



IMPLEMENTATION OF AN ESP32-BASED ESP-NOW NODE NETWORK FOR SMART AGRICULTURE MONITORING AND IRRIGATION CONTROL

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ABSTRACT

Water waste, unpredictable weather, lack of real-time monitoring, and reliance on manual irrigation techniques are some of the problems agriculture faces today. This paper presents a smart agriculture monitoring and irrigation control system based on the ESP32 that uses ESP-NOW wireless communication to tackle these challenges. The proposed system includes one main control node and two sensor nodes. In the field, the sensor nodes monitor temperature, humidity, motion, rainfall, and soil moisture. Irrigation automatically adjusts to reduce water waste and improve efficiency based on set threshold values. Using the ESP-NOW protocol, sensor data is transmitted wirelessly to the main node. It is then periodically uploaded via Wi-Fi to a cloud platform for remote monitoring through a mobile app. The system works well in off-grid and remote agricultural areas because it is solar-powered with a rechargeable Li-ion battery backup. The experiment results show reliable sensing, stable multi-node operation, dependable wireless communication, and effective automatic irrigation control. For smart agriculture, the proposed model offers an affordable, scalable, and energy-efficient solution.



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I. INTRODUCTION

The increasing rate of the global population requires more agricultural production, but climate change and improper agricultural practices are major challenges. The integration of artificial intelligence with IoT and cloud computing will make agriculture smarter, more efficient, and data-driven. This paper proposes an IoT-based system for monitoring the growth of the paddy crop. The proposed system uses sensors to measure temperature, humidity, soil moisture, and water levels. The data is then analyzed using a cloud platform. The system will help farmers to optimize irrigation, increase crop production, and reduce water wastage. The proposed technique is a cost-effective solution for precision agriculture [1], [2]. Agriculture is important for a country's economy. Precision agriculture uses machine learning methods to improve yield. Agriculture is an important sector in the economy of a nation. Precision agriculture uses machine learning algorithms to enhance crop forecasting and decision-making. Machine learning (ML) extracts valuable information from past data to help in soil mapping, seed choice, irrigation, disease identification, weed management, and crop quality assessment. Cameras observe plant health, identify diseases, and assist in harvesting, sorting, and field robotics. Computer vision is the next level of smart farming. All these enhance automation, reduce expenses, and enhance agricultural productivity and efficiency by integrating deep learning with big data [3], [4]. The Internet of Things (IoT) has brought new opportunities for efficiency and automation in many areas, and agriculture is not an exception. IoT systems are based on the interconnected devices, sensors, and communication protocols to gather and share data and provide real-time monitoring and smart control of physical environments [5]. This technology in agriculture enables farmers to have an insight into valuable field conditions every time and act swiftly in reaction to forthcoming alterations.

IoT-based smart irrigation systems assist in automatizing the process of water management to achieve this by evaluating sensor information to find out the real requirements of crops. These systems have the capability of controlling irrigation in a more efficient way by measuring soil moisture and other environmental parameters that would help eliminate water wastage and enhance crop growth [6]. This type of IoT-based solution offers a stable and affordable way of modern agriculture to facilitate efficient use of resources and sustainable farming initiatives. Agriculture has had a significant application of wireless sensor networks, which monitor the environment in an efficient way but with minimal power consumption. The systems assist in gathering the precise field information and aid in managing the farm better [7]. With the help of the IoT and sensors, the agricultural system will be able to track the crops in real time and automatically control the irrigation process. This enhances efficiency of resources and has been a trusted solution to smart applications in agriculture [8]. IoT is revolutionizing the world of modern agriculture. IoT enables farmers to track the conditions of their fields remotely and automates critical tasks such as watering and fertilizing. This paper describes a real-time monitoring system based on IoT technology and environmental sensors to continuously measure temperature, soil moisture, and water levels. The system relies on the data collected to control the pumps and cooling fans to maintain optimal conditions for crops. It transmits data to the cloud through Wi-Fi for real-time viewing and analysis. The GSM modules enable the farmer to receive real-time notifications. The proposed system enhances agricultural productivity by ensuring that resources are optimally utilized and appropriate measures are taken [9]. In this paper, the performance of a cluster-based agricultural IoT network using BLE and Raspberry Pi 3 B+ is presented. The proposed network is designed for precision agriculture and greenhouse systems. The testbed is a combination of sensors and low-power communication modules. The results of the experiments conducted indoors and on the farm indicate that the testbed is reliable, scalable, and easy to manage [10].

II. RELATED WORK

In smart agriculture, we employ the use of wireless sensor networks based on IoT technology to measure the soil moisture, temperature, humidity, and water level in the field. Wi-Fi, Bluetooth, Zigbee, and LoRa technologies are normally employed to help the long-distance transmission of this data. But in large-scale agriculture, these technologies may sometimes experience problems of range, battery life, and connectivity. Mesh networking solves this problem. Here, the devices communicate with each other. This makes the network robust and reliable. ESP-based networks such as Wi-Fi Mesh and ESP-NOW are the best for this purpose because they are fast, battery-efficient, and highly effective in large outdoor farms [11].

III. PROPOSED SYSTEM ARCHITECTURE

The proposed system is a smart agriculture system developed using IoT technology. This system is capable of monitoring the field in real time, automatically controlling irrigation, and enabling users to view data remotely using a mobile application. The system is developed in a distributed fashion, consisting of two sensor nodes and one main node. The two sensor nodes are responsible for field sensing and device control, such as pumps. The main node is responsible for collecting all the data, making decisions based on the data, and sending the data to the cloud for remote access. For better understanding and future development, the whole system is broken down into various functional units [12], [13].

A. Power Supply

The power supply unit is made for ongoing use in remote agricultural areas. Each node gets its power from a solar panel and a rechargeable Li-ion battery. The voltage regulation circuit provides a steady power supply to the microcontroller, sensors, and communication modules. The system relies on renewable energy sources and is built to work for a long time with little maintenance.

B. Sensor and Control Unit

The sensor and control unit observes the field and environmental conditions. The sensor nodes are equipped with soil moisture sensors, temperature and humidity sensors, rain sensors, and PIR motion sensors. The sensors are responsible for collecting real-time data regarding the soil conditions, environmental changes, and activities in the field. The ESP32/NodeMCU microcontroller is responsible for processing the sensor data and making decisions based on the predefined thresholds.

C. Communication Unit

The communication unit is the brain that shuttles data among the sensor nodes, the main node, and the cloud. First the sensor nodes toss their processed data wirelessly straight to the main node. Once there, the main node stitches the pieces together and runs its own cleanup routine. After that minute of gathering, it pulls the connection to the sensors, boots up its Wi-Fi card, and blasts the polished data out to the cloud. As soon as the upload finishes, the mobile app gets a quick refresh. Doing it this way cuts power use, lightens the traffic load, and forces the data to ship safely—that's the double-edged advantage [14].

D. Actuation Unit

The actuation unit controls the field devices based on sensor values and system decisions. Relay modules control the actuators, which may be water pumps or motors. When the soil moisture content is below the set level, the irrigation motor turns on automatically. But when the moisture content is adequate, the motor turns off to avoid wasting water. Temperature actuation can also be applied to ventilation control in indoor or protected agriculture.

E. Monitoring and User Interface Unit

The monitoring unit allows both local and remote access to agricultural data. The main node has an LCD display that provides real-time data from the sensors. The cloud-based mobile app allows farmers to monitor the conditions in the fields remotely. The mobile app updates the sensor data after each communication cycle, allowing farmers to make decisions without necessarily being in the field.

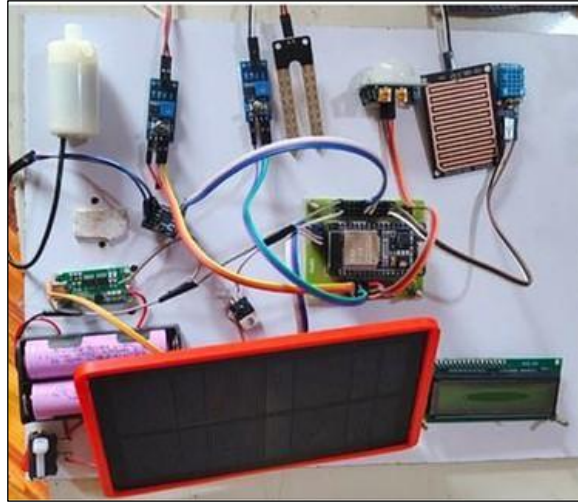


Figure 1: Experimental Setup of Nodes 1 and 2 (Tx).

Source: Authors, (2026).

F. Node-wise Monitoring and Interface Description

1) Node 1 Monitoring Unit

Node 1 acts as a transmitter sensing unit placed in the agricultural field. It constantly checks soil moisture, temperature, humidity, rainfall, and motion with the built-in sensors. The ESP32/NodeMCU processes the sensor data on-site and operates the irrigation motor through a relay when the soil moisture drops below the set threshold. The processed data from Node 1 is sent wirelessly to the main node during the data collection phase. Node 1 runs on solar power and has battery backup. This setup allows for continuous monitoring with little human involvement.

2) Node 2 Monitoring Unit

Node 2 is a duplicate sensing node with the same hardware configuration as Node 1. Node 2 is placed in a different region of the field to measure the variations in environmental conditions. Node 2 monitors soil and weather variables using the same sensors and makes decisions at the local level using the microcontroller. Node 2 makes decisions about motor control based on soil moisture content to enhance irrigation. Data from Node 2 is transmitted to the main node periodically.

3) Main Node Monitoring and User Interface Unit

The main node is the central unit for monitoring and user interaction in the system. It receives data from Node 1 and Node 2 and combines the data for processing. The main node shows real-time values of the sensors and the system status on an LCD connected to it. The system supports on-site monitoring. After collecting data from the sensor nodes, the main node waits for one minute. It then disconnects from the sensor nodes and connects to a Wi-Fi network. Finally, the combined data uploads to a cloud platform and an online mobile application.

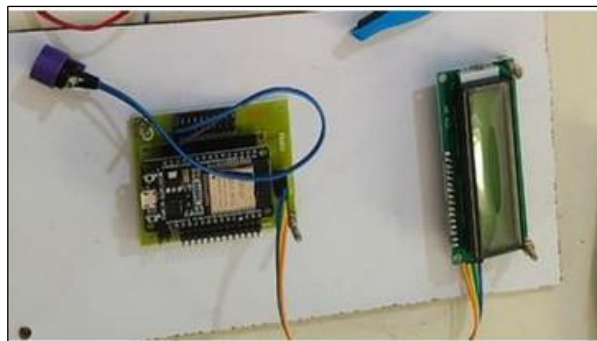


Figure 2: Experimental Setup Of Main Node (Rx).

Source: Authors, (2026).

IV. METHODOLOGY

The existing system adopts a node-based system over wireless monitoring of agriculture and provision of automatic irrigation. System operation will involve data collection procedures of the environment, on site data processing, transmission of data wirelessly and long distance monitoring via cloud network. The installed sensing nodes, which are called Node 1 and Node 2, exist in the agricultural field at different points. The nodes are powered by a solar power unit that is backed by rechargeable lithium-ion battery and a voltage regulation circuit to give continuous stable power. In these nodes, there are various sensors that detect moisture of soil level, temperature, humidity, rainfall, water level and motion sensors. The sensors constantly scan the field and the environmental parameters to be able to generate real-time data concerning human conditions of crops as well as soils.

The sensing node is equipped with an ESP32 or NodeMCU microcontroller to work on the sensor data obtained. The sensor readings are compared against preset threshold values and the irrigation motor is automatically turned on or off by a controller with the use of a relay module. This is a local control mechanism that enables the system to be reactive without having to be connected to the internet all the time. The data that is gathered at the field nodes is sent wirelessly, and it is uploaded to a cloud platform through the main node. This information can be monitored remotely in agricultural conditions and irrigation status by using a mobile application. This type of controlled communication will decrease the amount of power consumed, reduce the use of Wi-Fi frequently, and increase the reliability of the system, particularly in remote agricultural settings.

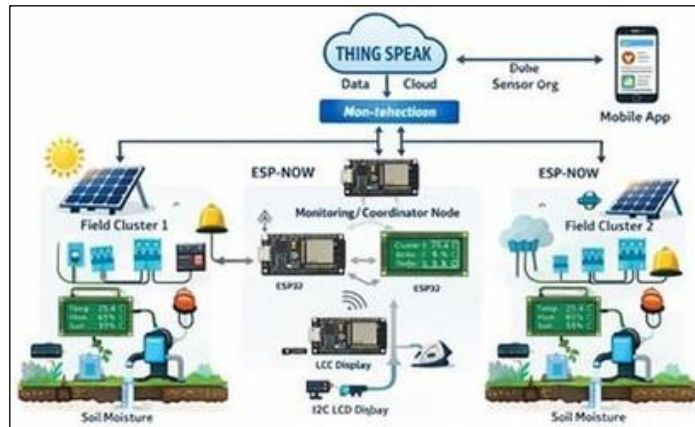


Figure 3: Block Diagram Of Proposed Design (Cluster-Based WSN Architecture).

Source: Authors, (2026).

V. COMPARISON WITH TRADITIONAL SYSTEMS

Table 1 highlights the advantages of the proposed system over conventional irrigation and monitoring approaches.

Table 1: Comparison Table.

Parameter	Traditional System	Proposed System
Monitoring	Manual	Automatic
Irrigation Control	Manual	Smart Control
Power Source	Grid Power	Solar Power
Water Usage	High	Optimized
Remote Monitoring	Not Available	Mobile App

Source: Authors, (2026).

VI. RESULTS & DISCUSSION

The proposed IoT-based smart agriculture system was successfully implemented and tested in real-time conditions, as evident from the images of the hardware setup. Two sensor nodes were used to monitor the soil moisture, temperature, humidity, rainfall, and motion. The central receiver and control unit was the main ESP32-based node. The whole system was powered by a solar panel and 18650 Li-ion rechargeable batteries.

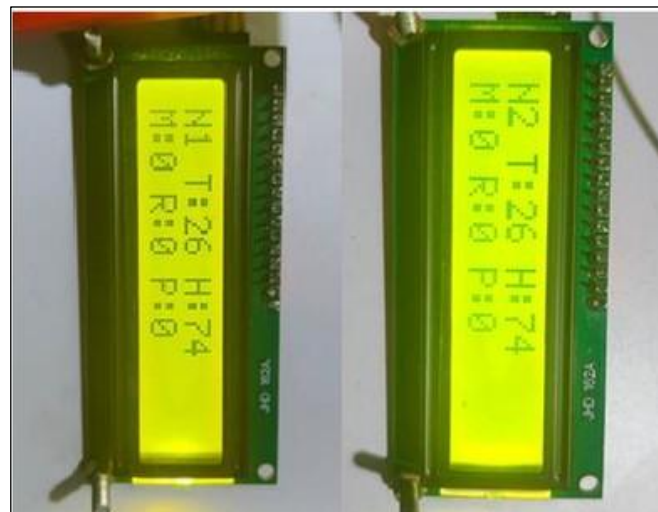


Figure 4: Real-time LCD monitoring Node 1 and 2 (Tx).

Source: Authors, (2026).

A. Motion Detection Performance.

Case 1: No Motion Detected (P = 0)

Under the normal field environment, the LCD display indicated parameters like the node identifications, temperature, humidity, soil moisture conditions, rainfall conditions, and the motion value were indicated as zero. P = 0 meant that no movement was in the area under observation. In this scenario, the system would keep on doing regular environmental checks, and the irrigation management was to be performed solely in reliance on the soil moisture. This guaranteed the appropriate water use and the constant functioning of the systems.

Case 2: Motion Detected (P = 1)

In the event that the movement was detected in the monitored region, the motion sensor output was switched to P = 1. This update would be reflected instantly on the display, and this proved that the sensor was able to detect motion. The quick response achieved dependable sensing attributes and wireless data transmission between field nodes and the central node. The results of both sensing nodes were consistent, and this indicated the reliability and scalability of the system.

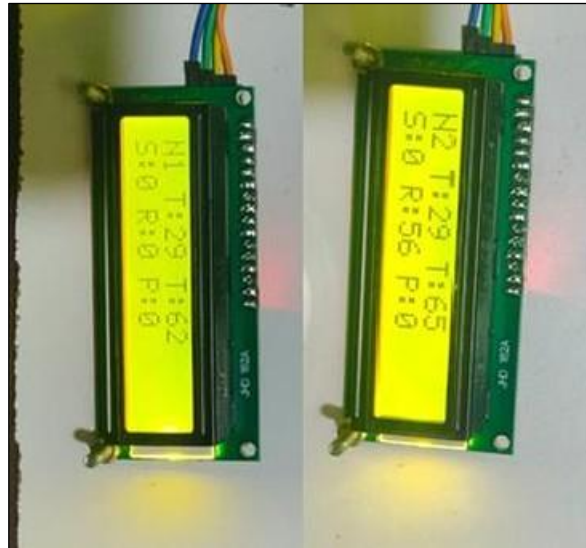


Figure 5: Real-time LCD monitoring of Main Node (Rx).
Source: Authors, (2026).

Case 3: Motion Sensor - P:0

Under normal conditions, the LCD displayed the following readings: Node ID: N2, Temp: 28°C, Hum: 52-53%, Moisture (S): 0, Rain (R): 56, and Motion (P): 0. This indicates that there was no motion detected, and therefore the system was in monitoring mode. The irrigation system relied solely on the soil moisture level.

Case 4: Motion Sensor - P:1

With the detection of motion by the transmitter node, the receiver displayed the following readings: Node ID: N2, T:28°C, H:53%, S:0, R:0, P:1. The quick change from P:0 to P:1 confirms that there was motion detected. This also confirms that the wireless communication system is functioning well and that there is real-time synchronization between the sensor node and the master receiver unit.

Rainfall Detection Analysis

During the test, the system logged Node ID: N2, T:28°C, H:53%, S:0, and R:0. This shows that there was no rainfall detected and the sensor plate was dry. The R:0 value also shows that the rain sensor was in its normal dry state with no water droplets on the sensor. However, when rainfall happens, the sensor reading changes from R:0 to R:1 because of the higher conductivity on the sensor plate. This reading is then transmitted to the main node and shown on the LCD display. This makes it possible for automatic irrigation control to prevent overwatering and water wastage.

Soil Moisture-Based

Irrigation Response During the test, the system logged Node ID: N2 with S:0. This shows that the soil was moist above the dry level, and the pump was in the OFF state. However, when the soil moisture level goes below the set value (S:1), the motor turns on automatically. This shows that the irrigation system has closed-loop control with very little human intervention.

Wireless Communication Performance

The communication network connecting N1, N2, and the central node performed well under all test scenarios. The data from the sensors measured at each node was sent and received correctly with no signs of data loss. The information transfer happened in a very short time span, enabling the control unit to process the data and make changes to the system operations instantly. This quick communication enabled the control unit to make irrigation decisions instantly based on real-time field conditions. The combination of

ESP-NOW communication for local node communication and Wi-Fi communication for updating data remotely functioned without any interruptions. Both communication systems functioned in perfect harmony, ensuring a continuous flow of data even after multiple cycles of data transmission. The system functioned flawlessly under all test conditions, with no signs of unexpected shutdowns or communication losses.

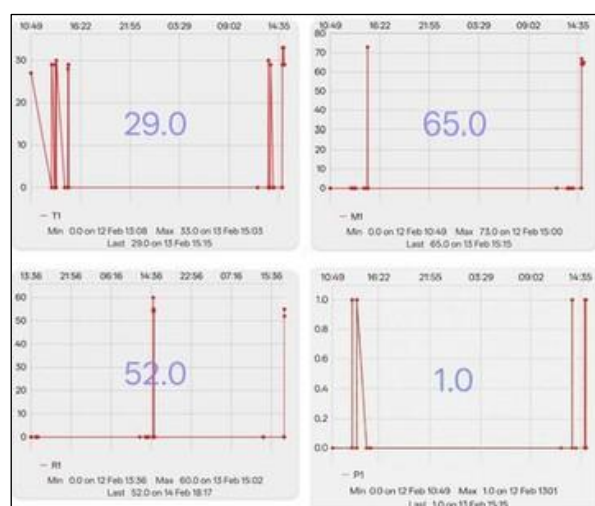


Figure 6: Real-time Graphs from Tx-Node1 (Temperature, Moisture, Rain, Motion Sensor Values).
Source: Authors, (2026).



Figure 7: Real-time Graphs from Tx-Node2 (Temperature, Moisture, Rain, Motion Sensor Values).
Source: Authors, (2026).

Figures shows the real-time graphs of Tx-Node1 and Tx-Node2 for temperature, soil moisture, rain detection, and motion detection. The readings from the sensor remained constant in normal environmental conditions. The temperature readings were around 29-30°C for Node1 and 52-54°C for Node2 during peak measurements. The moisture levels remained constant, indicating proper soil condition monitoring without any abrupt changes. The rain sensor output changed distinctly between low (0) and high (1), indicating proper detection of rainfall events. The motion sensor output changed rapidly between 0 and 1 upon detecting motion, indicating proper intrusion detection. From the graphs, it can be seen that there is synchronized data transmission from both the transmitter nodes. This indicates the efficacy of the proposed wireless monitoring system.

Solar Energy Performance

The solar panel was able to power the ESP32, sensors, LCD, and wireless communication components effectively. The 18650 Li-ion battery was also able to provide a backup power source effectively, even when the sunlight changed temporarily. This is evidence that the system is effective for agricultural fields that are remote and require little maintenance.

Comparative Analysis

Compared to traditional manual systems, the proposed model cuts down on labor and reduces water waste with automatic control. It enhances crop protection by using real-time monitoring and allows for scalable multi-node deployment. Overall, it provides a smarter and more efficient farming solution.

Future Enhancements

Then, we are thinking of incorporating LoRa so that the system can extend its range and remain connected within the fields. After that, we will implement AI to detect problems in the crops before they become major issues. Other ideas are in the pipeline, including a smart dispenser that will deliver the correct amount of fertilizer only where it is needed, push notifications that will send notifications to your phone at the correct time, and a camera that will detect any unwanted visitors.

Overall Observation

During the testing phase, N1 and N2 ensured that their sensors were functioning properly. There were no significant changes or fluctuations in the values of temperature, humidity, soil moisture, rainfall, and motion. The ESP-NOW communication feature functioned properly, sending packets with little delay and no losses. On the receiving end, the values were displayed properly on the screen as they passed through the "listening," "displaying," and "updating" phases. When the sensor detected motion, it responded immediately, providing us with a real-time perspective of the intruders. The node network is very reliable for communication, consumes very little power, and can be established in an agricultural field without any special preparations.

VII. CONCLUSION

This paper presented an IoT-based smart agriculture monitoring and irrigation system that uses two sensor nodes and one main node to collect and send real-time field data. The combination of solar power and low-power wireless communication allows for continuous operation in remote areas. Automatic irrigation, which relies on soil moisture, reduces both water wastage and manual work. Experimental results show better efficiency, reliability, and scalability when compared to traditional methods. This makes the system a practical and cost-effective solution for precision agriculture.

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IX. AUTHOR'S CONTRIBUTION

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Approval of the final text: Kota Venkat Kumar, Marneedi Soujanya, Karnati Chaitanya Keerthi, Mohammed Mastan Vali Yash, Kodavandla Vignesh, Sravan Sikakolli.

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