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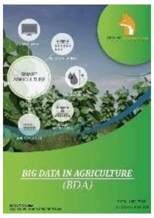

RESEARCH ARTICLE

IOT-BASED SMART IRRIGATION AND ENVIRONMENTAL MONITORING SYSTEM USING CLOUD PLATFORM AND MOBILE APP INTEGRATION

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ABSTRACT

Efficient water management and intelligent crop monitoring are critical challenges in modern precision agriculture. Traditional irrigation systems lack adaptability, remote accessibility, and real-time environmental monitoring. This research presents a hybrid dual-mode IoT-based multi-zone smart irrigation system using ESP32 controller, integrating automatic moisture-based control and manual mobile app based operation. The system monitors three independent agricultural area using soil moisture sensors and controls a centralized irrigation pump via relay-based switching. Environmental parameters including temperature, humidity, and CO levels are simultaneously recorded. The online platform supports operational modes: automatic irrigation based on crop-specific thresholds and manual override through mobile app based control. Real-time sensors data and pump status are transmitted to online Thing Speak cloud for monitoring and historical data analytics. Experimental evaluation demonstrates reliable multi-zone irrigation management, improved water efficiency, and real-time remote supervision capability of the proposed. The proposed system provides a scalable and cost-effective solution for intelligent agriculture management applications.

KEYWORDS

Smart Irrigation, ESP32, Dual-Mode Control, IoT Agriculture, Precision Farming, Cloud Monitoring, Thing Speak

1. INTRODUCTION

Food security has been a significant issue with the increasing world population. Smart use of resources in agriculture is one of the solutions. Nonetheless, agriculture continues to have some problems: intensive farming; guess-work decision-making; the effects of climate change, which include infrequent weather and soil erosion; and inefficient utilization of resources such as water and fertilizers, which are expensive and detrimental to the environment (Bhatnagar et al., 2024; Rust et al., 2022; Shahab et al., 2024). The growing consumption of food, the growing population, and climate change are having even more significant pressure on our water resources. Irrigation has occupied a major part of freshwater resources in the globe and when not effectively undertaken, waste of water, soil erosion and loss of crop production is experienced (Kumar et al., 2023; Wudil et al., 2022).

The traditional method of irrigation is manual or programmed. The techniques fail to factor in the moisture content of the soil that already exists and other environmental factors and thus crops tend to either be under watered or over-watered (Siwar et al., 2022). This can be harmful to productivity and permanence. The use of Internet of things (IoT) technology in the agricultural industry nowadays offers novel and precise irrigation methods. Farmers can monitor the moisture level of the soil and the weather and do this with wireless modules and sensors. Their ability to manage watering at the point as opposed to working to a set schedule is then possible. Microcontrollers like Arduino, ESP8266, and ESP32 are popular choices of these smart systems that are inexpensive and simple to operate. Despite the huge advancement, existing models of irrigation still have several flaws. Most of the systems that are reported are a single zone irrigation system lacking multi crop management. In addition, several of the designs lack the capability to be manually overridden and can only operate in automatic mode which is not so adaptable in the field of farming. In addition, the environmental monitoring (temperature, humidity, gas concentration) parameters are not very common to be incorporated. This restricts the ability of the system to provide specific agricultural intelligence. Real-time multi-parameter visualization and state monitoring of pumps, though occasionally included in it, is not always included in integrated architecture, although cloud-based monitoring (Kim et al., 2020).

This paper is a Hybrid Dual-Mode IoT system that concerns the control of irrigation of three crop areas with ESP32 microcontroller and real-time cloud and mobile connectivity. The system controls the various levels of moisture-soil content of Wheat, Rice and Sugarcane crops soil and includes a variety of moisture sensors, environmental units, pump switching system by relays and Wi-Fi communication via Thing Speak. The system mode of operation is a new feature. Irrigation under automatic mode is automatically triggered when moisture limit is exceeded. The system has a mobile app interface that allows operators to override the system automation when in manual mode. This dual functionality renders it to be reliable and flexible in the field. The data uploaded on the online cloud include real-time sensors data like soil moisture, temperature, humidity,

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CO concentration and motor pump status to continuously monitor, visualize and analyze the data in the past. The key objectives of this research are given below:

- Development of a smart multi-zone irrigation system with automatic and mobile app based manual control.
- Integration of environmental sensing with cloud monitoring for real-time data and optimized water use.

2. RELATED WORK

The Internet of Things (IoT) technologies have lowered the irrigation process of the fields by the farmers (Javaid et al., 2022). Sensors are also emerging as a significant instrument that is being employed by researchers to improve the yield of crops and water efficiency (Kassim, 2020;Sushma et al., 2024). The first advances were based on Arduino-controllers, which reacted to soil-moisture sensors and turned on the pumps when the moisture level fell below a specific threshold. Its solutions were working with a single irrigation zone and reduced manual labor but did not have phone and cloud surveillance (Khan et al., 2023; Rao et al., 2023).

The later study incorporated GSM modules so that the farmers could receive SMS alerts about the soil condition. The SMS messages proved useful, but the data was just presented on the plain screen, and the systems could not perform real-time analytics. Also, most of the GSM systems could not result in the functioning with other types of crops and tracking of other environmental parameters (Aqeel et al., 2023). The cheap availability of Wi-Fi microcontrollers such as ESP8266 and ESP32 enabled the development of new models that could transmit data to the cloud using Wi-Fi (Zhou et al., 2022).

Such devices were usually connected to visualization tools like Thing Speak or Blynk (Ramli and Jabbar, 2022). Though these platforms showed real time on moisture trends, many implementations were not overridden manually. In addition, most of the designs were only quantifying soil moisture without considering temperature, humidity and gas concentrations which also play a role in determining the health of plants (Lee 2015)

3. MATERIALS AND METHODS

The proposed system is a multilayered layered IoT-based smart irrigation system which integrates sensing, data processing, communication, cloud monitoring, and a dual-mode (automatic and manually controlled) control system. It offers real time analysis of soil conditions making irrigation decisions automatically and gives users the opportunity to analyze soil condition remotely via online cloud platform. The entire architecture is outlined in this section.

3.1 Data Acquisition Layer

Data acquisition layer assembles the on-field real time environmental and soil parameters. The different sensors are distributed across the different areas of the crops and have the ability to measure the soil moisture to generate an analog signal that is subsequently read by the ESP32 ADC pins. Digital sensors can measure temperature, humidity and in certain applications, gas levels to give a more detailed picture of crop water needs. This distributed sensing ensures irrigation decisions. The layer of control and processing provides the framework for the reception and transmission of data to the application layer

3.2 Control and Processing Layer

Within this layer is the framework of the reception and transmission of data to the application layer. Control and Processing Layer is used to define the control and processing layer (to the application layer). The control layer and the processing layer are designed based on ESP32 microcontroller that is at the heart of the computational unit of a system. ESP32 was chosen because it has built-in Wi-Fi, enough input/output analogue ports, sufficient processing cores and power consumption. The microcontroller interprets sensor data continuously and compares the value of the soil-moisture data to crop-specific threshold values. The system has two modes:

- Automatic Mode
- Manual Mode

There will be irrigation in Automatic Mode when the moisture content of the soil falls below the set point. A relay panel activates the water pump that stays on till the upper moisture indicator has been reached. Through Manual Mode, a farmer can use a mobile application to control irrigation.

This mode will be used to override the automatic decisions, and irrigation can be turned on and off. The purpose of the choice is maximized water consumption and excess irrigation is prevented.

3.3 Cloud Monitoring and Layer Communication

The communication layer sends field real-time information to the cloud. ESP 32 has Wi-Fi connectivity, and it periodically broadcasts sensor readings to the Thing Speak cloud server. The plots against each environmental parameter are plotted on a specific cloud field in question, and this enables the structuring of visualization. The cloud system displays real time soil moisture, temperature, humidity and pump status graphs. The graphs will assist in monitoring the performance and behavior of the irrigation system with time. The cloud communicates the manual control commands of the mobile application to the ESP32 that enables the remote control anywhere. This is a cloud-based solution that increases more clarity, data documentation and long-term performance analysis.

3.4 Operational Workflow

Its operation is based on cyclical and constant observation and intelligent control. This is a system that works on real time responsive sensing-processing-decision-actuation cycles in order to be efficient in irrigation. Once ESP32 has been booted, it sets up all pins, connects to Wi-Fi and connects to the cloud. After having started, the system enters a data-acquisition phase. In the crop zones, volumetric water content is constantly determined at soil-moisture sensors.

Temperature and humidity are also considered to put in perspective climatic conditions which influence crop water demand. The analog signal of sensor is changed to the digital one by the inbuilt ADC in ESP32 and is processed on board. Noise filtering and simple threshold conditioning stabilize the readings. Each area of crop has predetermined moisture limits based on the amount of irrigation needed in the absence of multi-zone crop-specific irrigation control.

- Lacks operating as hybrids (automatic/manual).
- Poor integration of monitoring the environment.
- Inadequate multi-parameter visualization via the cloud.
- Very little in the way of real-time pump status monitoring.

In finding a solution to these shortcomings, the proposed system presents a hybrid two mode multi-zonal irrigation system based on ESP32. This architecture includes three autonomous soil moisture sensors to control irrigation to crops, environmental sensors, real-time visualization using Thing Speak and mobile-based capability of manual override. This combined solution increases flexibility, scalability and practical applicability in the modern system.

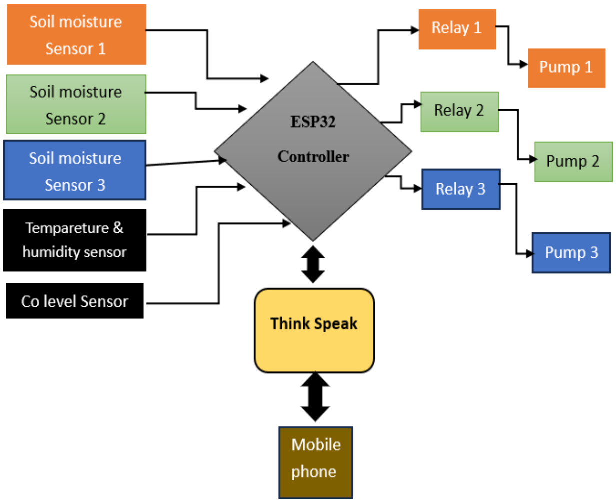

Figure 1 : Complete workflow diagram

3.5 Hardware Design

The proposed smart irrigation system hardware design will be designed to provide reliable sensing, efficient processing, reliable communication, and safe actuation. It consists of a combination of various sensing devices, a microcontroller with Wi-Fi capabilities and an electrically isolated relay to operate irrigation valves. All elements have been selected based on their performance, cost-efficiency, scalability and their real-world applicability in agriculture.

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3.5.1 ESP32 Microcontroller Unit

The core of the system is the ESP32 which processes and communicates wirelessly. Its in-built Wi-Fi, multiple channels 12-bit ADCs, dual-core processors and low power mode has rendered it perfect to the application of IoT in agriculture. The ADC has the capability to read soil moisture analog signal correctly, whereas the GPIO pins have an interface with environmental sensors and relay modules. Wi-Fi is internal, and thus it does not need an outer protective shell, which reduces the cost and complexity of design. ESP32 real-time multi-tasking also enables it to check sensors, send data to the cloud, and implement control logic in real-time, without affecting its performance, which simple microcontrollers like the Arduino Uno do not have.

3.5.2 Soil Moisture Sensing Units

There are several soil moisture sensors installed across various soil zones in crops. They sense fluctuations in soil resistance or capacitance which indicates water content with the resultant output of analog voltage proportional to moisture content. These are sent to the ADC of ESP32, which is used to convert them into digital values and applied to make crop-specific irrigation decisions. This distributed sensing makes sure that there is even watering and better utilization of water.

3.5.3 Sensors of Environmental Monitoring

The atmospheric data are given in real-time by temperature and humidity sensors, allowing evaporation-transpiration and stress in crops to be analyzed. This climate consciousness further develops irrigation logic with the association of soil moisture dynamics with the environmental condition. They can also be equipped with optional gas sensors to check the quality of air that can affect the health of crops.

3.5.4 Relay Module and Pump Actuation System

The signals on the ESP32 low voltage are connected to the high voltage water pump by an electrically isolated relay. Upon transmission of a command by ESP32 the relay coil is energized, connecting contacts to turn on the pump. In case of an increase in soil moisture beyond the highest point or the activation of a manual stop, the relay will be disconnected, and the pump will be turned off. It is used to prevent the back-flow voltage on a microcontroller, which extends its life in farms.

3.5.5 Power Supply Configuration

The system has a stabilized power supply to give constant voltage to the ESP32, sensors and relay unit. Voltage regulation removes sensor reading oscillations resulting due to variations in power. The renewable sources can be easily included in the structure, including solar panels, to increase the sustainability of remote fields.

Table 1: Hardware components

Component	Model/Type	Function	Operating Voltage
ESP32	Wi-Fi MCU	Processing & Communication	3.3V
Soil Moisture Sensor	Analog Type	Soil Water Measurement	3.3–5V
Temp & Humidity Sensor	Digital	Climate Monitoring	3.3–5V
Relay Module	1-Channel	Pump Switching	5V
Water Pump	DC/AC Pump	Irrigation	12V/220V

3.6 Experimental Setup

We experimented with the smart irrigation system that was proposed in a controlled experiment farm. The objective of the experiment was to measure the precision of real-time sensing, pump reaction, dual-mode switching and cloud monitoring stability. On a small prototype board, we put together the hardware, i.e. ESP32 microcontroller, soil moisture, environment sensors, a relay module and water pump (El Mezouari et al., 2022). We used various containers of soil to form various moisture conditions of crop zones. All the containers had soil-moisture sensors inserted at the same depth so that the readings could be similar. The soil surface had environmental sensors to monitor the temperature and humidity of the air. The relay module connected the ESP32 and the irrigation pump, which could safely control the work of the pump. The system was operated by a regulated power supply, and Wi-Fi was used to connect it to Thing Speak to synchronize in real-time in the cloud. We have performed Automatic and Manual tests. We dried the soil artificially in the Automatic Mode and then put in moisture gradually to see the automatic deactivation of the pump when the moisture increased to the top value. In Manual Mode, we tested remote control and override capabilities and sent irrigation commands via a mobile interface. The setup provided consistent performance, proper threshold detection, consistent relay switching, and transmitting cloud data.

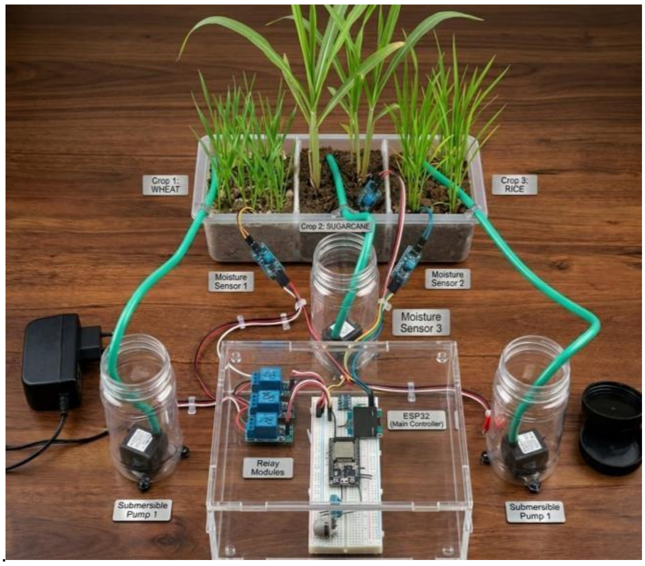

Figure 2: Prototype of the proposed smart irrigation system

3. Results and Discussion

The performance of the proposed system was evaluated based on soil moisture response behavior, pump activation accuracy, dual-mode switching efficiency, and cloud monitoring reliability. Three soil moisture sensors were continuously recorded on the Thing Speak cloud platform by us. The Crop 1, Crop 2 and Crop 3 graphs distinctly depict the changes in the moisture content at varying irrigation levels. In a few cases, the readings were near 0% which means there was dry soil. Moisture increased gradually or in spurts depending on the rate of absorption of the soil after irrigation. The trends are upwards, which is an indication that water is infiltrating the soil. After the enough moisture was reached, the values stabilized in the specified range, which confirmed the accuracy of the sensors as well as the ability to record the values in real time.

Figure 3: Real-time soil moisture variation during automatic irrigation cycle.

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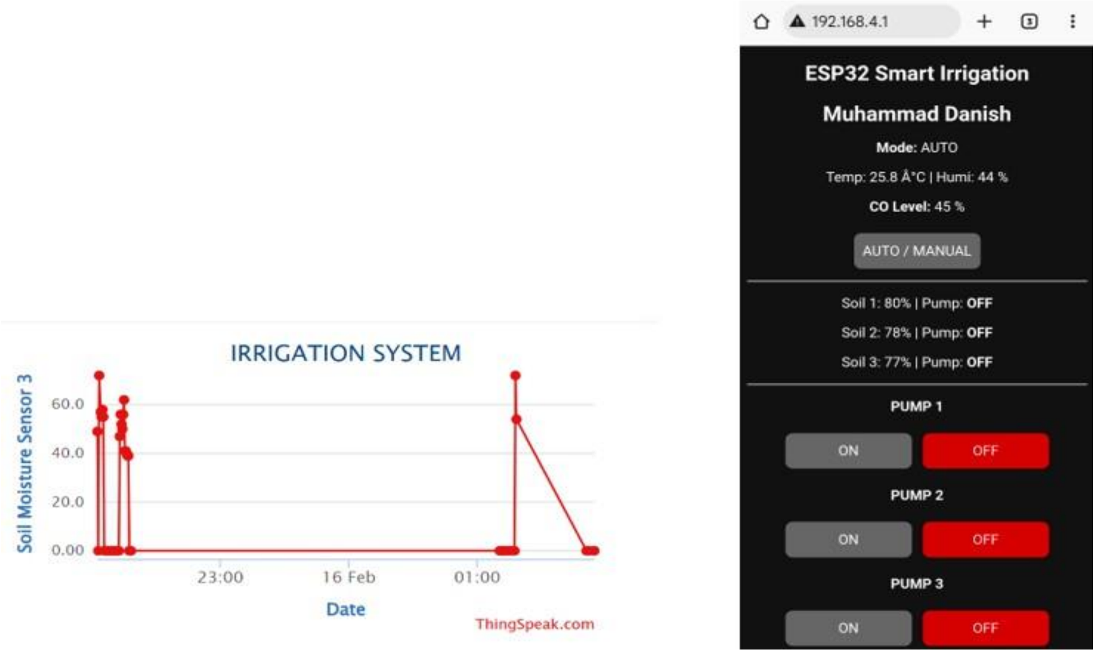

ESP32 Smart Irrigation

Muhammad Danish

Mode: AUTO

Temp: 25.8 Â°C | Humi: 44 %

CO Level: 45 %

AUTO / MANUAL

Soil 1: 80% | Pump: **OFF**

Soil 2: 78% | Pump: **OFF**

Soil 3: 77% | Pump: **OFF**

PUMP 1

ON OFF

PUMP 2

ON OFF

PUMP 3

ON OFF

Figure 4: Real-time soil moisture variation during automatic irrigation cycl**e.**

The data of three various soil moisture sensors were constantly checked and recorded on the Thing Speak cloud platform. The graphs of Field 1, Field 2 and Field 3 indicate distinct variations in soil moisture in various irrigation conditions. The moisture levels were also near 0 percent in a number of instances, which pointed to dry soil. When the soil was irrigated, the moisture content increased, at a slow pace sometimes and at a rapid pace at other times, according to the rate at which the soil wouldabsorb the water. The fact that the graphs are on an upward trend proves that water is infiltrating the soil as it was anticipated. Once sufficient moisture was attained, the values stabilized with the anticipated range. These findings indicate that there is proper operation of the soil moisture sensors and the real time data are being recorded in the cloud without failure.

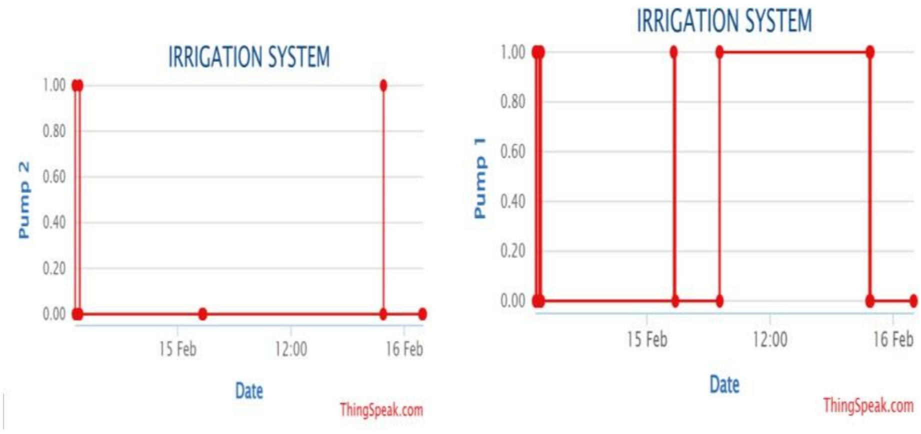

Figure 5: Pump activation and deactivation response during threshold crossing.

Figure 6: Pump 3 Status and Dual mode activation

The subsystem of environmental monitoring was assessed based on the real-time data tendencies, which were measured on the Thing Speak cloud platform, as illustrated in Fig.□oton. The graphical representation proves the fact of constant transmission of the data and constant recording of the atmospheric parameters. Based on the Field 4 chart (Temperature and Humidity), the values recorded at the chart vary moderately, with a very

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small margin of approximately 25.4 o C to 26.6 o C. It is gradually decreasing until midnight and slightly increasing after 01:00. The trend points to a normal variation in the environment in the short term when it is tested under controlled conditions. There are no sudden spikes or signal drops to indicate that the sensor functions and the Wi-Fi communication are stable. Likewise, the Field 5 chart (MQ2/air parameter trend) indicates that the data transition is smooth between about 49 and 57 units. The increment is observed at the beginning of the morning and then gradually decreases. No irregular oscillations or gaps in the data set, which means that there were no changes in the cloud or sensor shutdown. The tightness of the data points is an indication that there was a little environmentaldisturbance during testing, and this proves the strength of the sensing subsystem. Although the irrigation decisions in the present implementation are mainly moisture-driven, the presence of real-time data on the atmosphere improves contextual awareness and future development towards climate-adaptive or predictive irrigation decisions. On the whole, the findings of the environmental monitoring prove stable sensing accuracy, good cloud integration, and stable real-time visualization of the suggested system performance.

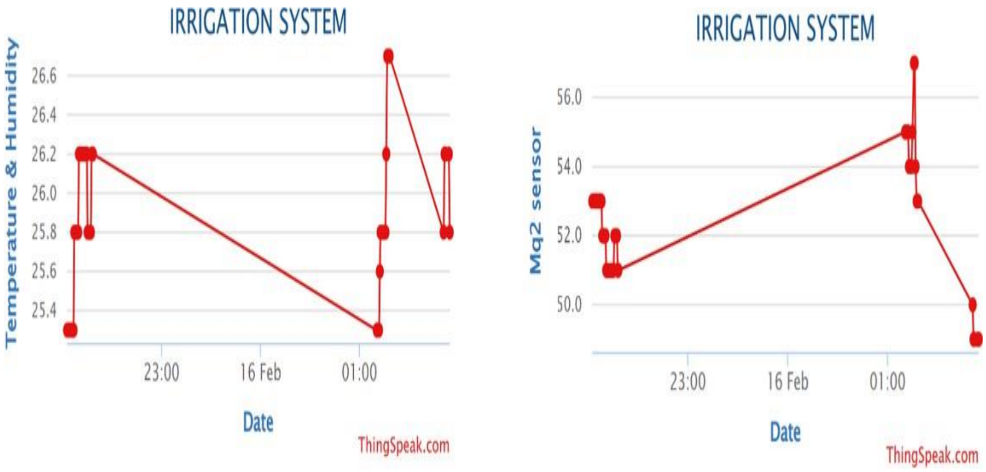

Figure 7: Environment monitoring

The comparative analysis to the recently published systems on the IoT-based irrigation frameworks was to assess the performance and novelty of the system. Its comparison is centered on such key characteristics as multi-zone support, dual-mode operation, cloud monitoring, environmental sensing, and mobile control. The specific comparison is mentioned in Table 2.

Table 2: Comparative evaluation of existing IoT-based irrigation systems and the proposed

System	Dual-Mode Operation	Cloud Monitoring	Mobile App	Environmental Monitoring	Cost	Accuracy	Ref
IoT based Monitoring	No	No	No	No	Medium	High	Hartono et al., 2024
Smart irrigation system using soil moisture	No	No	Yes	No	Medium	Medium	Newton et al., 2003)
Open source weather station	No	No	Yes	No	High	Medium	(Duguma et al., 2024)
IoT based system for real time monitoring	No	No	No	No	Medium	High	(Ioannou et al., 2021)
IoT-based smart irrigation	No	No	Yes	No	Medium	Medium	(Abhishek et al., 2021)
Proposed System	No	No	Yes	No	Low	High	-

Table 2 indicates that most existing systems do not have multi-zone irrigation and dual mode operation. Other studies provide cloud monitoring but lack features and do not allow complete mobile remote control. Our suggested system addresses these gaps by providing a variety of crops, automatic and manual control, monitoring the environmental conditions, and synchronizing with the cloud in real time, all on a single framework. It proves that our method is more practical, scalable, and flexible than the past one.

4. CONCLUSION

In this research work, the design and implementation of an IoT-based smart multi-crop irrigation system based on ESP32 microcontroller, real-time cloud monitoring and two-mode control is presented. The system combines multi-zone soil-moisture sensor, environment sensor, auto irrigation with threshold and remote manual override using cloud platform. It shows proper moisture sensing, constant relay-based pump control and proper Wi-Fi connection with the Thing Speak cloud server. The threshold control is a hysteresis-driven control which prevents over-irrigation, avoids relay chatter and provides efficient water utilization and mechanical stability. The system is validated by experimental results that indicate that the system responds immediately when moisture thresholds are violated and does not respond to alterations in Automatic and Manual modes. The dual-mode control architecture provides flexibility in operation, which means that farmers can alternate autonomous irrigation and user control with change of environmental factors and crop requirements. Cloud monitoring offers real-time visualization, transparency and logging of historical data- all needed in performance assessment and optimization in the future. The findings reveal that the system is cost-effective, scalable, energy-saving and applicable to realistic agricultural implementation. All in all, the designed smart irrigation system helps to manage the water resources in a sustainable manner and practice accurate agriculture by reducing the amount of wastage and guaranteeing the plant hydration.

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