unified platform. Compared with conventional irrigation methods that depend on manual observation and farmer availability, the developed system provides continuous environmental monitoring and automatic irrigation based on actual soil conditions. The successful implementation and testing results indicate that the proposed system can improve irrigation efficiency, reduce unnecessary water consumption, and simplify irrigation management for chili cultivation.

4. Conclusion

This study presented the design and implementation of an Internet of Things (IoT)-based smart farming system for chili cultivation using the ESP32 microcontroller. The proposed system integrates a capacitive soil moisture sensor, a DHT22 sensor, a relay module, and a DC water pump to provide automatic irrigation based on real-time environmental conditions. The developed architecture successfully combines environmental sensing, wireless communication, database management, and a web-based monitoring dashboard into a unified smart irrigation platform.

The implementation results demonstrated that the proposed system was capable of continuously monitoring soil moisture, air temperature, and relative humidity while transmitting sensor data to the web server through a Wi-Fi network. The automatic irrigation mechanism successfully activated the water pump whenever the soil moisture fell below the predefined threshold and stopped irrigation after the desired moisture level was reached. In addition, the web-based dashboard enabled users to monitor environmental conditions in real time, access historical data, and manually control the irrigation process remotely through various web browsers.

System evaluation using Black Box Testing confirmed that all functional components operated according to the system requirements. Communication between the ESP32, sensors, database, and web application was successfully established with response times below three seconds. Furthermore, the usability evaluation achieved an overall score of 88.8%, indicating that the developed system is highly feasible and user-friendly for practical deployment.

Overall, the proposed IoT-based smart farming system provides an effective solution for improving irrigation efficiency, reducing dependence on conventional manual irrigation, optimizing water utilization, and supporting sustainable chili cultivation through real-time environmental monitoring and automated irrigation management. Future work may extend the system by integrating additional environmental sensors, cloud-based data management, and mobile notification services to further enhance its functionality and scalability.

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