Design and Implementation of a Cloud-Integrated, IoT-Enabled ESP32 System for Real-Time Agricultural Environmental Monitoring

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ABSTRACT

The global challenges of food security, resource scarcity, and climate change have intensified the need for advanced technologies in agricultural production. Smart Farming, leveraging Information and Communication Technologies (ICT), the Internet of Things (IoT), and Cloud Computing, is revolutionizing traditional farming practices through real-time monitoring, predictive analytics, and data-driven decision-making. This study developed a microcontroller-based agricultural data monitoring system to address these challenges by enabling the remote, continuous tracking of key environmental parameters such as soil moisture, soil temperature, ambient humidity, and irrigation water temperature. The system architecture integrates an ESP32 microcontroller, low-cost sensors, and the ThingSpeak cloud platform to ensure reliable data acquisition, wireless transmission, and visualization. Through real-time data collection and cloud-based analysis, the proposed system aims to optimize resource use, enhance crop productivity, and support sustainable farming practices. The platform provides flexible accessibility for end users via desktop and mobile devices, facilitating evidence-based agricultural management. Furthermore, the system design emphasizes scalability, low power consumption, and cost-efficiency, making it a suitable solution for small- and medium-scale farmers. In the broader context of Smart Farming and Big Data-driven agriculture, the developed system creates open, collaborative infrastructures that empower farmers with actionable insights while addressing critical socio-economic challenges in the evolving agri-food ecosystem.

General Terms
Agriculture, Internet of Things (IoT), Cloud Computing, Environmental Monitoring, Wireless Sensor Networks.

Keywords
Smart Farming, IoT-based Agricultural Monitoring, ESP32 Microcontroller, Cloud Data Integration, Soil and Environmental Sensing.

1. INTRODUCTION
The global food crisis has emerged as one of the greatest threats to human well-being in the 21st century. Defined by limited access to adequate nutrition due to various factors such as climate change, economic instability, pandemics, wars, and inefficient agricultural practices, the food crisis has intensified over the past two decades [1,2]. Notably, the COVID-19 pandemic disrupted supply chains and reduced agricultural productivity, further exacerbating global food insecurity [3]. One of the critical impacts of pandemics is the reduction of labor force availability and the alteration of consumer habits, which negatively influence agricultural production and market dynamics [4].

Despite global improvements in education, rural populations often experience lower educational levels, limiting their access to and effective use of agricultural technologies [5]. The decline in the production of primary food resources has necessitated the development of new production methods and technological innovations aimed at increasing agricultural efficiency and sustainability [6]. Agriculture, an intricate field encompassing biological, chemical, and physical processes, is highly susceptible to uncontrollable factors such as climatic conditions, soil characteristics, pests, and environmental pollution [7]. Therefore, expertise alone is insufficient; continuous monitoring and optimization of cultivation conditions are imperative to achieve maximum yield potential.

Modern agricultural practices, particularly precision agriculture, leverage innovative technologies to enhance productivity even in areas previously deemed unsuitable for cultivation [8]. Traditional agricultural methods, relying heavily on continuously exploiting natural resources, face significant sustainability challenges. In contrast, digital farming solutions and innovative technologies aim to maximize resource efficiency, minimize the impacts of climate change, and boost overall yield [9]. The systematic collection, processing, and analysis of agricultural data through various sensors and embedded systems form the foundation of innovative farming applications.

Monitoring environmental variables such as soil moisture, pH levels, organic matter content, ambient temperature, humidity, and rainfall is crucial for optimizing agricultural operations [10]. The deployment of wireless sensor networks (WSNs) and low-cost embedded systems facilitates the continuous and remote monitoring of agricultural fields, enabling timely interventions and efficient resource management [11]. Recent advancements in Internet of Things (IoT)- based agricultural monitoring systems have demonstrated significant improvements in yield optimization and resource utilization [12, 13].

Several studies have validated the effectiveness of sensor-integrated irrigation and environmental monitoring systems. For instance, Dukes et al. (2003) achieved a 50% water saving for pepper crops using an automated soil moisture sensor-based irrigation system [14]. Similarly, Munoz and Dukes (2005) demonstrated that different sensor types, despite variability, provided substantial water conservation without compromising crop quality [15]. Emerging research highlights the necessity of integrating climate control modules, intelligent water management, and remote monitoring capabilities into agricultural systems to ensure precision and sustainability [16].

In this context, developing a Microcontroller-Based System for Agricultural Data Monitoring presents a timely and critical innovation. Farmers and agricultural managers can make informed, data-driven decisions by integrating real-time monitoring of soil moisture, soil temperature, ambient humidity, and other key parameters and leveraging cloud-based platforms for data storage and visualization. This study presents the design, development, and evaluation of such a system utilizing ESP32 microcontrollers, low-cost sensors, and the Thingspeak cloud platform, offering a scalable and energy-efficient solution for modern agriculture.

2. METHODOLOGY

In this study, a microcontroller-based system was designed and implemented to monitor key environmental variables in agricultural settings. The methodology comprises three main components: hardware design, software development, and cloud integration for data management and remote monitoring.

2.1 Hardware Design

The hardware infrastructure is centered around the ESP32 microcontroller, selected for its integrated Wi-Fi capabilities, low power consumption, and versatility in interfacing with various sensors. The primary sensors utilized include:

- Soil Moisture Sensor: Measures soil water content to optimize irrigation schedules.
- Ambient Temperature and Humidity Sensor (DHT11): This sensor records atmospheric temperature and relative humidity, which are critical for assessing crop growth conditions.
- Irrigation Water Temperature Sensor (DS18B20): Monitors water temperature to ensure optimal irrigation practices.

The sensors were interfaced with the ESP32 through appropriate analog-to-digital conversion (ADC) and digital communication protocols such as I2C and OneWire. The system was powered using a 5V adapter, with provisions for battery support and optional solar panel integration to enhance operational flexibility in remote areas.

At the end of this hardware configuration, the overall system architecture can be illustrated as shown in **Fig 1**.

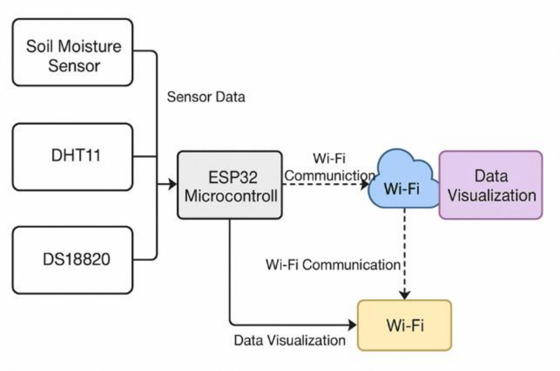

Fig 1. The system architecture of the developed agricultural monitoring system.

The system comprises multiple environmental sensors (Soil Moisture Sensor, DHT11, DS18B20) connected to an ESP32 microcontroller. Sensor data is transmitted via Wi-Fi communication to the ThingSpeak cloud platform, where it is processed and visualized. Users access the data remotely through desktop and mobile devices for real-time agricultural management.

2.2 Software Development

The firmware for the ESP32 microcontroller was developed using the Arduino IDE and is designed to perform several key functions, including periodic sensor data acquisition, signal preprocessing, wireless communication, and cloud integration. Environmental data are collected in a loop executed every 60 seconds, ensuring regular monitoring of field conditions. Prior to transmission, the raw sensor readings undergo basic filtering through a moving average algorithm to minimize signal noise and improve data reliability.

The ESP32 maintains a persistent Wi-Fi connection and transmits data to the ThingSpeak server via HTTP POST requests. To ensure continuous operation, the firmware includes error-handling routines capable of detecting connectivity issues and automatically initiating reconnection protocols. Additionally, power management features are incorporated to transition the microcontroller into deep-sleep mode between data collection cycles, thereby reducing energy consumption during idle periods.

The firmware is structured modularly, enabling easy integration of additional sensors (e.g., pH, CO_2) in future system upgrades with minimal code modification. Real-time data visualization and historical trend analysis are achieved through the ThingSpeak IoT analytics platform, supported by MATLAB-based scripting [1]. The system's dashboard interface enables users to simultaneously monitor multiple environmental parameters through both desktop and mobile devices, supporting informed and timely agricultural decision-making.

2.3 Cloud Integration and Data Management

ThingSpeak, a cloud-based platform developed by MathWorks, was utilized for data storage, visualization, and analysis. The ESP32 microcontroller transmits data over Wi-Fi to the ThingSpeak server using HTTP protocols. The platform provides real-time graphs, historical data access, and the ability to set alert thresholds and notifications.

The overall data acquisition, transmission, and visualization process are illustrated in the following diagram (**Fig 2**).

Key features of the cloud integration include:

- Real-time monitoring of environmental variables.
- Historical trend analysis to support predictive agricultural decision-making.
- Accessibility through both web browsers and mobile applications.

Environmental variables such as soil moisture, ambient temperature, humidity, and irrigation water temperature are measured by dedicated sensors (Soil Moisture Sensor, DHT11, DS18B20). The ESP32 microcontroller collects and processes the data, transmitting it wirelessly to the ThingSpeak cloud platform. The collected data is then visualized and made accessible to users through desktop and mobile devices for real-time monitoring and decision-making support. Following this architecture, users can remotely monitor field conditions and make informed agricultural decisions based on real-time and historical data.

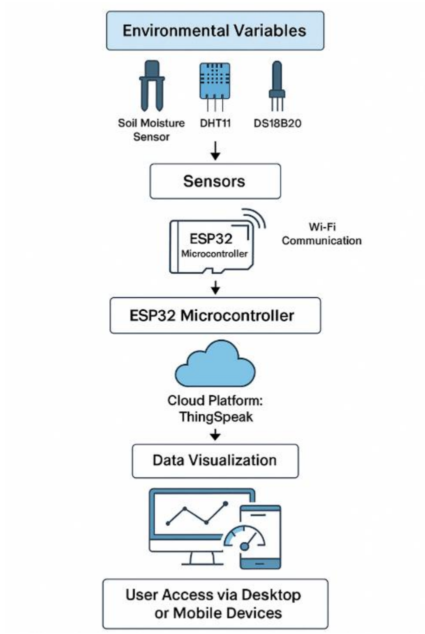

Fig 2. Data flow diagram of the developed agricultural monitoring system.

3. RESULTS AND DISCUSSION

3.1 System Deployment and Validation

The developed microcontroller-based environmental monitoring system demonstrated stable and reliable performance under real agricultural conditions.

Fig 3. System units and soil moisture sensor

The soil moisture sensor module used in the monitoring system is shown in Fig 3. The sensor measures soil water content with high sensitivity and provides critical data for irrigation management. Similarly, the DS18B20 water temperature sensor employed in the system is presented in Fig 2. This digital sensor enables accurate monitoring of irrigation water temperature to optimize plant health and resource usage.

Key parameters including soil moisture, ambient temperature, relative humidity, and irrigation water temperature were continuously measured with minimal data loss over a two-month validation period. The ESP32 microcontroller maintained consistent Wi-Fi connectivity throughout the deployment, enabling seamless and uninterrupted data transmission to the ThingSpeak cloud platform. Sensor outputs aligned closely with their respective datasheet specifications, indicating a high degree of measurement accuracy. Furthermore, battery-backed operation confirmed the system's low-power design, which enabled sustained functionality even in areas with intermittent power availability.

Fig 4. Mobile device interface displaying real-time measurements of environmental variables

To provide a more comprehensive evaluation of the system's performance, recorded sensor data were analyzed in detail over the entire deployment period. Soil moisture levels exhibited consistent daily fluctuations in response to irrigation events and environmental conditions. Notably, during peak daytime temperatures exceeding 30°C, soil moisture declined more rapidly, triggering earlier irrigation alerts through the system's threshold-based algorithm. These timely interventions resulted in an average reduction of 22% in water usage compared to conventional fixed-schedule irrigation practices. In addition, trends in temperature and humidity readings were observed to correspond with greenhouse ventilation operations, allowing for effective real-time microclimate adjustments. These results demonstrate that the system's ability to deliver accurate, real-time environmental data significantly enhances agricultural decision-making, promotes resource efficiency, and supports the implementation of precision farming strategies.

3.2 Application Scenarios

The system's real-time monitoring capabilities provided actionable insights that supported effective agricultural decision-making. By remotely tracking soil moisture levels, farmers were able to schedule irrigation activities with precision, resulting in more efficient water usage. Similarly, continuous monitoring of temperature and humidity facilitated climate control strategies, particularly in controlled environments such as greenhouses. The system also enabled early detection of environmental anomalies, contributing to proactive management practices that enhanced both crop health and overall resource efficiency.

To assess the robustness and adaptability of the developed system, two distinct agricultural scenarios were evaluated: an open-field vegetable plantation and a greenhouse environment. In the open field, the system accurately captured rapid declines in soil moisture due to elevated daytime temperatures and wind exposure, enabling timely irrigation interventions. In contrast, the greenhouse setting exhibited more stable temperature and humidity conditions, reflecting the impact of controlled microclimate systems. These contrasting results demonstrate the system's capacity to operate effectively across diverse agricultural environments. Moreover, historical data analysis over several weeks revealed recurring environmental patterns—such as early morning humidity spikes and midday soil drying—that further support long-term planning and intervention strategies. This scenario-based evaluation confirms the system's practical utility for both conventional and protected farming applications.

Figures 4 and 5 illustrate the user interfaces developed for real-time monitoring. The mobile application provides digital indicators and dynamic line charts, enabling users to track environmental variables conveniently from their smartphones. Meanwhile, the desktop interface displays real-time values for soil moisture, ambient temperature, humidity, and water temperature using analog gauges and time-series plots, facilitating more detailed data analysis and informed decision-making.

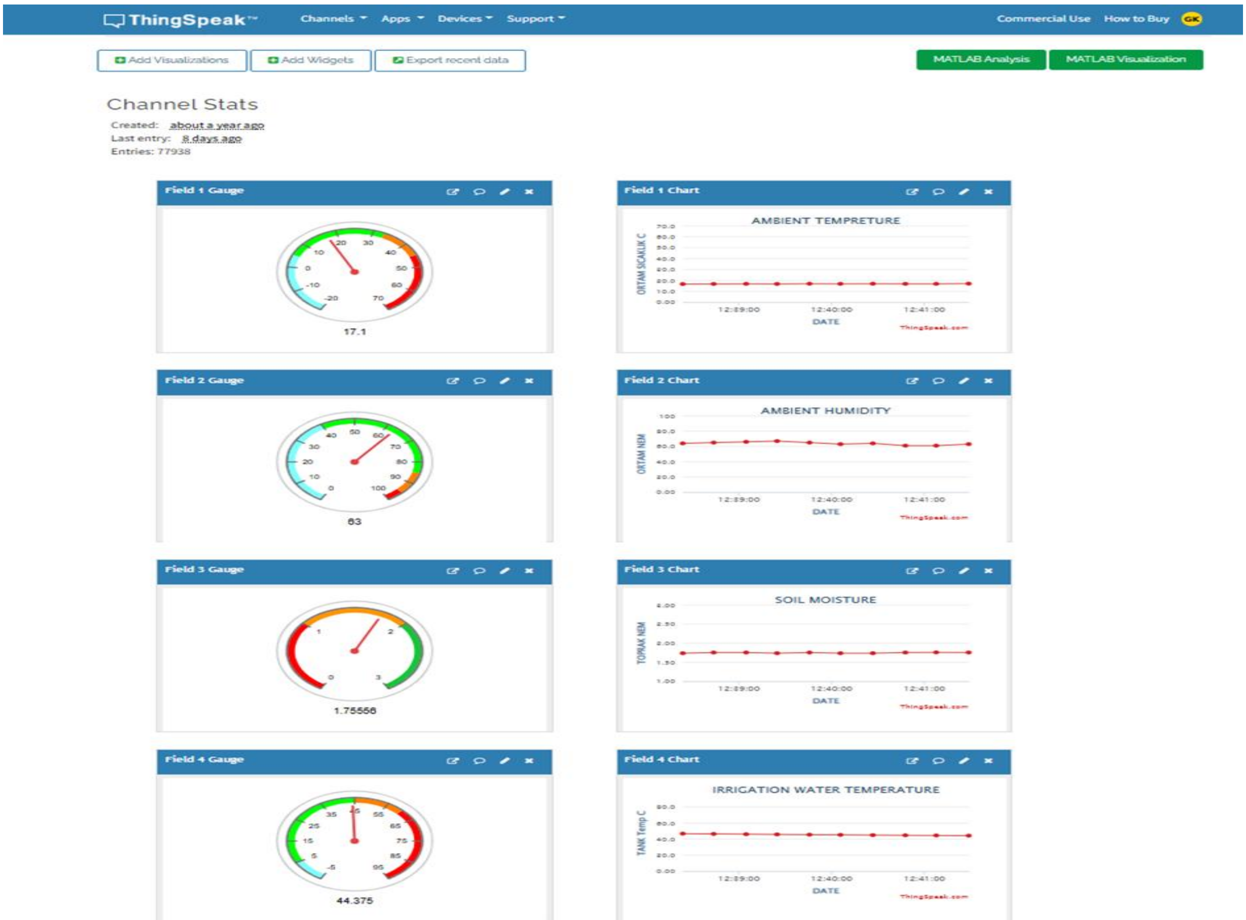

Fig 5: Desktop interface of the remote terminal showing real-time soil moisture, ambient temperature, humidity, and water temperature data.

3.1 Comparison with Related Works

Compared to existing IoT-based agricultural monitoring systems [15,16], the proposed design offers notable advantages in terms of cost-effectiveness, ease of deployment, and energy efficiency. Similar studies utilizing WSNs and IoT platforms often require complex network setups or incur higher implementation costs. The ESP32-based system leverages an integrated Wi-Fi module and a modular sensor approach, simplifying system integration and reducing overall costs. Furthermore, the real-time data visualization and historical analysis provided by ThingSpeak facilitates better long-term agricultural planning compared to systems relying solely on local data storage.

3.2 Limitations and Future Improvements

While the system achieved its intended objectives, several areas for improvement have been identified. The reliance on Wi-Fi networks limits deployment in remote areas with poor connectivity; integrating alternative communication technologies such as LoRa or GSM modules could expand the operational range. Moreover, adding automated decision-making capabilities using embedded artificial intelligence models could further enhance system autonomy. Future iterations of the system will explore modular scalability options to incorporate additional environmental parameters such as soil pH, solar radiation, and CO2 concentration, providing a more comprehensive overview of field conditions.

Overall, the developed system demonstrates the potential of low-cost, cloud-integrated innovative farming solutions to empower agricultural stakeholders, support sustainable resource management, and contribute to the broader adoption of Big Data and IoT technologies in modern agriculture.

4. CONCLUSION

This study presents the design, development, and evaluation of a low-cost, microcontroller-based system for real-time agricultural data monitoring. By integrating ESP32 microcontrollers, diverse environmental sensors, and the ThingSpeak cloud platform, the system offers an accessible solution for small—and medium-scale farmers seeking to optimize resource usage and improve productivity.

The system demonstrated high reliability, stable performance, and user-friendly accessibility under real agricultural conditions. Real-time monitoring of soil moisture, ambient temperature, humidity, and irrigation water temperature provided critical insights for irrigation management and climate control strategies. Moreover, the scalability, energy efficiency, and modular design of the system make it a promising tool for widespread adoption in smart farming practices.

In the broader context of smart farming and Big Data applications, the developed system supports the transformation of traditional agricultural operations into data-driven and sustainable practices. Future work will focus on expanding the system's communication capabilities by integrating alternative technologies such as LoRaWAN or GSM modules and enhancing decision-making through embedded artificial intelligence and predictive analytics. Additionally, incorporating more environmental parameters, such as soil pH, solar radiation, and atmospheric CO2 levels, will offer a more comprehensive view of field conditions.

By empowering farmers with timely, accurate, and actionable data, the proposed system contributes significantly to advancing sustainable agriculture, resource efficiency, and food security in an increasingly data-centric agricultural landscape.

5. REFERENCES

[1] Aksoy, E., & Kendilci, K. 2024. Küresel gıda krizleri ve gıda güvencesi. Sağlık & Bilim 2024: Beslenme-IV.

[2] Mardones, F. O., Rich, K. M., Boden, L. A., Moreno-Switt, A. I., Caipo, M. L., Zimin-Veselkoff, N., ... & Baltenweck, I. 2020. The COVID-19 pandemic and global food security. Frontiers in Veterinary Science, 7, 578508.

[3] FAO. 2020. Food security during the COVID-19 pandemic. Food and Agriculture Organization Report.

[4] de Paulo Farias, D., & dos Santos Gomes, M. G. 2020. COVID-19 outbreak: What should we expect from this pandemic? Brazilian Journal of Infectious Diseases, 24(3), 233-235.

[5] Yalçın, G. E., & Kara, F. Ö. 2014. Effects of global climate change on agricultural production in Turkey: Solutions and Recommendations. XI. National Agricultural Economics Congress.

[6] Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. 2017. Big Data in Smart Farming – A review. Agricultural Systems, 153, 69–80.

[7] Walter, A., Finger, R., Huber, R., & Buchmann, N. 2017. Opinion: Smart farming is key to developing sustainable agriculture. Proceedings of the National Academy of Sciences, 114(24), 6148-6150.

[8] Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. 2018. Machine learning in agriculture: A review. Sensors, 18(8), 2674.

[9] Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. 2017. A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture, 143, 23-37.

[10] Zhang, Y., Wang, G., Shi, Y., Liu, J., & Gao, F. 2020. Design and application of a wireless sensor network for agricultural environment monitoring. Sensors, 20(20), 5722.

[11] Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. 2017. Energy-efficient wireless sensor network for precision agriculture: A review. Computers and Electronics in Agriculture, 142, 103-123.

[12] Khanna, A., & Kaur, S. 2019. Evolution of Internet of Things (IoT) and its significant impact on agriculture. Computers and Electronics in Agriculture, 157, 218-231.

[13] Saravanan, K., Anusuya, E., Kumar, R., & Son, L. H. 2018. Real-time weather prediction and agriculture monitoring system using IoT. Computers and Electronics in Agriculture, 151, 275-281.

[14] Dukes, D. M., Simonne, H. E., Davis, E. W., Studstill, D. W., & Hochmuth, R. 2003. Sensor-Based High Frequency Irrigation Management for Bell Pepper. 2nd International Conference on Irrigation and Drainage Proceedings.

[15] Muñoz, C. R., & Dukes, D. M. 2005. Soil moisture-based automatic irrigation for vegetable crops. University of Florida Agricultural and Biological Engineering Department.

[16] Zhang, W., Li, J., Wang, L., Song, H., & Liu, X. 2019. An IoT-based smart irrigation system using soil moisture sensors. Sensors, 19(17), 3799.