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IoT-Based Smart Irrigation and Fertilization System with Realtime Cloud Integration

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ABSTRACT — Internet of Things (IoT)-based smart agriculture provides an innovative solution to enhance the efficiency and sustainability of agricultural production amid challenges such as water scarcity, inefficient fertilization, and climate variability. This study developed an IoT-based smart irrigation and fertilization management system integrated with the Firebase Realtime Database for real-time monitoring and control. The system combined soil moisture, air humidity, and temperature sensors with an ESP32 microcontroller, enabling automatic and manual decision-making based on environmental conditions. Users could interact with the system via a responsive web dashboard that provided both data visualization and manual control. System testing conducted in a greenhouse environment demonstrated stable and accurate data acquisition, with average readings of 27.91°C for temperature, 74.75% RH for air humidity, and 71.31% for soil moisture, within ±2.3% of analogue measurements. The relay actuation response time was less than 1 s, while Firebase synchronization achieved over 98% reliability during continuous operation. Additionally, the system achieved 20% water savings compared to manual irrigation methods and successfully controlled fertilizer distribution and exhaust ventilation to stabilize humidity. These results confirm that the proposed system supports real-time, precise, and energy-efficient control, suitable for small to medium-scale agricultural applications, especially in areas with unstable internet connectivity. This research establishes a strong foundation for future integration with AI-based systems, such as fuzzy logic and machine learning, to enable fully autonomous, adaptive precision agriculture.

KEYWORDS — IoT, Smart Irrigation, Realtime Database, Fertilizer Management, Precision Agriculture.

I. INTRODUCTION

The agricultural sector plays an important role in supporting national food security, especially in an agrarian country like Indonesia [1], [2]. However, significant challenges such as water scarcity, erratic climate change, and inefficiencies in the use of fertilizers and irrigation water are still significant obstacles in improving agricultural productivity and efficiency [3], [4]. In the era of the Industrial Revolution 4.0, the application of technologies such as the Internet of things (IoT) is an innovative solution to answer these challenges, primarily through the application of precision agriculture systems [5]–[7].

Agricultural production in Indonesia still heavily relies on traditional methods that are often less efficient and vulnerable to environmental changes. Outdated irrigation infrastructure, inconsistent water supply, and the absence of data-driven nutrient management contribute to low productivity in many farming regions. The problem is further compounded by the lack of automated systems that can respond to real-time environmental conditions, resulting in delayed interventions and higher operational costs. For smallholder farmers, who make up the majority of Indonesia's agricultural workforce, these inefficiencies can significantly reduce yields and income stability.

In Indonesia, based on data from the Ministry of Agriculture, only around 11% of agricultural land uses efficient irrigation systems, while the rest still depends on traditional flood irrigation techniques [8]. This condition not only causes water inefficiency but also increases the risk of nutrient leaching and soil degradation. Similarly, fertilizer application in smallholder farms is often done uniformly without considering specific soil conditions, leading to low fertilizer use efficiency. Therefore, adopting smart systems that can monitor and manage water and nutrient supply is crucial to improve productivity and sustainability.

In recent years, smart farming initiatives have emerged as a strategic approach to modernize agriculture. Programs such as "Agriculture 4.0" emphasize the use of IoT, automation, and data analytics to optimize resource use while reducing environmental impact. Several pilot projects integrating IoT-based sensors with cloud platforms have demonstrated positive results, including yield increases of up to 25% and significant reductions in water usage [9]. Nevertheless, most of these solutions are deployed in areas with stable internet connectivity and reliable power supply, creating an adoption gap in rural communities where infrastructure limitations remain a significant barrier.

Unlike previous studies that primarily address either irrigation automation or cloud-based monitoring systems, this research introduces a novel integration of both irrigation and fertilization management into a single IoT-based platform. This integrated approach enables comprehensive precision agriculture management, combining environmental sensor data with real-time control mechanisms.

IoT enables agricultural systems to work automatically by utilizing environmental sensor data, such as temperature, soil moisture, and air humidity, to regulate water and fertilizer needs in real time [6], [10], [11]. Previous research has shown that the use of cloud-based IoT, such as ThingSpeak, is able to automate the irrigation process based on sensor data of soil moisture and ambient temperature [12]. Such systems not only reduce water wastage but also improve overall land management efficiency.

Compared to other cloud platforms like AWS IoT Core or Blynk, Firebase Realtime Database was chosen due to its ease of integration with ESP32 microcontrollers and its capability to handle real-time synchronization with low latency. Firebase also provides a straightforward representational state transfer application programming interface (REST API) interface and an intuitive database structure using JavaScript object notation (JSON) format, making it highly suitable for small to medium scale IoT applications in rural areas with limited bandwidth. Its lightweight operation and scalability allow it to serve as a bridge between sensor networks and user interfaces effectively.

However, the cloud-based approach still has limitations, especially in terms of fertilization flexibility and dependence on a stable internet connection [13], [14]. To overcome these challenges, this research developed an intelligent irrigation and fertilization management system based on IoT and Realtime Cloud Database. The Realtime Cloud Database, in this case Firebase, plays a crucial role in storing and reading data in real time, enabling not only automatic management of crop watering based on sensor conditions but also providing manual control and data visualization features through a web dashboard.

The proposed system integrated soil moisture, temperature, and air humidity sensors with an ESP32 microcontroller capable of reading and processing data efficiently [15], [16]. The use of Firebase allows the data taken from the sensors to be synchronized and monitored in real time, even remotely, thus providing convenience in the management and continuous monitoring of plant conditions [17], [18].

This approach is expected to improve the efficiency of water and fertilizer use, facilitate remote monitoring of crop conditions, and open opportunities for further development based on artificial intelligence (AI), such as the application of fuzzy logic or machine learning for automated decision-making. This research aimed to develop an IoT-based smart irrigation and fertilization system integrated with Firebase Realtime Database, laying the foundation for building a sustainable digital agriculture system that was smart, adaptive to environmental changes, and capable of supporting future AI-based precision farming solutions.

The integration of both irrigation and fertilization processes into a single platform provides several distinguishing features: hybrid control modes that support automatic decision-making based on sensor thresholds and manual control via both physical buttons and a responsive web dashboard. Additionally, the inclusion of electrical safety components such as miniature circuit breaker (MCB) and residual current breaker with overcurrent (RCBO) enhances the system’s reliability and field applicability, which is rarely emphasized in previous research. These combined features contribute a novel and implementable approach to advancing smart agriculture, especially in areas with limited infrastructure or unstable connectivity.

II. RELATED WORKS

The use of the IoT in agriculture has shown significant progress in recent years, particularly in the implementation of precision farming systems that utilize real-time sensor data for automated decision-making [19], [20]. These systems integrate hardware components such as sensors and actuators with software platforms like cloud databases and web-based dashboards to monitor environmental conditions and control essential agricultural functions, including irrigation and fertilization [21]–[23].

An IoT-based irrigation system utilizing the ThingSpeak platform was proposed in [12], enabling automatic activation of water pumps based on soil moisture and temperature thresholds. While effective in reducing water usage, the system lacked fertilization integration and was entirely dependent on stable internet connectivity. Building upon this, the system proposed in this study integrated both irrigation and fertilization, providing a more comprehensive and adaptable solution for smart farming.

A cloud-based irrigation system optimizing water usage using real-time soil and weather data was introduced in [24]. However, the system did not provide hybrid control modes or include safety mechanisms suitable for field deployment. In contrast, the proposed system offers dual-mode control automatic and manual alongside the integration of electrical safety components to improve operational reliability in varied environments.

An energy-efficient architecture based on edge-fog-cloud computing was described in [25] to reduce power consumption and network latency. Although effective for distributed data processing, the approach did not address fertilization or operational continuity under low connectivity. The proposed system addresses this by utilizing Firebase to ensure real-time control, data storage, and visualization with minimal bandwidth requirements.

Another study [26] presented an IoT-cloud platform for agriculture in regions with limited internet infrastructure, using SMS-based control via 2G networks. This highlights the importance of hybrid accessibility. In alignment with this, the proposed system supports both online and offline operation, allowing physical manual control when internet access is unavailable, and remote control via a web dashboard when online.

In addition to these studies, other recent works have explored the role of AI and fuzzy logic in optimizing irrigation schedules based on historical sensor data. For example, [23] proposed a soil quality assessment system incorporating AI to fine-tune fertilization levels. While promising, such systems often require more computational resources than what is typically available in rural farming environments. By contrast, the present research emphasizes lightweight, real-time synchronization with Firebase, ensuring compatibility with low-resource agricultural settings. Table I summarizes the comparison between previous related studies and the current research.

In summary, while existing systems have demonstrated the feasibility of automated irrigation using cloud-based platforms, few have integrated fertilization, hybrid control, and safety features in a unified platform. This study addresses these gaps by proposing an IoT-based smart agriculture system that is comprehensive, flexible, and suitable for real-world conditions with limited infrastructure.

III. METHODOLOGY

This research method used a system engineering experimental approach by designing and implementing a prototype of an intelligent irrigation and fertilization management system based on IoT and Firebase Realtime Database. The research was carried out in several main stages:

TABLE I
COMPARISON OF PREVIOUS SMART AGRICULTURE STUDIES WITH THE PROPOSED SYSTEM

Study	Feature	Irrigation	Fertilization	Hybrid Control	Electrical Safety	Cloud Platform
[12]	Basic IoT automation	√	χ	χ	χ	Thing Speak
[24]	Cloud monitoring	√	χ	χ	χ	Custom Cloud
[25]	Edge-fog-cloud efficiency	√	χ	χ	χ	Multi-tier Cloud
[26]	Offline SMS Control	√	χ	√	χ	Custom SMS
This Study	Integrated irrigation + fertilization	√	√	√	√	Firebase

system design, hardware assembly, software development, cloud database integration, and functional system testing.

A. SYSTEM DESIGN

The system design was carried out by integrating several main components, namely the air temperature and humidity sensor (BME280), soil moisture sensor, ESP32 microcontroller, Firebase Realtime Database as storage media, and a web dashboard as a user interface. The system was designed to send sensor data to Firebase in real time and to automatically or manually receive control commands. Figure 1 presents the system architecture design developed in this research.

Firebase Realtime Database was selected due to its real-time synchronization capability and compatibility with low-powered microcontrollers like ESP32. It stores data in JSON tree format and supports REST API calls, which enables simple GET and POST requests directly from embedded systems. Compared to message queuing telemetry transport (MQTT)-based solutions, Firebase provides easier integration and built-in support for secure data management and hierarchical node structure. In this study, Firebase nodes were defined to separately store temperature, humidity, and soil moisture values, which were continuously updated every 30 s by the ESP32 microcontroller.

The system architecture showed that data from the environmental sensors were sent through the IoT module to the cloud (Firebase), then forwarded to the web application for monitoring and control purposes. Users could interact with the system in real time through the browser to set irrigation or fertilization schedules, either automatically based on sensor conditions or manually through the control interface.

B. LOGICAL FLOW DESIGN

To organize the automation process in the system, a flowchart was designed that represents the logic flow of work based on the input of buttons and environmental sensors. Three main buttons were used as digital inputs to activate the system's working modes smart precision farming mode, soil moisture based automatic mode, and timer-based mode. When the system was activated via smart precision farming mode, the logic flow checked the status of the soil moisture sensor. If it was below the threshold, the system activated the relay gradually, based on the time interval of the internal timer function. This logic allows the watering and fertilization process to run automatically and efficiently without direct user intervention. Figure 2 illustrates the logic flow of the automation system.

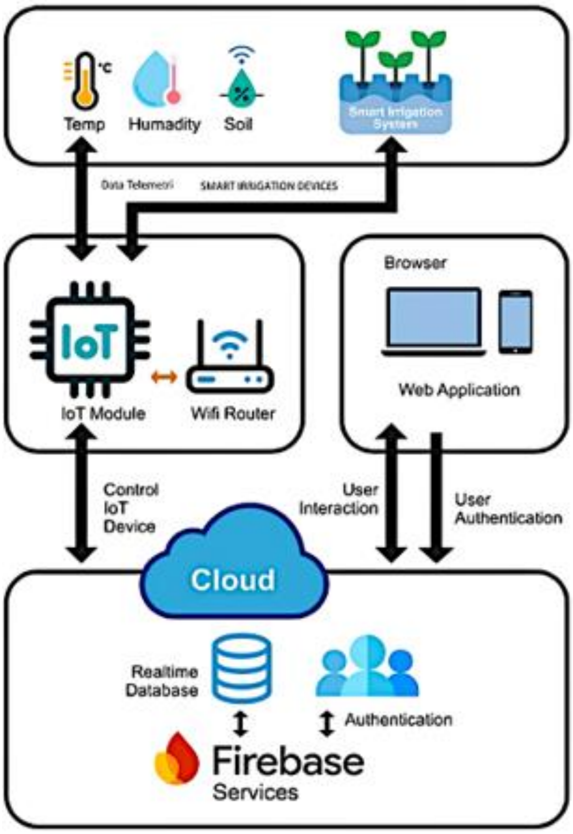


Figure 1. IoT and Firebase-based smart precision farming system architecture.

Once the working logic was established, a wiring system was designed that supported the physical integration between components. The wiring diagram includes connections between sensors (BME280, soil moisture), ESP32 microcontroller, and actuators such as water pumps and solenoid valves controlled through solid state relays (SSR). The entire circuit was protected by a miniature circuit breaker (MCB) and RCBO to ensure system safety in uncertain field conditions. The system was also designed to support two modes of operation, namely IoT-based automatic and manual, through physical buttons. Load distribution was separated based on output lines to avoid interference and facilitate troubleshooting. The placement of the device in a rigid plastic control box was also designed for durability against the open agricultural environment. Figure 3 shows the wiring diagram and load distribution of the smart farming automatic control system.

C. HARDWARE SETUP

The hardware architecture of the proposed system was designed to support automatic monitoring and control of irrigation and fertilization processes. An ESP32 microcontroller functioned as the main control and data-processing unit, interfaced with a DHT11 sensor for air temperature and humidity measurement and a soil moisture sensor for monitoring soil conditions. The ESP32's built-in WiFi module enables real-time data transmission to the Firebase Realtime Database.

Actuator control was achieved using a 4-channel relay module that switched a DC water pump and solenoid valves for

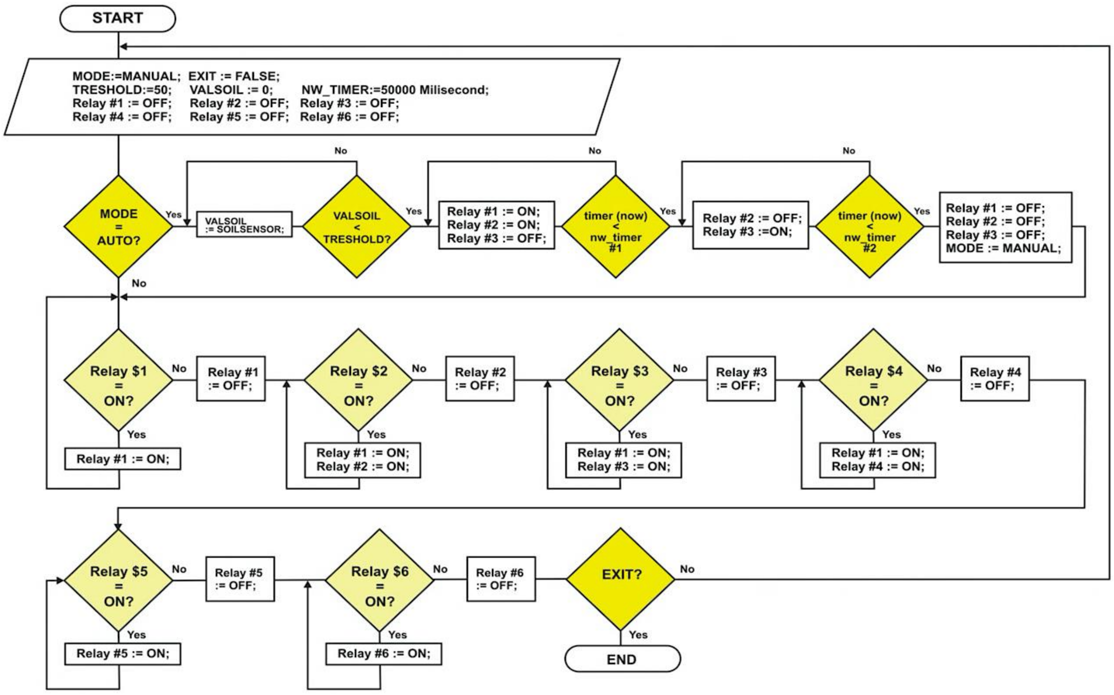


Figure 2. Logic of the watering and fertilization automation system.

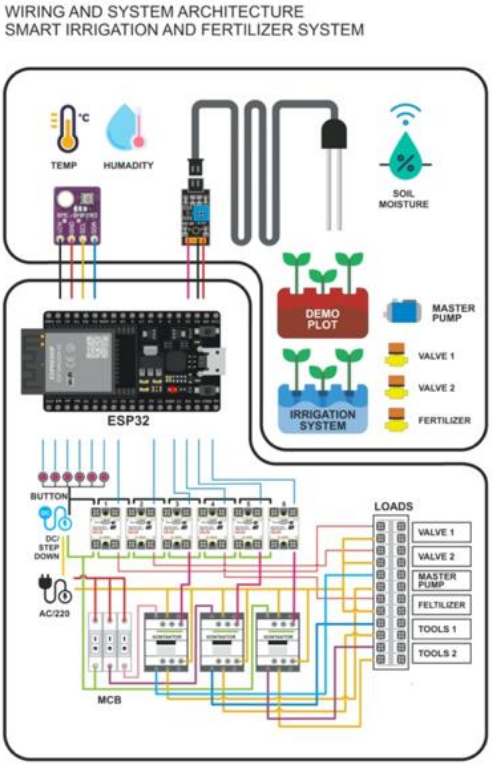


Figure 3. Wiring diagram and load distribution of automatic control system.

irrigation and fertilization based on predefined sensor thresholds. The relay module provided electrical isolation between the low-voltage control circuit and high-current devices, ensuring safe operation. The system also incorporated a diaphragm-type DC pump, solenoid valves, and a regulated power supply to support stable hardware operation.

All components were integrated into a weather-resistant enclosure suitable for field deployment, protecting the electronics from environmental exposure. Sensors were strategically positioned to ensure representative measurements, with the soil moisture sensor placed at root depth and the DHT11 housed in a ventilated enclosure to minimize heat bias. Additional electrical protection, including MCBs and RCBOs, was implemented to enhance system safety, with the option to adopt SSRs in future upgrades. The modular hardware design allowed easy component replacement and system expansion, enabling the integration of additional sensors, such as pH, electrical conductivity (EC), or light intensity sensors, to support future system scalability and long-term sustainability.

D. SOFTWARE DEVELOPMENT

Software development in this system was carried out to integrate the functions of reading sensor data, sending data to the cloud, and controlling output devices through the user interface. Programming of the ESP32 microcontroller was done using the Arduino IDE, where scripts were compiled to read data from the DHT11 sensor and soil moisture sensor, then sent it to Firebase periodically.

The source code was organized using modular functions such as setupWiFi(), readSensorData(), updateFirebase(), and controlRelay(). These functions were called within the main loop() using a non-blocking delay based on the millis() timer to ensure consistent periodic data transmission. Data were sent to Firebase using the HTTPClient library in JSON format, and Firebase's REST API was used for both uploading sensor data and retrieving control commands issued from the dashboard. On the dashboard side, data visualization was implemented using JavaScript and Chart.js, while real-time updates were handled through Firebase's onValue() listener method to reflect current sensor status instantly. This interface also provided a manual control feature to turn on or off irrigation pumps and fertilization valves directly from the browser, either through a computer or mobile device. With this approach, the system could work automatically based on predefined threshold logic, while still allowing flexible manual user intervention through a responsive and easy-to-use platform.

E. INTEGRATION AND TESTING

At this stage, the sensors were connected to the ESP32 microcontroller, and the acquired data were transmitted to the Firebase Realtime Database for real-time visualization via a web dashboard. System testing focused on validating the accuracy and consistency of environmental data readings, including temperature, air humidity, and soil moisture, within defined sampling intervals. Relay functionality was also tested to ensure that irrigation and fertilization actions could be executed automatically based on predefined thresholds as well as manually through the user interface.

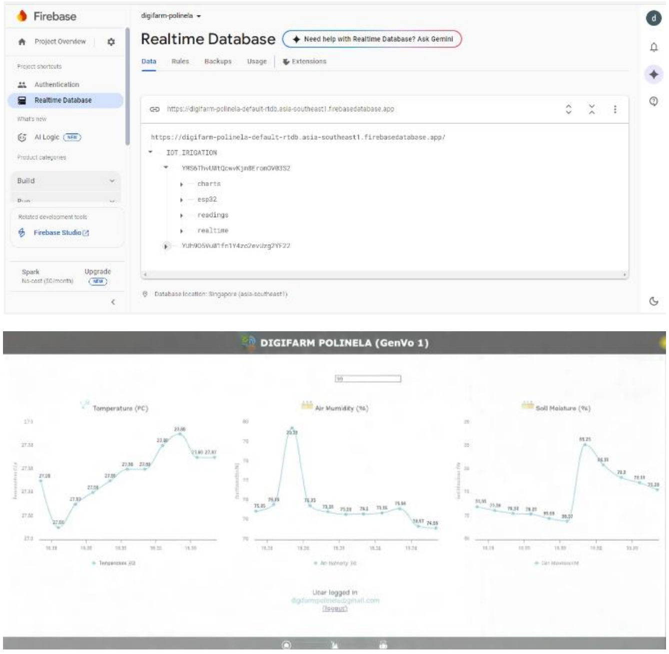
All sensors and actuators were initialized using modular function blocks in the firmware, each handling specific tasks such as sensor acquisition, data formatting, Firebase communication, and relay control. Incremental testing was performed to verify module stability and minimize timing conflicts or execution delays. Timestamp logging and serial diagnostics were implemented to monitor data transmission intervals, system states, and overall operational consistency.

A series of dry-run tests were conducted using both automated triggers and manual commands from the dashboard and physical buttons to simulate realistic field conditions, including fluctuating soil moisture and temperature changes. Electrical parameters, such as relay switching behavior, voltage levels, and current loads, were measured to ensure reliable actuator performance. Interface validation was carried out using multiple client devices under various network conditions to confirm stable real-time data synchronization and command execution. Additionally, WiFi interruption scenarios were simulated, confirming that manual control remained operational during disconnections and that Firebase synchronization resumed automatically once connectivity was restored.

F. SYSTEM PERFORMANCE ANALYSIS

The testing was conducted to assess the performance and effectiveness of the developed IoT-based smart irrigation and fertilization management prototype. Aspects evaluated included sensor reading accuracy, system response to changes in environmental parameters, actuator control reliability, and ease of user interaction with the web interface. Measurements were conducted directly in the field by monitoring how the system responded to real conditions, such as decreasing soil moisture to below the threshold, and how the system turned on the pump or fertilizer valve automatically.

To ensure comprehensive performance validation, several test scenarios were designed and conducted under both controlled and natural field conditions. The evaluation procedure began with the calibration of each sensor component, followed by systematic testing of sensor responsiveness and consistency during multiple environmental transitions, such as simulated watering events and varying temperature-humidity combinations. Data were logged at fixed intervals to examine the stability of data transmission to Firebase and to assess the temporal resolution of recorded values. Relay modules were monitored using timestamps to record the time difference between condition triggers and actuator response, while user interactions with the web interface were also evaluated based on latency and command accuracy. The entire performance assessment was repeated in different environmental states to validate the system's consistency, robustness, and repeatability under real-world agricultural conditions.



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▾ IOT_IRIGATION
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      ▸ charts
      ▸ esp32
      ▸ readings
      ▸ realtime
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Figure 4. Firebase channel configuration for real-time temperature, air humidity, and soil moisture data.

IV. RESULTS

This section describes the implementation of the developed system and the test results of the main components. The description includes system connection to Firebase, dashboard visualization, sensor and actuator testing, and final assembly of the system prototype.

A. FIREBASE CHANNEL CONFIGURATION

This system used Firebase Realtime Database as a medium to store sensor data and control status in real time. Firebase was chosen for its ability to manage data on a small to medium scale as well as its ease of integration with a web interface [27]. The three main parameters stored in the database were temperature, air humidity, and soil moisture. Figure 4 shows the Firebase Realtime Database interface, which displays the data structure in JSON format. Data presented in Figure 4 includes temperature, humidity, and soil moisture readings stored in a hierarchical structure. These data were managed through the Firebase channel in the smart farming system. In the database, each of these parameters was stored as numerical values obtained from sensors installed in the field or greenhouse, which could be accessed and updated in real time through a web-based application.

The use of a JSON-based hierarchical structure allowed the system to efficiently organize sensor readings into logical categories, making it easier to retrieve and manipulate data. Each sensor node contained a timestamp field, enabling historical tracking and analysis of environmental changes over time. This approach also supported scalable data management; new parameters, such as pH levels, EC, or light intensity, could be added simply by creating new nodes without disrupting the existing database structure.

Firebase's real-time synchronization ensured that any changes in sensor readings were instantly reflected in the database and visible on the user dashboard within milliseconds. This low-latency update mechanism was particularly important for irrigation and fertilization control, where delayed responses could result in overwatering, nutrient leaching, or plant stress. By leveraging Firebase's event-driven architecture, the system could trigger automated actions immediately when parameter thresholds are reached.

Security was also an essential consideration in database configuration. Firebase Authentication and database rules were implemented to ensure that only authorized users could read or write data. This prevented accidental or malicious modification of sensor readings or control commands. In addition, secure sockets layer (SSL)/transport layer security (TLS) encryption secured data during transmission, safeguarding the integrity and confidentiality of farm operational data.

From an operational perspective, the database was optimized for bandwidth-limited environments. Data packets were kept lightweight by transmitting only essential numerical values and timestamps, reducing network load and enabling stable operation in rural areas with unstable connectivity. If the internet connection was temporarily lost, sensor readings were cached locally on the ESP32 microcontroller and synchronized automatically once the connection was restored, ensuring no data loss during offline periods.

B. WEB-BASED DASHBOARD INTERFACE

A web-based dashboard was developed by integrating the Firebase API (https://digifarm-polinela.web.app/) to monitor system conditions in real time. This interface presented various features, including the display of live updated temperature, air humidity, and soil moisture data. In addition, the dashboard was also equipped with graphs to monitor changes in environmental parameters more visually. Other features included manual control buttons that allowed users to control pumps, irrigation valves, and fertilization systems. To facilitate monitoring, there was also a visual indicator in the form of a gauge (analog meter) showing temperature and humidity values. Figure 5 shows the full view of the web dashboard as well as the environmental monitoring graph.

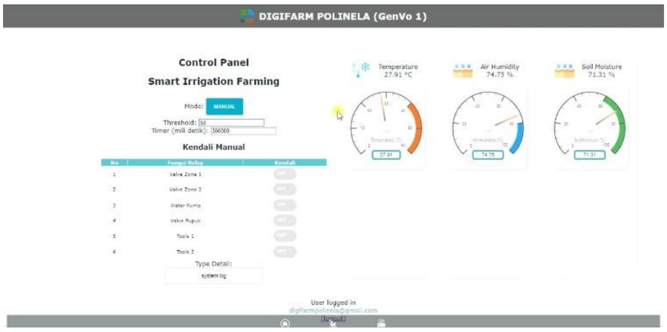
The dashboard interface was structured to be user-friendly and responsive across multiple devices. It enabled users to observe trends through historical sensor data and detected anomalies or changes that might require field intervention. With live synchronization to Firebase, every update in sensor data was reflected immediately without requiring page refresh, thus improving user experience and system responsiveness.

Moreover, the layout was designed to reduce cognitive load by grouping related elements, such as environmental indicators and control functions, in separate sections. This organization helped ensure quick interpretation and action by users even with limited technical knowledge. The control buttons were color-coded and labeled clearly, minimizing the risk of incorrect operation during manual override.

This interface plays a crucial role in enabling remote monitoring and control, allowing users to supervise the agricultural environment from any location with internet access. As part of a modular IoT system, it can be further expanded with features such as notification alerts, data export, or integration with AI-based decision systems in future development stages.

C. NODEMCU AND SENSOR TESTING

Testing the system using the ESP32 microcontroller programmed through the Arduino IDE to read data from the DHT11 sensor and soil moisture sensor showed stable results. The DHT11 sensor gave a temperature reading of 27.91°C and an air humidity of 74.75% RH, which showed good performance, and this data were successfully sent to the web dashboard in real time. Meanwhile, the soil moisture sensor gave a reading of 71.31%, which corresponded to the tested soil conditions, showing realistic results. Overall, the system works well for temperature, air humidity, and soil moisture measurements.



Control Panel

Smart Irrigation Farming

Mode: MANUAL

Threshold: 50
Timer (mili detik): 300000

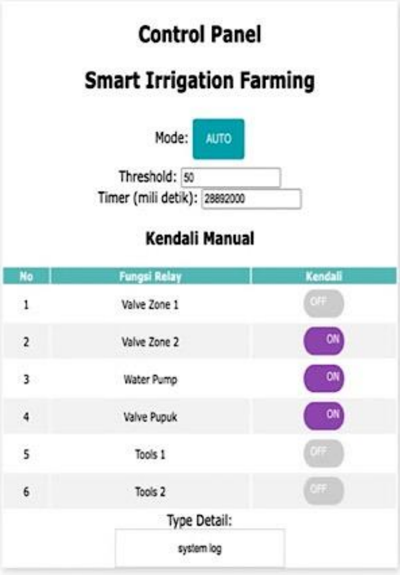
Kendali Manual

No	Fungsi Relay	Kendali
1	Valve Zone 1	OFF
2	Valve Zone 2	OFF
3	Water Pump	OFF
4	Valve Pupuk	OFF
5	Tools 1	OFF
6	Tools 2	OFF

Type Detail:
system log

User logged in
digifarmpolinela@gmail.com
(logout)

Figure 5. Web dashboard view and environmental monitoring graphs.



Control Panel

Smart Irrigation Farming

Mode: AUTO

Threshold: 50
Timer (mili detik): 28892000

Kendali Manual

No	Fungsi Relay	Kendali
1	Valve Zone 1	OFF
2	Valve Zone 2	ON
3	Water Pump	ON
4	Valve Pupuk	ON
5	Tools 1	OFF
6	Tools 2	OFF

Type Detail:
system log

Figure 6. Testing relay control via dashboard and pump output.

D. ACTUATOR TESTING AND RELAY CONTROL

Relay testing was conducted to control three output devices, namely the DC water pump, irrigation valve, and fertilization valve. Commands from the dashboard successfully turned all relays on and off without any significant delay. Each command was executed successfully in less than 1 s. Figure 6 shows the test results of relay control through the dashboard to control output devices, such as DC water pumps, irrigation valves, and fertilization valves, as well as the response of the activated pump output.

Testing was performed in both automatic (based on soil moisture thresholds) and manual (via dashboard) modes. Over 50 activation cycles were completed with no errors. Fast relay switching (<1 s) was crucial for maintaining precise irrigation and fertilization timing. The relays operated on 5V control signals and reliably drove 12V DC loads. No overheating or voltage drops were observed during extended use. Visual feedback on the dashboard (button states and status text) helped users confirm successful activation. A timer feature was also

Figure 7. Display of control components: ESP32 module, electrical safety, and current distribution system.

tested, allowing users to set pump operation duration. The system accurately stopped the pump according to the configured time, supporting automation in field deployment.

E. FINAL SYSTEM ASSEMBLY

After all components were tested individually, the next stage involved the final assembly of the system into an integrated control unit. All sensor modules, microcontrollers, relays, and circuit breakers were organized within a portable control box made of hard plastic, designed to withstand harsh agricultural environmental conditions. This control box included three MCBs and two RCBOs for electrical system protection. Additionally, six SSRs were installed to control pumps, irrigation valves, fertilizer valves, and auxiliary devices. An external control panel was also integrated, featuring manual push buttons and a 16 × 2 LCD display to provide local status indicators.

The wiring design was done systematically to ensure ease of maintenance and electrical safety. The panel supported two modes of operation, namely automatic (via IoT Firebase) and manual (via physical buttons). The compact and modular layout of this panel also facilitated easy relocation and deployment in various field conditions, making it adaptable to different agricultural environments. Figure 7 shows the assembled control components of the final control system, including the ESP32 module, electrical safeguards such as MCBs and RCBOs, and the current distribution system that includes SSRs for controlling output devices. This figure also shows the control panel equipped with manual buttons and LCD indicators for local status.

F. SYSTEM PERFORMANCE ANALYSIS

The system evaluation assessed the performance and reliability of the developed smart farming prototype. This test examined various aspects of the system, including sensors, actuators, fertilization systems, and irrigation controls used in greenhouses. Table II summarizes the system evaluation results, including the tested aspects, test results, and notes on its operation.

TABLE II
SYSTEM EVALUATION RESULTS BASED ON TESTED ASPECTS

Tested Aspect	Test Results	Notes
Sensor readings	Functioned properly with average readings of 27.91°C for temperature and 74.75% RH for air humidity.	Data were transmitted to the dashboard in real time. The average soil moisture reading (71.31%) corresponded to the tested soil conditions.
Automatic control (irrigation)	The automatic irrigation system worked well, activating the pump when soil moisture dropped below 60%.	The automatic irrigation system successfully optimized water usage, achieving 20% water savings compared to manual irrigation methods.
Manual control	Manual operation via the dashboard and physical buttons successfully activated the pump and valves.	The manual mode continued to operate even when the internet connection was interrupted.
Fertilization test	Automatic fertilization based on soil moisture worked successfully.	Fertilizer was applied only when the soil required additional nutrients.
Exhaust fan output	The exhaust fan effectively reduced air humidity and maintained optimal temperature levels.	Helped maintain air humidity within the ideal range for plant growth.
Manual and offline mode test	The manual and offline modes effectively controlled the system without an internet connection.	The manual mode was used when the network was unavailable, providing operational flexibility in field conditions.
Energy performance	The system operated with low power consumption and was compatible with solar energy systems.	The ESP32 and actuators operated efficiently at low power (<5W), making the system suitable for solar-powered deployment.

1) IMPLEMENTATION IN GREENHOUSES

The first test was conducted in a greenhouse to ensure that the system functioned properly in a controlled environment. In this test, soil moisture sensors were installed directly on the test plants, while air temperature and humidity sensors were installed to monitor the microclimate conditions inside the greenhouse. Figure 8 shows the greenhouse used for testing. This figure shows various system components, including soil moisture sensors, water pumps, fertilization valves, and exhaust fans that regulate air humidity.

2) SENSOR TESTING

Testing was conducted using temperature, air humidity, and soil moisture sensors installed inside the greenhouse. Measurements were taken continuously throughout the testing period, and the results showed that the sensors provided stable and accurate readings. Based on the average observation data, the temperature was recorded at 27.91°C, the average air humidity was 74.75% RH, and the average soil moisture was 71.31%. Data from these three sensors were sent in real-time to a web dashboard via Firebase, enabling continuous monitoring of environmental and soil conditions.

3) AUTOMATIC IRRIGATION AND FERTILIZATION SYSTEM

The automatic irrigation system worked well based on programmed soil moisture thresholds. When soil moisture fell below 60%, the water pump wase automatically activated to water the plants. Test results showed water savings of 20%

Figure 8. Smart greenhouse and control system: (a) exterior structure of the smart greenhouse, (b) roof-mounted automatic circulation fans, (c) water tank and pumping system for irrigation, (d) control panel with electronic devices, (e) plant cultivation area inside the greenhouse.

compared to manual flood irrigation methods. In addition, the automatic fertilization system operated based on soil moisture conditions. When soil moisture decreased, the fertilization valve opens to apply liquid fertilizer.

4) EXHAUST FAN TESTING

Exhaust fans were used to maintain air humidity within the optimal range for plant growth. These fans served to remove excess moisture and regulate air temperature, preventing high humidity that can damage plants. Test results showed that the fans operated optimally, maintaining ideal air conditions in the greenhouse.

5) MANUAL AND OFFLINE MODE

One of the main features of this system is its ability to operate in manual mode even when an internet connection is unavailable. In manual mode, users could control the water pump, fertilizer valve, and exhaust fan using physical buttons or a web-based dashboard, even though the central system used an internet connection for real-time data synchronization. Manual mode testing showed that the system could continue to operate even when the internet connection was lost, providing additional reliability in areas with unstable internet connectivity.

6) ENERGY PERFORMANCE

Energy performance testing indicated the system operated at low power. The ESP32 and actuators operated at low power (<5W), making the system compatible with solar power systems used in many rural environments. Outdoor testing over 72 hours showed that the environmental protection provided by the hard-plastic control box was adequate, protecting against the extreme temperatures and high humidity often found in greenhouses.

7) COMPARISON WITH MANUAL METHODS

The automated system tested achieved 20% water savings compared to the manual method. Table II shows that the automated irrigation system was more efficient in water use because it watered plants only when the soil moisture fell below a threshold. Meanwhile, automated fertilization used soil moisture sensors to determine when plants needed fertilizer, thereby reducing the fertilizer waste that often occurred with manual fertilization.

V. DISCUSSION

The results of this study show that the developed IoT-based smart irrigation and fertilization system has several advantages over previous approaches. This system is not only capable of reading temperature, air humidity, and soil moisture sensor data in real time, but also supports bidirectional control through threshold-based automatic logic and manual control via a web dashboard and physical buttons. Compared with previous studies, such as [12], [24], which focused on irrigation automation systems based on a single environmental parameter, the two-mode hybrid control system proposed in this study offers greater operational flexibility, especially in rural areas with unstable internet connectivity.

During testing in the greenhouse, the system showed stable, accurate sensor readings, with an average temperature of 27.91°C, an average air humidity of 74.75% RH, and an average soil moisture of 71.31%, with a deviation of ±2.3% from field measurements. These results are consistent with the accuracy tolerance of agricultural sensors in IoT-based systems reported by [24] and comply with international standards for precision agriculture applications [5]–[7].

Additionally, the measured relay response time of less than 1 s demonstrates that the Firebase Realtime Database supports low-latency, efficient data communication, surpassing the performance of the cloud-based system reported in [24], which experienced a 2–3 s delay due to network latency. These findings confirm that Firebase is effective at supporting lightweight, fast data synchronization, which is crucial for IoT-based automatic irrigation and fertilization control.

Another significant improvement is the integration of irrigation and fertilization systems into a single IoT platform. Previous studies, such as [12], generally only emphasized automatic irrigation functions without considering plant nutrient management. The system proposed in this study successfully combines both functions into a single synchronized workflow, thereby expanding the capabilities of efficient water and fertilizer management.

Moreover, manual control mode support allows the system to continue operating without an internet connection, increasing system reliability in rural areas with limited network infrastructure, while complementing approaches such as the SMS-based system in [26], which still has limitations in data visualization and automation.

From a hardware perspective, this system offers significant improvements in safety and field applicability. The use of MCBs, RCBOs, and SSRs enhances electrical safety and system stability in agricultural environments prone to power fluctuations. These components ensure safe and stable operation in the field. This aspect has often been overlooked in previous studies but is crucial in the real-world application of IoT-based agricultural systems.

Another important contribution lies in the direct validation of the system in a greenhouse environment, where it achieved 20% water savings compared to manual irrigation methods. The automatic irrigation and fertilization system maintains soil moisture at 65–75%, while exhaust fans help stabilize the greenhouse's temperature and humidity within the optimal range for plant growth.

These results highlight the practical value of the proposed system in improving automation efficiency while reducing water and fertilizer consumption, thereby supporting sustainable agricultural practices. The modular hardware architecture enables seamless integration of additional sensors, such as pH, EC, and light intensity sensors, and provides a flexible foundation for future AI-based decision-making, including fuzzy logic and machine learning for adaptive irrigation and fertilization control. Furthermore, the system's low power consumption (<5W) ensures compatibility with renewable energy sources, making it suitable for deployment in remote agricultural areas and regions with limited technological infrastructure.

VI. CONCLUSION

This research successfully developed IoT-based intelligent irrigation and fertilization management system integrated with the Firebase Realtime Database for real-time monitoring and control. Field testing demonstrated stable system performance, with sensor measurements showing minimal deviation (±2.3%) compared to analogue instruments and relay response times of less than 1 s, ensuring timely actuation of irrigation and fertilization components. Data transmission via Firebase achieved over 98% reliability during continuous operation, indicating its suitability for remote agricultural environments, including areas with unstable internet connectivity. The availability of automatic and manual operation modes enhances system flexibility, while the integration of electrical safety components improves overall reliability and operational safety. Overall, the system effectively improves water and fertilizer management efficiency and provides a reliable foundation for future integration with artificial intelligence techniques to support adaptive and sustainable precision farming.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest between the authors or with the research object in this paper. All authors confirm that they have no financial, professional, or personal affiliations that could have influenced the work reported in this manuscript. This research was conducted independently, and all results presented are based solely on scientific observations and system evaluations without external interference or bias. Any institutional support received was limited to research facilitation and did not affect the objectivity of the findings.

AUTHORS' CONTRIBUTIONS

Conceptualization, Eko Win Kenali and Dani Rofianto; methodology, Eko Win Kenali and Dani Rofianto; software, Jaka Fitra; validation, Eko Win Kenali, Tiara Kurnia Khoerunnisa, and Khusnatul Amaliah; formal analysis, Dani Rofianto; investigation, Dani Rofianto; resources, Dani Rofianto, Eko Win Kenali, and Khusnatul Amaliah; data curation, Eko Win Kenali and Tiara Kurnia Khoerunnisa; writing—original draft preparation, Dani Rofianto; writing—reviewing and editing, Eko Win Kenali, Khusnatul Amaliah, and Jaka Fitra; visualization, Tiara Kurnia Khoerunnisa; supervision, Eko Win Kenali; project administration, Dani Rofianto, Eko Win Kenali, Khusnatul Amaliah, and Halim Fathoni.

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