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An IoT-Based Smart Agriculture System with Crop-Speacific Irrigation Optimization Using Cloud Analytics and Sensor Data

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***Abstract*—**Farming plays a key role in India's economy, yet handling water wisely and tracking soil conditions live remains tricky. Most fields rely on fixed schedules or basic automated setups - these can lead to too much water used and loss. One way around these issues involves using connected devices powered by IoT tools. These setups use physical sensors across the land to track key dirt properties like heat, wetness, water content, and acidity levels. A small computer called ESP32 picks up details about the environment, such as moisture and light. These readings travel to the internet network, where complex math happens using past results for different plants. What comes next is a forecast showing how much water each field might need. Instead of relying on old schedules or guesswork, the new method adjusts timing based on actual physical rules, not rigid rules set ahead of time. Farmers far away can now tap into smarter watering decisions without needing to physically visit the land. Putting auto and hand-operated setups together makes the new system work better under pressure. It demonstrates how using IoT alongside data handling leads to sharper, long-term farming decisions. Testing with 2,880 data entries confirmed its reliability. Outcomes included smarter watering for crops depending on weather shifts. Watering slowed when rain was predicted. During hot spells, supplies tightened but without loss. Overall use rose against older methods relying on fixed schedules.

Index Terms—Smart irrigation, Internet of Things (IoT), soil moisture sensing, ESP32 microcontroller, precision agriculture

I. INTRODUCTION

Farming still supplies most of the world's food, even though weather changes are getting harder to manage, there's less water around, while farmers need to grow more each year. Old ways of growing crops depend too much on steady watering and watching by hand, methods that frequently waste resources and slow down plant development. Because of this, smarter farm tools are becoming necessary - ones that track soil and weather details nonstop, helping growers choose better dates, amounts, and methods to raise stronger harvests.

Thanks to new tech in the Internet of Things, farmers can now track key soil details using affordable gadgets that work right away. Real-time updates come easily when small sensors connect through networks from distant locations. Watching conditions like dampness, warmth, air moisture, or acid levels happens fast without needing constant visits. Still, most current systems rely on fixed limits set ahead of time - limits that ignore how varied each growing field really is. Still, these rigid systems fail to consider unique plant needs along with site-specific differences - making them less useful when trying precise farming methods.

This study tackles its own limits by designing a farm tool that uses live sensing together with care tailored to crops. Instead of fixed rules, it checks actual soil and surroundings data against known growing needs, helping pick better times for watering. A method for saving water also appears here - how long it should run depends solely on rate of flow and each plant's thirst. Using user-guided input together with smart automation, the suggested method works to boost how efficiently water is used, cut back on excessive irrigation, while offering an honest and reliable way forward for today's precise farming practices.

II. LITERATURE SURVEY

A. Background

The agricultural sector is increasingly encountering difficulties owing to water scarcity and climate change, and traditional irrigation systems lack adaptability to dynamic agricultural conditions. IoT-based smart irrigation systems facilitate continuous environmental observation and auto- mated irrigation based on cloud processing of sensor data. Various predictive irrigation systems have been described in the literature. Research in [1] and [2] combined real- time sensor data with past data and weather predictions based on predictive and machine learning algorithms for optimized irrigation planning. Although these systems are beneficial for water conservation, they impose increased computational and power complexities and fail to address network resilience and data security issues.

A detailed survey in [3] emphasized the importance of soil moisture in precision irrigation and described communication technologies such as WiFi, GSM, and LoRa, but neglected data privacy and security issues. Cloud-based threshold-controlled irrigation systems were proposed in [4], which are convenient to use but lack predictive capabilities and security from unauthorized access. Low-cost ESP32-based monitoring systems for small-scale farmers were described in [5]; however, these systems are mainly passive and lack automated irrigation control and security features.

B. Cybersecurity Aspects in Smart Irrigation

The combination of WiFi sensors and cloud management systems expands the attack surface of smart irrigation systems. This includes unauthorized access, unencrypted data, and attacks such as denial-of-service or spoofing of sensors, which may affect irrigation and result in crop damage. However, intelligence is the primary concern of most studies, with security as the secondary aspect.

C. Research Gap and Motivation

While IoT sensing and cloud visualization are well-developed, most irrigation networks are either cost-effective or smart, and most WiFi-based irrigation systems are insecure. This paper proposes a single ESP32-based system that combines soil and pH sensing with weather-aware decision-making, including device authentication and encrypted communication for secure and efficient precision agriculture.

III. PROPOSED SYSTEM IMPLEMENTATION

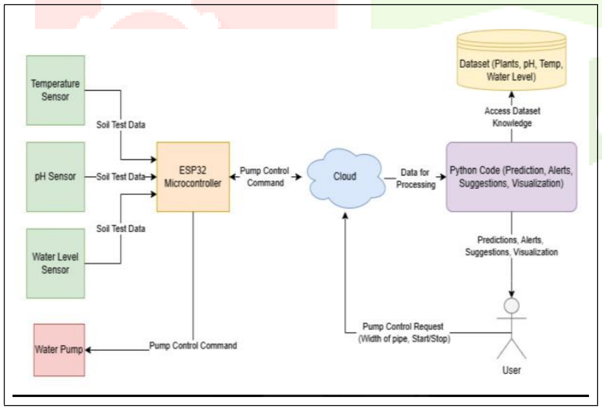

Fig. 1. System Architecture

The proposed solution offers an IoT-based smart irrigation and soil monitoring system for data-driven water management in agriculture. The system is designed to improve crop health with reduced unnecessary water use, through the integration of field-level sensing, cloud-level analysis, and automated irrigation control.

The system is divided into four functional layers: hardware for sensing and actuation, local data acquisition and preprocessing, cloud-level data analysis, and user interface with irrigation control.

A. Sensing and Actuation Hardware

The hardware component deals with the acquisition of soil and environmental information as well as the control of irrigation. The ESP32 microcontroller is used as the main controller owing to its wireless capabilities, low power efficiency, and sufficient processing power. Various sensors are connected to the ESP32 microcontroller to acquire information about soil moisture, pH, temperature, humidity, and water availability, and a relay module facilitates the safe control of the irrigation pump.

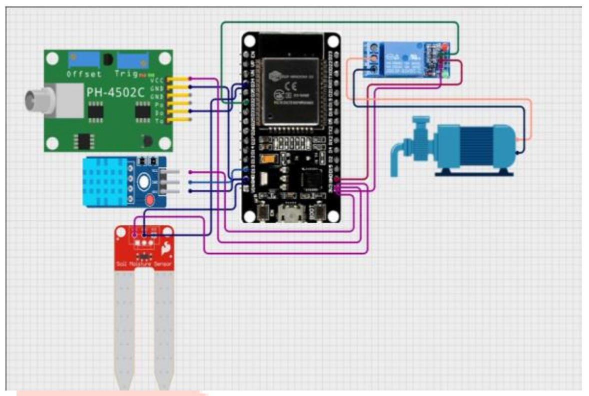

Fig. 2. Hardware Architecture

1) **ESP32 Microcontroller**: The brain of the system for acquiring sensor data and control.
2) **Soil Moisture Sensor**: Used to detect the soil moisture level.
3) **Temperature and Humidity Sensor (DHT11)**: Used to detect the temperature and humidity of the environment.
4) **pH Sensor (PH-4502C)**: Used to detect the pH value of the soil.
5) **Relay Module (5V)**: Used for safe switching of the water irrigation pump.
6) **Water Pump (Motor)** : This is used to supply water to the crops and is controlled indirectly through the relay module.
7) **Power Supply** : Supplies power(3.3V or 5V) to ESP32 and different components.

B. Local Data Acquisition and Preliminary Processing

During the startup process, the ESP32 initializes all the sensors and continuously checks the environmental factors. The sensor data is time-stamped, filtered for noise and anomalies, and processed at the local level by scaling and threshold tests to reduce data transmission. The critical conditions, such as low soil moisture or unusual environmental values, are identified at the edge level and sent to the cloud for decision-making.

C. Wireless Data Transmission and Cloud Integration

The ESP32 sends verified sensor readings, along with timestamps and device information, to the cloud server through Wi-Fi connectivity using optimal communication protocols. The cloud retains this information for long-term analysis and optimization of irrigation systems.

Algorithm 1: Wireless Sensor Data Acquisition and Automated Irrigation Control

```
Function System_Initialization() is
    Initialize ESP32 microcontroller
    Initialize DHT11, pH, and soil moisture sensors
    Configure relay module for pump control

Function Main_Loop() is
    while System is active do
        temperature ← ReadTemperature ()
        humidity ← ReadHumidity ()
        pH ← ReadPH ()
        soilMoisture ← ReadSoilMoisture ()
        SendDataToCloud (temperature, humidity, pH, soilMoisture)
        if ShouldActivatePump (soilMoisture) then
            ActivatePump ()
        Wait for predefined interval

Function ActivatePump() is
    duration ← CalculatePumpDuration()
    Turn relay ON
    Wait for duration
    Turn relay OFF
```

The functional process of the smart agriculture system using ESP32 is explained in Algorithm 1. After initializing the system, the ESP32 module periodically reads the temperature, humidity, soil moisture, and pH levels from their respective sensors. The readings are then sent to the cloud for monitoring. The irrigation requirement is calculated based on the soil moisture levels by comparing them with certain thresholds. If the requirement arises, the water pump is turned on through a relay module for a calculated time period and then turned off to avoid waterlogging.

D. Cloud-Level Data Analytics and Decision Making

Out in the field, a part called cloud analytics handles where data lives and how it helps make smart choices using sensor inputs. Through Wi-Fi, readings like moisture, temperature, air dampness, and acid content travel to a main hub - here they're kept in an organized form for looking back later. Live sensor data gets matched against known standards stored online - this comparison shapes more precise choices on watering needs. Decisions now rest on solid comparisons instead of guesses.

E. Irrigation Time Estimation Model

Water use requires calculating how long it should be applied, using math instead of set limits. The duration, T, follows this formula:

$$T = \frac{W_r}{Q} \tag{1}$$

where W_r is the required volume of water (L) and Q is the pump flow rate (L/min).

The value of W_r is calculated depending on the soil moisture deficit as follows:

$$W_r = A \times D \times (\theta_{opt} - \theta_{cur}) \tag{2}$$

where A is the irrigated area (m^2), D is the effective root zone depth (m), θ_{opt} is the optimal soil moisture content for the crop, and θ_{cur} is the current soil moisture content. The calculated irrigation time T is used to control the relay module for accurate pump control.

F. User Interface and Irrigation Execution

The farmer can control the system from a web or mobile application that displays sensor data, notifications, and control inputs. The user inputs are checked in the cloud server before acting on them, and the ESP32 then controls the irrigation pump using a relay. The sensor data after irrigation is checked to ensure that the target soil moisture level has been reached.

IV. METHODOLOGY

The methodology used in this project outlines the systematic process used for designing, developing, and implementing the proposed IoT-based smart irrigation and soil monitoring system. The methodology is centered on the integration of sensing components, embedded control, data processing on the cloud, and intelligent irrigation control for effective water management

. The entire methodology is broken down into five main stages: system architecture design, sensor data acquisition, data transmission and integration on the cloud, decision-making and irrigation optimization and feedback control.

A. System Architecture Design

The proposed system has a four-layer architecture, which includes the sensing layer, control layer, cloud processing layer, and application layer. The sensing layer is responsible for collecting real-time soil and environmental information using a distributed sensor network. The control layer, which is ESP32-based, is responsible for edge-level validation, preprocessing, and communication management. The cloud processing layer is responsible for data storage, analysis, and decision-making based on crops.

1) **Perception Layer**: Consistently tracks soil and environmental conditions through sensors connected to the ESP32, with filtered data processed and stored at the edge.
2) **Transport Layer**:The transport layer allows for both real-time and historical data analysis by sending processed sensor data from the ESP32 Wi-Fi module to the cloud via common Internet protocols.

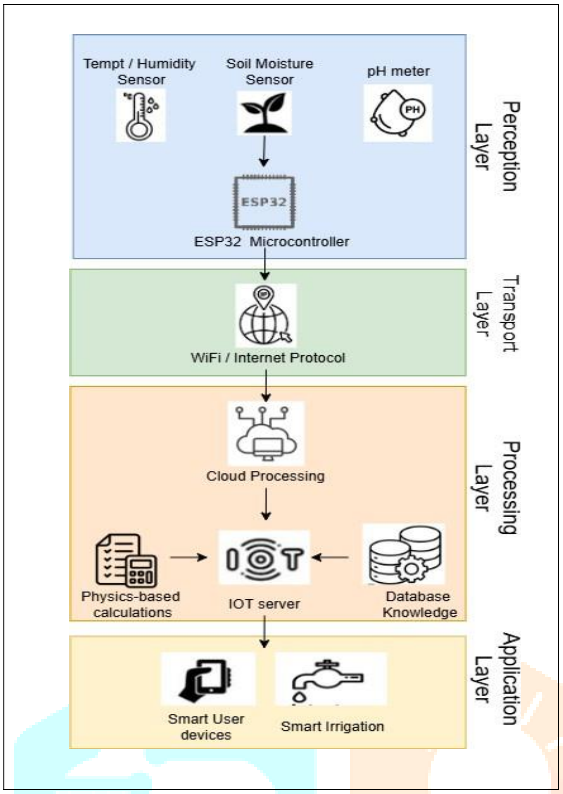

Fig. 3. IOT System flow diagram

3) **Processing Layer**:Computes irrigation demand and duration by comparing sensor data with crop requirements kept in a knowledge base at the cloud level.Based on the crop's water needs from the dataset, the suggested model determined the irrigation time dynamically.
4) **Application Layer**: Sends validated irrigation commands from the cloud to the field station, where the ESP32 controls the pump via a relay and post-irrigation data is collected for analysis.

V. RESULTS AND DISCUSSION

The proposed IoT-based smart irrigation system was tested using a structured data set of 2,880 records. Covers various agricultural conditions such as crop type, soil type, climate, temperature variations, and weather conditions, to ensure realistic testing of the performance of the system.

A. Dataset-Based Irrigation Analysis

Cloud-level analysis used the dataset as a reference model to calculate the optimal irrigation need. The real-time sensor reading was matched to the nearest dataset conditions based on crop type, soil type, temperature range, and prevailing weather conditions, and the corresponding irrigation need was used to calculate the irrigation time.

For instance, the irrigation need for banana farming under dry soil and desert climate conditions varied greatly depending on the weather conditions. Under sunny conditions, the irrigation need was about 17% higher than the normal conditions, while under rainy conditions, the irrigation need was close to zero.

B. Crop-Specific Water Requirement Trends

Analysis of the data showed that there were varying irrigation demands depending on the type of crop, with water-demanding crops like banana and rice requiring more irrigation, while less water-demanding crops needed less irrigation. Higher temperatures, especially between 20-30°C, resulted in increased irrigation demands due to high evapotranspiration rates.

The proposed system was able to vary irrigation demands depending on the trends, unlike the conventional systems that relied on thresholds to irrigate all crops uniformly.

TABLE I
CROP-WISE WATER REQUIREMENT UNDER DIFFERENT WEATHER CONDITIONS

Crop Type	**Weather**	**Temperature Range**	**Water Requirement (liters/unit area)**
Banana	Sunny	20–30°C	High
Banana	Rainy	20–30°C	Very Low
Rice	Normal	10–20°C	High
Wheat	Sunny	20–30°C	Medium
Sugarcane	Windy	20–30°C	Very High

C. Effect of Weather Conditions

The effect of weather conditions on irrigation was significant. Irrigation was increased in sunny and windy weather due to higher evaporation rates, while it was avoided or reduced in rainy weather. The proposed system dynamically incorporated weather conditions to avoid irrigation in rainy weather, thus conserving water resources.

TABLE II
IMPACT OF ENVIRONMENTAL CONDITIONS ON IRRIGATION REQUIREMENT

Condition	**Observed Trend**	**Irrigation Action**
High Temperature	Increased evaporation	Increase irrigation time
Rainy Weather	Natural soil moisture	Skip irrigation
Windy Climate	Rapid moisture loss	Moderate increase
Clay Soil	High water retention	Reduced irrigation
Dry Soil	Low retention	Frequent irrigation

D. Optimization of Irrigation Time

The suggested model provided accurate water supply by dynamically calculating the irrigation time based on the crop's water requirements from the dataset and the pump's flow rate. Compared to the conventional timer-based irrigation system, the irrigation time was reduced in ideal weather conditions and increased only when required, guaranteeing greater water efficiency.

E. Water Conservation and System Efficiency

The irrigation system was turned on only if needed and varied according to the crop type and weather conditions, resulting in a substantial reduction in water loss and preventing the crop from being waterlogged due to rainfall or high temperatures. The ESP32-based system allowed efficient data transfer and minimized power consumption, ensuring continuous and stable system operation.

F. Discussion

The obtained results clearly show that the combination of IoT-based sensing and cloud-level dataset analysis for decision-making is a more intelligent and adaptive irrigation system compared to the traditional ones. The application of a large and varied dataset allowed for precise crop-aware decision-making, regardless of the environmental conditions. The proposed system not only enhances the precision of irrigation but also helps in sustainable water management.

G. Graphical Analysis of Crop Water Requirement

1) **Average Water Requirement vs Crop Type**

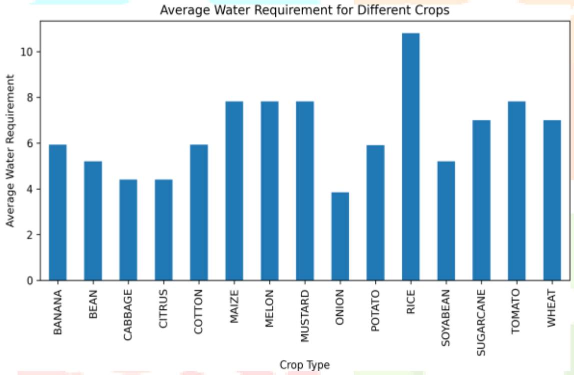

Fig. 4. Average water requirement across different crop types

Figure 4 depicts the average water requirement of various crops, which clearly shows that water-intensive crops like rice, sugarcane, and banana require substantially more irrigation water than crops like mustard and bean, thus underlining the need for crop-specific irrigation.

2) **Effect of Weather Condition on Water Requirement**

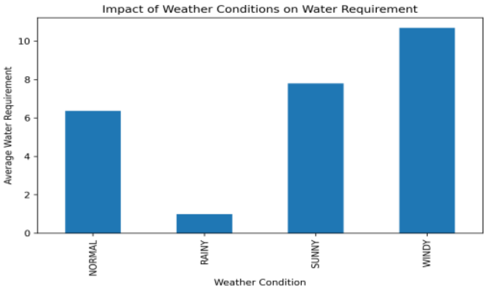

Fig. 5. Variation of water requirement under different weather conditions

Figure 5 explains the effect of weather conditions on the water requirement of crops, where water requirements are high in sunny and windy weather due to high evapotranspiration rates, but decrease in rainy weather, thus underlining the need for weather-specific irrigation.

3) **Water Requirement vs Temperature Range**

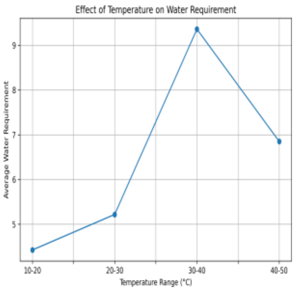

Fig. 6. Effect of temperature variation on crop water requirement

Figure 6 explains the effect of temperature on water requirements, where the water requirement increases with an increase in temperature due to high evaporation rates, thus justifying the need for temperature sensing in smart irrigation systems.

4) **Regional Variation in Water Requirement**

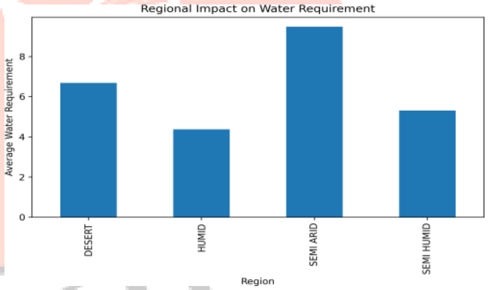

Fig. 7. Regional variation in crop water requirement

Figure 7 explains the variation in water requirements of crops in various regions, where the water requirement is high in hotter regions due to high evaporation rates, thus supporting the need for region-specific irrigation systems.

5) **Soil Type vs Water Requirement**

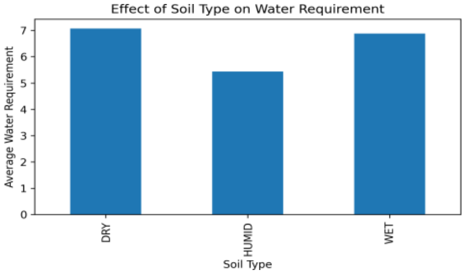

Fig. 8. Influence of soil type on water requirement

Figure 8 explains the effect of soil type on water requirements, where arid soils require more irrigation water than humid soils due to low water retention capacity, thus underlining the need for soil-specific irrigation management.

H. *Comparison Table: Existing vs Proposed System*

TABLE III
Comparison of Existing Irrigation Systems and Proposed System

Parameter	Existing Systems	Proposed System
Irrigation Control	Fixed timers or thresholds	Crop-specific dynamic control
Decision Basis	Soil moisture only	Soil, crop, weather, temperature
Water Usage	High wastage possible	Optimized water utilization
Adaptability	Low	High
Cloud Analytics	Limited or absent	Integrated cloud-based analysis
Weather Awareness	Not considered	Fully integrated
Security Consideration	Rarely addressed	Designed with secure cloud access
Scalability	Limited	Highly scalable
Farmer Interaction	Manual only	Automated with manual override

VI. Conclusion and Future Scope

A. *Conclusion*

This paper presents an IoT– driven approach to smart farming designed to make irrigation beyond simple schedules and into real-time optimization. By interconnecting the field sensors tracking moisture, temperature, humidity, pH and a structured agricultural dataset, we've built a system that understands the specific needs of different crops. Rather than treating every field the same, our architecture uses cloud-based analytics to make intelligent, localized decisions that adapt as environmental conditions shift.

In contrast to the existing timer-controlled or threshold based irrigation systems, the proposed method uses a mathematical irrigation time estimation model to estimate accurate water delivery times. After testing the system against a wide range of datasets, we found that it's remarkably good at adapting its logic to different variables—whether it's a specific crop type, a change in soil composition, or a sudden spike in temperature. This adaptability really paid off; we managed to significantly cut down on water waste without ever letting the soil drop below its ideal moisture levels.

B. *Future Scope*

There is enough room to improve and upgrade the proposed system in order to increase its efficiency and usability. One of the more impactful changes would be integration of live weather APIs; this will allow the system to be predictive rather than being a purely reactive system. The system can be made intelligent by layering it with machine learning. By training the system over machine learning models using historical sensor data and seasonal changes to climate, the irrigation system will become significantly more accurate over time.

Additional upgradation like security measures with blockchain based data integrity and strong authentication can be added to make the system more resilient to cyber attacks. Further, constant security updates can be passed for regular monitoring. The system can be scaled to handle large scale agricultural applications by merging LoRa or NB–IoT communication systems. Furthermore, mobile application support and multiple language support will make the system more usable for farmers in various regions.

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