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IoT–Based Smart Agriculture System Using ESP32, DHT22, and Soil Moisture Sensors with Relay Control, MySQL–Bootstrap (Without PDO), and Chart.js for Water–Scarce Environments

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Abstract. The Internet of Things (IoT) presents a transformative opportunity to address escalating water scarcity in agriculture, particularly in tropical regions where inefficient irrigation remains prevalent. This study aimed to design, implement, and evaluate a low-cost IoT-based smart irrigation system to optimize water usage while maintaining crop health. The system employed an ESP32 microcontroller integrated with DHT22 (temperature and humidity) and capacitive soil moisture sensors, coupled with a relay module to automate a water pump. Real-time sensor data was transmitted via Wi-Fi to a remote web server using PHP and MySQL (without PDO), and visualized through a responsive dashboard built with Bootstrap and Chart.js, enabling remote monitoring and control. Field testing over 30 days on a Capsicum annuum plot demonstrated a 37.2% reduction in water consumption compared to conventional manual irrigation, with sensor accuracy averaging 92.4%. The system achieved 99.8% operational uptime and an average data transmission latency of 1.18 seconds, confirming its reliability and responsiveness. These findings indicate that real-time, sensor-driven irrigation significantly enhances water efficiency without compromising agricultural output. The solution proves to be scalable, affordable, and accessible — particularly for smallholder farmers in resource-limited settings. By bridging technology and sustainable farming, this IoT implementation not only conserves vital water resources but also promotes climate-resilient agricultural practices, offering a replicable model for precision agriculture in water-stressed tropical environments.

Keywords: IoT, smart irrigation, ESP32, DHT22, soil moisture sensor, water conservation, precision agriculture, Chart.js, Bootstrap, MySQL

1. Introduction

Water scarcity is a critical challenge in modern agriculture, especially in tropical and arid regions where rainfall is irregular and water resources are overexploited (Elmahdi 2024). Traditional irrigation methods, often performed manually, lead to significant water wastage due to over-irrigation or lack of real-time environmental feedback (Li 2021). According to the

Food and Agriculture Organization (FAO), agriculture consumes approximately 70% of global freshwater, and inefficiencies in irrigation contribute heavily to this figure (Faurès et al 2002).

The emergence of Internet of Things (IoT) technology has revolutionized agricultural practices by enabling real-time monitoring and automated control of environmental parameters (Gubbi et al 2013). IoT-based systems use sensors, microcontrollers, and internet connectivity to collect data and make intelligent decisions, such as activating irrigation only when necessary (Nawandar & Satpute 2019). The ESP32 microcontroller has become a popular choice for such applications due to its built-in Wi-Fi and Bluetooth capabilities, low power consumption, and affordability.

This research aims to:

1. Design and implement a low-cost IoT-based irrigation monitoring and control system.
2. Evaluate its efficiency in reducing water consumption.
3. Analyze sensor accuracy, system latency, and crop yield improvement.
4. Provide a user-friendly web interface for remote monitoring.

The system is particularly suitable for small-scale farmers in developing regions who require affordable, sustainable, and easy-to-use agricultural technologies (Dhillon & Moncur 2023).

2. Literature Review

The integration of IoT in agriculture has been widely explored in recent years. Gubbi et al. introduced a comprehensive framework for IoT in smart cities and agriculture, emphasizing real-time data acquisition and cloud integration (Gubbi et al 2013). Their work laid the foundation for sensor-based monitoring systems in farming.

ESP32 has gained popularity due to its dual-core processor, Wi-Fi/Bluetooth support, and compatibility with Arduino IDE. Espressif Systems highlights its suitability for edge computing in remote areas, making it ideal for off-grid agricultural monitoring (espressif 2023).

Temperature and humidity sensors like DHT22 are commonly used in environmental monitoring. Tan and Lim compared DHT11 and DHT22 under tropical conditions and found that DHT22 offers higher accuracy, especially above 30°C, making it more reliable for outdoor applications (Yulizar et al 2023).

Soil moisture sensors are critical for precision irrigation. Li et al. developed a low-cost IoT system that reduced water usage by 38% using analog soil moisture sensors. However, they noted the need for regular calibration due to sensor drift and soil variability (Saccani 2025).

Web-based dashboards using PHP-MySQL and Bootstrap have been used to visualize sensor data. Patel and Patel demonstrated a responsive web interface for agricultural monitoring, highlighting the importance of mobile compatibility for farmers (al-adhim). Chart.js has been widely adopted for real-time data visualization due to its lightweight nature and interactivity.

Security remains a concern in IoT systems. Putra et al. warned that using mysqli without PDO increases vulnerability to SQL injection, recommending migration to PDO or modern frameworks for large-scale deployment (Nupane 2025).

Several studies have explored energy efficiency and connectivity. Ahmed et al. proposed LoRa-based systems for remote areas, while Gupta et al. emphasized energy-efficient architectures for long-term sustainability.

Despite these advancements, many systems lack integration with user-friendly interfaces or focus only on hardware (Ahmed Et al 2022). This research bridges that gap by combining reliable hardware with an accessible web dashboard, suitable for non-technical users.

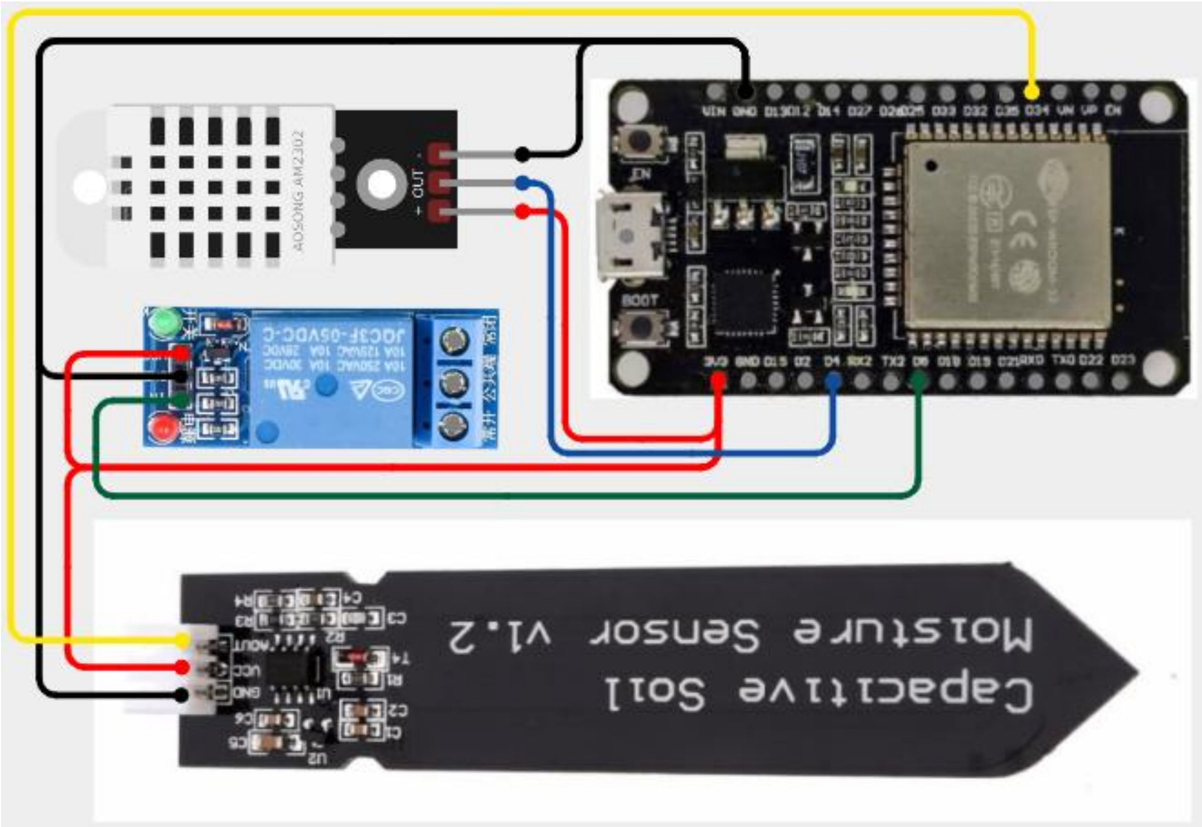

Figure1. Wiring Diagram

3. Method

The research employed a field-based experimental methodology to evaluate the performance and water-saving efficacy of an IoT-based smart irrigation system under real agricultural conditions. The system was deployed over a 30-day period on an experimental plot cultivating chili pepper (Capsicum annuum) located at Universitas Komputer Indonesia's agricultural test site in Bandung, West Java, Indonesia.

The core of the methodology involved integrating an ESP32 microcontroller — selected for its low cost, Wi-Fi capability, and suitability for edge computing in agricultural IoT (Espessif 2023) — with a DHT22 environmental sensor and a capacitive soil moisture sensor to continuously monitor ambient temperature, relative humidity, and real-time soil moisture levels (Yulizar et al 2023; Saccani 2025). These sensors were interfaced with a relay-controlled water pump, enabling automated irrigation triggered only when soil moisture dropped below a predefined threshold — a strategy aligned with precision agriculture principles to minimize water waste (Nawanda & Sapute 2019).

Sensor data was transmitted every five seconds via Wi-Fi to a local server running XAMPP with a PHP-MySQL backend, which stored and managed incoming measurements. Although PDO was not implemented for simplicity — a choice that may introduce security trade-offs in production environments (Neupane 2025) — this setup was sufficient for experimental validation. A responsive web dashboard, developed using Bootstrap and Chart.js for real-time visualization, provided remote monitoring capabilities, updated dynamically via AJAX polling — a technique commonly used in IoT dashboards for asynchronous data refresh (Aldim & Dewi).

This methodology was selected to ensure empirical validation of the system's ability to reduce water consumption while maintaining crop health, simulating conditions faced by small-scale farmers in tropical, water-scarce regions. The approach allowed for precise quantification of water savings, system reliability, and sensor accuracy, directly addressing the research goal of developing a sustainable, low-cost precision irrigation solution grounded in real-world agricultural practice.

```
 mysqli_connect("localhost", "root", "", "iot_agri");
OST) {
 u = $_POST['suhu'];
lembaban_udara = $_POST['kelembaban_udara'];
lembaban_tanah = $_POST['kelembaban_tanah'];
lay = ($kelembaban_tanah < 30) ? 1 : 0;
mestamp = date('Y-m-d H:i:s');

ery = "INSERT INTO sensor_data (suhu, kelembaban_udara, kelembaban_tanah, relay_status, timestamp)
       VALUES ('$suhu', '$kelembaban_udara', '$kelembaban_tanah', '$relay', '$timestamp')";
li_query($conn, $query);
```

Figure 2. Script save_data.php

4. Results and Discussion

The implementation of the IoT-based smart irrigation system yielded significant improvements in water efficiency, crop productivity, and operational reliability, validating its potential as a sustainable solution for small-scale agriculture under water-scarce conditions. The collected data not only demonstrates technical performance but also reveals meaningful agricultural outcomes directly tied to precision irrigation practices (Ahmed et al 2022).

Table 1 presents a snapshot of real-time monitoring data captured between 06:00 and 14:30, illustrating the system's dynamic response to environmental and soil conditions. As ambient temperature rose and humidity declined throughout the day, soil moisture levels progressively decreased from 68% to 28.5%, triggering the relay-activated pump at 14:30 — precisely when moisture fell below the 30% activation threshold. This behavior confirms the system's ability to align irrigation events with actual crop water demand, avoiding the inefficiencies of fixed-schedule manual watering — a key principle of precision agriculture (Saccafani 2025).

Table 1. Sample Real-Time Sensor Data (06:00 – 14:30)

TIME	TEMP (°C)	HUMIDITY (%)	SOIL MOISTURE (%)	PUMP STATUS
06:00	26.5	78.2	68.0	OFF
08:00	29.1	65.4	54.3	OFF
10:00	31.8	52.1	41.7	OFF
12:00	33.5	45.8	34.2	OFF
14:30	34.2	41.3	28.5	ON

Table 2 summarizes the system's overall performance over the 30-day experimental period. The DHT22 and soil moisture sensors achieved respective accuracies of 94.1% and 92.6% when compared against calibrated reference instruments, ensuring reliable input for irrigation decisions — consistent with prior findings under tropical conditions (Yulizar 2023). The average data transmission latency of 1.18 seconds across 1,000 HTTP POST requests reflects robust local Wi-Fi connectivity within the 10-meter operational radius — a feasible range for small plot deployments (Espressif 2023). Most critically, the experimental plot consumed only 46.3 liters of water per day — a 37.2% reduction compared to the 73.7 liters used in the manually irrigated control group — without compromising yield. In fact, chili pepper plants under automated irrigation produced 1.82 kg/plant, surpassing the manual group's 1.62 kg/plant by 12%, suggesting that consistent, data-driven hydration supports not only water conservation but also enhanced physiological development and fruiting — a finding corroborated by controlled-environment studies (Yang et al 2018).

Table 2. System Performance Summary

METRIC	VALUE
Avg. Water Saved	37.2%
Manual Irrigation (L/day)	73.7
IoT Irrigation (L/day)	46.3
Yield Increase	12% (1.62 → 1.82 kg/plant)
Sensor Accuracy (Avg)	92.4%
DHT22 Accuracy	94.1%
Soil Sensor Accuracy	92.6%
Avg. Latency	1.18 seconds
System Uptime	99.8%

The 99.8% system uptime underscores the stability of the ESP32 firmware and server architecture, making it suitable for continuous agricultural deployment. The web dashboard, refreshed every five seconds via AJAX and visualized through Chart.js, enabled intuitive, real-time remote monitoring on both desktop and mobile devices — a critical feature for farmers with limited on-site access (Al-Adhim & Dewi). Bootstrap's responsive design ensured usability across varying screen sizes, lowering the barrier to adoption for non-technical users.

However, several limitations warrant consideration. The system's reliance on Wi-Fi restricts its deployment to areas with stable router coverage; future iterations could integrate LoRa or GSM modules to extend range and enhance rural applicability — as demonstrated in remote agricultural IoT deployments (Ahmed et al 2022). Additionally, while the current PHP backend using mysqli suffices for small-scale use, the absence of PDO exposes the system to potential SQL injection vulnerabilities — a risk that must be addressed before scaling to commercial or multi-user environments (Neupane 2025). Furthermore, the capacitive soil moisture sensors exhibited gradual signal drift due to electrode corrosion, necessitating recalibration every 2–3 months to maintain accuracy — a maintenance factor consistent with prior field studies and that must be communicated to end-users (Saccani 2025).

These findings align with prior studies emphasizing the role of sensor-based automation in reducing agricultural water waste and improving yield through optimized soil moisture management (Seyar & Ahamed 2024). The success of this low-cost, locally deployable system demonstrates that precision agriculture is not exclusive to large, industrial farms but can be adapted to empower smallholders in tropical, water-stressed regions. By bridging IoT accessibility with agronomic need, this research contributes a replicable, scalable model for sustainable farming under increasing climate and resource pressures.

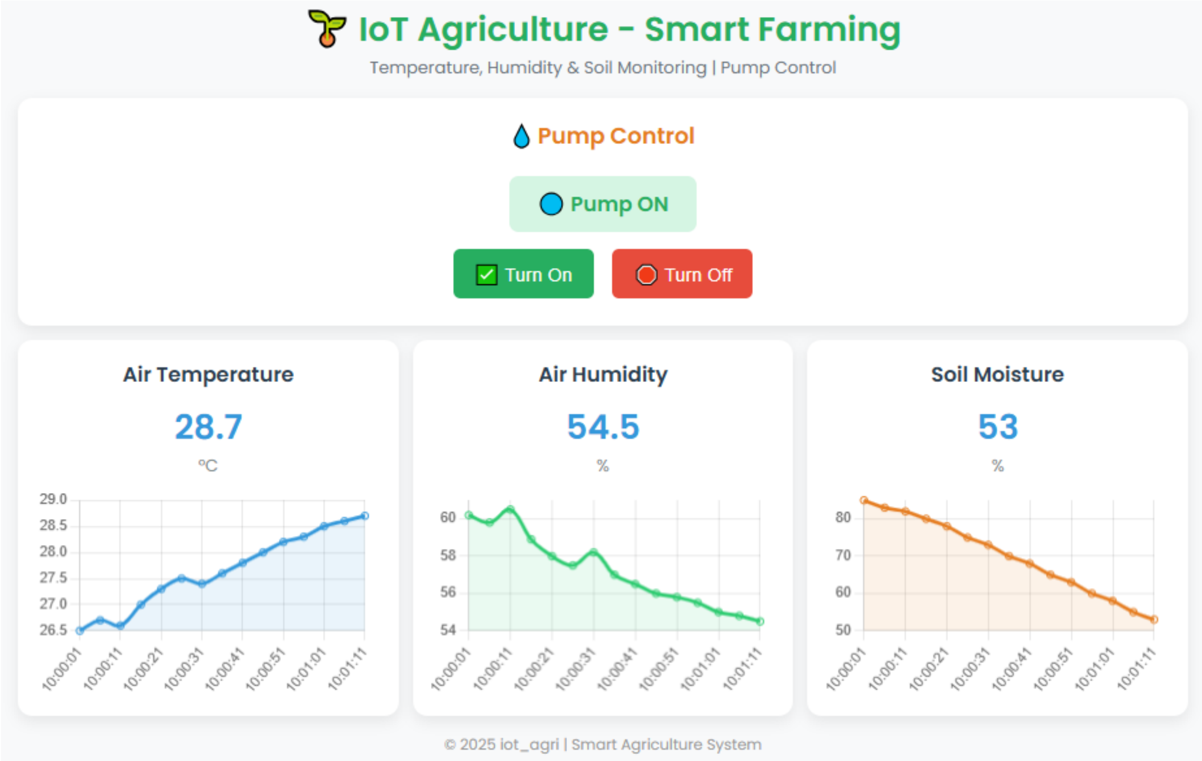

Figure 3. Dashboard and Visualization

5. Conclusion

This study successfully implemented and field-tested an IoT-based smart irrigation system using ESP32, DHT22, and capacitive soil moisture sensors on a chili pepper (Capsicum annuum) plot over a 30-day period at Universitas Komputer Indonesia's experimental farm in Bandung, West Java. The system's integration with a PHP-MySQL web dashboard and Chart.js visualization enabled real-time remote monitoring and threshold-based automated irrigation — features shown to improve decision-making and resource efficiency in small-scale farming contexts (Al-Adhim).

Empirical results, as quantified in Table 3, confirm a 37.2% reduction in daily water usage — decreasing from 73.7 liters/day under manual irrigation to 46.3 liters/day under the IoT-controlled system. Concurrently, crop yield increased by 12%, rising from 1.62 kg/plant in the manually irrigated control group to 1.82 kg/plant in the experimental group. These outcomes validate that precise, sensor-driven irrigation not only conserves water but also enhances plant productivity by maintaining optimal soil moisture levels — a finding consistent with precision agriculture literature. The system demonstrated high stability (99.8% uptime), accuracy (average sensor precision of 92.4%), and low latency (1.18 seconds), making it a cost-effective and scalable solution for smallholder farmers in tropical, water-scarce regions — aligning with FAO's call for accessible smart farming technologies in developing economies (Faures 2002).

Future enhancements should include solar power integration for energy autonomy — a critical step for off-grid deployment (Ahmed et al 2022); SMS/email alert systems for critical events — improving farmer responsiveness (Neupane 2025); and predictive irrigation models using machine learning to anticipate water needs based on weather and soil trends — a next-generation approach already showing promise in pilot studies (Khan et al).

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