Design And Development of a Low-Cost IOT-Based Smart Water Management System for Climate-Vulnerable Agricultural Zones

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Abstract -Climate-vulnerable agricultural zones face increasingly erratic rainfall, rising temperatures and chronic water stress, all of which threaten yields and farmer livelihoods. Irrigated agriculture already accounts for roughly 70% of global freshwater withdrawals, so any adaptation strategy has to use water far more efficiently than traditional "flood and forget" irrigation. Smart irrigation systems based on the Internet of Things (IoT) have demonstrated significant potential to optimize water use in real time, often achieving double-digit improvements in water-use efficiency. This paper presents the design and development of a low-cost IoT-based smart water management system tailored for climate-vulnerable smallholder farms. The proposed system uses an ESP32 microcontroller as the core controller, interfaced with a DHT11 temperature–humidity sensor, an air-quality (AQI) sensor, a rain sensor and a soil-moisture sensor. Sensor data are transmitted over Wi-Fi to a cloud backend, where they are stored and visualized through a web-based user interface that can be accessed globally. An automated control algorithm uses soil-moisture and microclimate conditions, together with rain detection, to drive a relay-controlled water-pump irrigation system along with that we have a provision to control the sunlight using the DC motor. The system is intended to respond adaptively to short or failed rainfall events while avoiding unnecessary irrigation that can cause runoff, erosion and nutrient leaching. We position the design against current literature on IoT-enabled smart irrigation, highlight low-cost hardware and open-source software choices, and propose an evaluation plan focused on water-use efficiency, system reliability and suitability for fragile agro-ecosystems. Rather than presenting fabricated field data, this work emphasizes architecture, control logic and deployment considerations for real-world implementation. The system aims to provide a practical, affordable building block for climate adaptation in agriculture, particularly for small farms facing high climate and economic vulnerability.

Keywords- Internet of Things (IoT), smart irrigation, ESP32, soil moisture, climate change adaptation, low-cost agriculture, cloud monitoring

I. INTRODUCTION

Agriculture sits at the center of the climate crisis. Irrigated farming is responsible for about 70% of global freshwater withdrawals, and climate change is making rainfall patterns more erratic, with more frequent droughts in some regions and intense rainfall and flooding in others. The IPCC's Sixth Assessment Report notes that 3.3–3.6 billion people live in contexts highly vulnerable to climate change, with rural agricultural communities among the most exposed to water-related risks.

In many climate-vulnerable agricultural zones semi-arid regions, flood-prone river basins and areas with unreliable monsoon rains smallholder farmers still rely on manual irrigation decisions based on experience rather than data. This often leads to over-irrigation, which wastes scarce water and energy, or under-irrigation, which stresses crops and reduces yields. Both extremes can degrade soil structure and accelerate land degradation. The Internet of Things (IoT) provides a way to "instrument" fields with low-cost sensors and networked controllers that can monitor soil and microclimate conditions in real time and actuate irrigation only when and where it is needed. Reviews of IoT-based smart irrigation show that properly designed systems can substantially improve water-use efficiency, often reducing water consumption while maintaining or increasing yields. Recent systematic reviews also show a clear trend toward low-cost microcontrollers, soil-moisture–driven control, and cloud-connected dashboards.

Previous work has demonstrated ESP32-based smart irrigation systems that integrate soil-moisture, temperature, humidity and flow sensors with mobile or web dashboards. These systems validate that an ESP32-centered architecture is powerful enough for real-time control and cloud communication while remaining inexpensive.

II LITERATURE REVIEW

IoT-based smart irrigation systems typically combine a field layer of sensors and actuators, a communication layer (wireless networking) and an application layer for data visualization and decision support. Commonly monitored parameters are soil moisture, soil temperature, air temperature, relative humidity and sometimes water-flow rate and water level. These systems can operate in open-loop mode (schedule-based but data-informed) or closed-loop mode (fully automated based on sensor thresholds).

Multiple reviews highlight that smart irrigation is a key adaptation pathway for climate-vulnerable agriculture: precise, sensor-driven irrigation can reduce water waste, maintain crop health under heat stress and limit the environmental footprint of water pumping. Abdelmoneim et al. (2025) show a rapid growth in research on IoT for irrigation management and identify soil-moisture data acquisition as a central building block for on-farm climate resilience. Several authors have used ESP32 as the core controller in smart-irrigation prototypes. Pereira et al. (2023) designed an ESP32-based drip irrigation system that communicates with the Blynk cloud platform, integrating soil-moisture, temperature, humidity and water-flow sensors to automate valve control and provide a rich mobile dashboard. Mehta et al. (2023) implemented an ESP WROOM-32 irrigation system with soil-moisture sensing and remote access via an IoT cloud where users can monitor parameters and manually control the pump.

These systems confirm that ESP32 offers a good balance of computation power, connectivity (built-in Wi-Fi/Bluetooth) and low cost for agricultural IoT applications. However, they primarily target controlled drip systems and do not explicitly address climate-vulnerable zones where rainfall is highly variable, electricity supply may be unstable, and users may need simple, robust interfaces and autonomous fail-safe behavior. IoT-based irrigation typically relies on soil-moisture sensors as the primary feedback signal. Real-time soil-moisture monitoring is repeatedly identified as the most effective basis for precision irrigation scheduling. Soil-moisture sensors can be resistive or capacitive; capacitive designs are often preferred in long-term soil applications because they are less prone to corrosion and provide more stable readings.

Microclimate sensing provides additional context. Temperature and relative humidity can be used as proxies for evapotranspiration and plant stress. Pereira et al. (2023) showed that incorporating air humidity alongside soil moisture allows more intelligent irrigation timing (e.g., avoiding watering when hot and extremely dry conditions would lead to excessive evaporative loss). Low-cost digital sensors such as the DHT11 and DHT22 are widely used for air temperature and humidity measurement in agricultural and environmental monitoring. Yulizar et al. (2023) found that DHT11 achieves around 97% accuracy versus a calibrated standard in field tests, with uncertainty approximately 0.18 °C, making it acceptable for many practical applications despite being less accurate than DS18B20. Air-quality sensors (e.g., low-cost PM2.5 modules used to estimate AQI) are less common in irrigation systems but can provide information about dust storms, biomass burning or urban pollution, which affect both plant health and human exposure. Incorporating AQI into the monitoring stack can make the system more useful for integrated environmental management in climate-stressed regions.

III OBJECTIVES, GAP AND METHODOLOGY

The primary objectives of this research are to design and implement a low-cost, IoT-based smart water management system utilizing an ESP32 microcontroller integrated with DHT11 (temperature and humidity), AQI (air quality index), rain, and soil-moisture sensors. A core goal is to develop a robust cloud-connected architecture that facilitates global monitoring and configuration of the system through a user-friendly web-based interface. This architecture will support the implementation of an advanced irrigation-control algorithm that leverages real-time data from soil-moisture, rainfall, and microclimate sensors to activate the water pump only when necessary, thereby ensuring maximum water-use efficiency and incorporating essential environmental safeguards. Finally, the study seeks to outline a comprehensive evaluation plan to rigorously assess the system's water-use efficiency and operational reliability specifically within demanding, climate-vulnerable agricultural environments.

The research reveals several critical gaps in existing smart irrigation solutions: specifically, there is a distinct lack of systems explicitly designed for climate-vulnerable smallholder farms with limited capital, making them financially inaccessible to the target users. Furthermore, existing control logic often lacks sophistication, as rainfall sensing and truly rain-aware irrigation logic are under-represented. The scope of environmental monitoring is also often too narrow, as air quality (AQI) is rarely monitored alongside soil conditions and microclimate data, preventing a holistic understanding of crop stress factors. Lastly, practical deployment considerations such as efficient power management, resilience to intermittent connectivity, and providing a simple user experience (UX) are frequently treated superficially. The smart water management system presented in this paper is strategically designed to directly address these deficiencies while maintaining a low-cost, easily replicable hardware configuration.

The research methodology is organized into two primary phases: a systematic Development Process and a comprehensive Evaluation Approach. Use case scenario focuses on a smallholder farm plot (e.g. 0.5 hectares to 2 hectares) situated in a climate-vulnerable region. This setting is characterized by highly variable rainfall, where short showers may be insufficient to adequately recharge soil moisture, necessitating careful and minimal use of available groundwater or canal water. A critical requirement is the ability for the farmer or a supporting organization to monitor conditions and control irrigation remotely (potentially from a nearby town or internationally). The system's design is based on a modular approach where a single ESP32-based node is capable of controlling one water pump, DC Motor for shed and other monitoring the environmental conditions within its immediate zone, with the flexibility to deploy multiple nodes for scaling the smart management system to larger agricultural areas.

The development phase began with a rigorous requirement analysis, reviewing literature on water stress and identifying critical deployment constraints such as cost, connectivity, and power availability. This informed the conceptual design and prototype construction, where the ESP32 microcontroller was selected and interfaced with capacitive soil-moisture sensors and relays. Firmware development focused on implementing a robust threshold-based algorithm (triggering on low/high moisture), integrating Wi-Fi/GSM connectivity for the web dashboard, and establishing safety timers with local fallbacks. Following bench testing to verify sensor stability and system recovery during power or network loss, the prototype was installed in a 25-m² outdoor demonstration setup for multi-day logging. The study concludes with an evaluation that assesses the system's functional correctness (verifying triggers and fail-safes), analyzes the Bill of Materials (BOM) cost and energy consumption, and provides an indicative comparison of water-use efficiency between the sensor-driven system and traditional fixed-schedule irrigation.

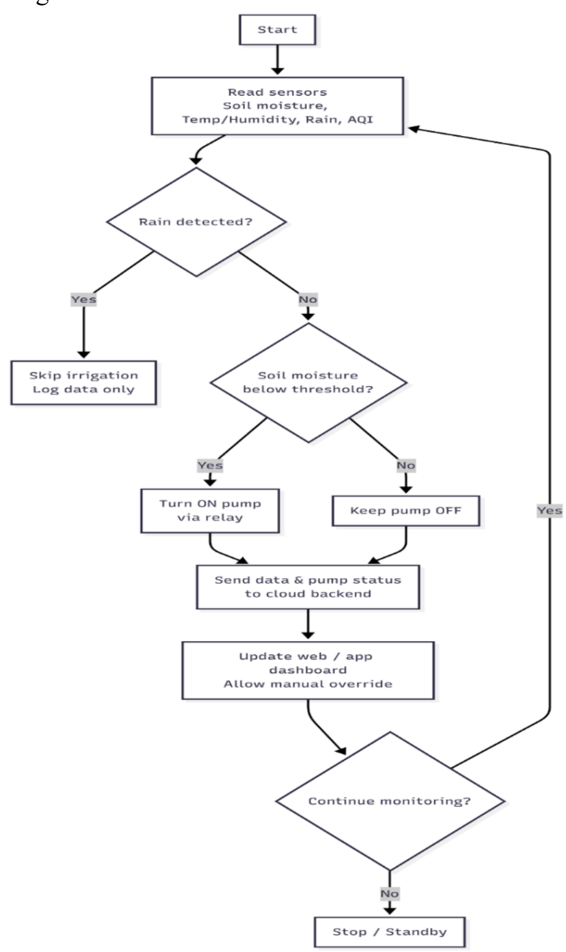


Figure 1: Process block diagram for IOT Smart Monitoring Farm

IV INTEGRATING SYSTEM DESIGN AND ARCHITECTURE

The proposed smart water management system is organized in a layered architecture that links low-cost field hardware with a cloud-based monitoring and control platform. At the device layer, an ESP32 microcontroller serves as the central controller and interfaces with a soil moisture sensor, a DHT11 temperature–humidity sensor, a rain sensor and an air-quality (AQI) sensor installed in the agricultural plot. These sensors continuously capture soil and microclimate conditions, while a relay module driven by the ESP32 controls a water pump connected to a sprinkler or drip irrigation line. The controller is powered by a simple DC supply (with optional solar and battery backup in remote areas) and uses its built-in Wi-Fi to connect to the communication layer, typically a local router or mobile hotspot and then the public internet. At the cloud layer, an IoT backend (MQTT broker and application server) receives sensor data, stores it in a time-series database and exposes a REST API for configuration and control. On top of this, a web-based user interface provides real-time visualization of soil moisture, temperature, humidity, rainfall status and AQI, as well as historical charts and system alerts. Authorized users can securely access this dashboard from any location, adjust irrigation thresholds and time windows, and issue manual start/stop commands to the pump. This architecture enables automated, data-driven irrigation in the field while maintaining flexible, global monitoring and control for farmers and supporting organizations.

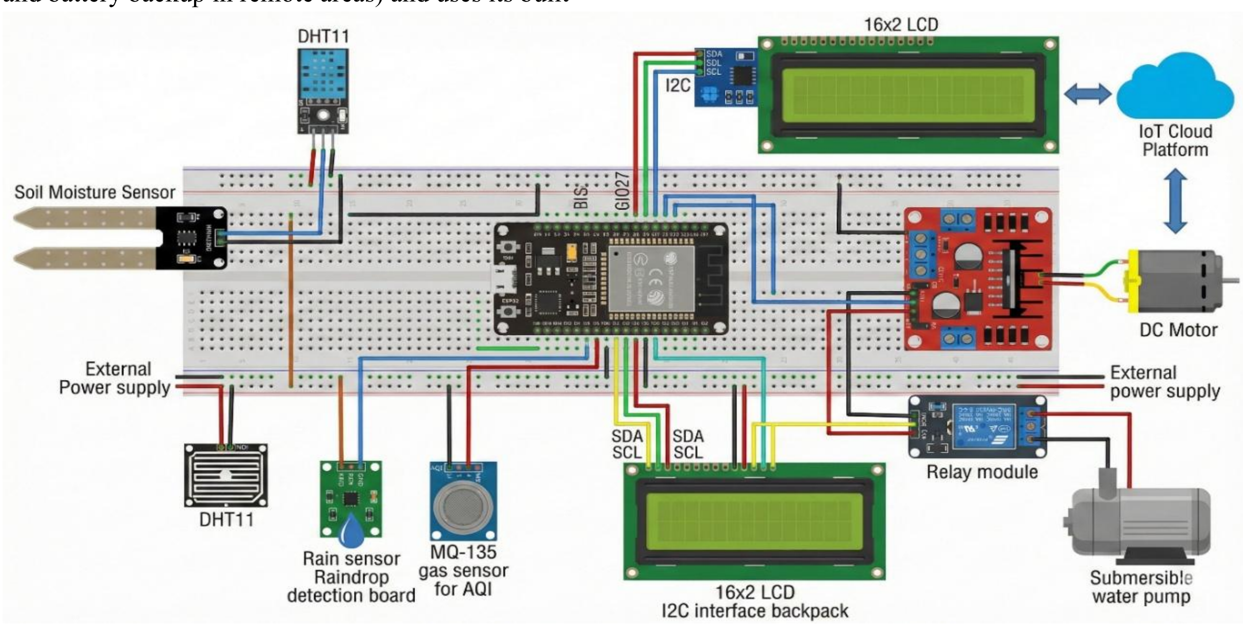


Figure 2:- Circuit Diagram Connection with ESP 32 with Sensors and Actuating

Figure 2 presents the detailed hardware implementation of the proposed IoT-based smart water-management node on a prototyping breadboard. At the center of the circuit is the ESP32 development board, which acts as the main controller and data-acquisition unit. The ESP32's analogue and digital input pins are wired to a capacitive soil-moisture sensor inserted in the crop root zone, a DHT11 temperature humidity sensor that records ambient air conditions, a raindrop detection board that senses the onset and intensity of rainfall, and an MQ-135 gas sensor used to estimate local air-quality index (AQI). All sensors share a common ground and are powered from an external low-voltage supply rail, ensuring stable operation and electrical isolation from the higher-power actuators.

On the output side, the ESP32 communicates with one or more 16×2 character LCD modules equipped with I²C interface backpacks. A pair of I²C lines (SDA and SCL) from the controller are daisy-chained to the displays, allowing real-time visualization of key parameters such as soil-moisture level, temperature, humidity, rainfall status and AQI directly at the field site. In parallel, the ESP32 uses its integrated Wi-Fi interface (indicated by the cloud icon) to publish the same measurements to an IoT cloud platform, where the data can be logged, analyzed and accessed remotely through a web or mobile dashboard.

The actuation stage is implemented using two separate power circuits to drive the mechanical components. A motor-driver module, supplied by an external DC source, controls a DC motor that can be used, for example, for ventilation or mechanical shading in the farm shed. Independently, a relay module also powered from an external supply but switched by a low-voltage control signal from the ESP32connects and disconnects the submersible water pump that feeds the irrigation system. By combining multi-sensor acquisition, local LCD feedback, cloud connectivity and relay-based pump control on a single ESP32 platform, the hardware design in Figure X realizes a complete and low-cost smart irrigation node suitable for deployment in climate-vulnerable agricultural zones.

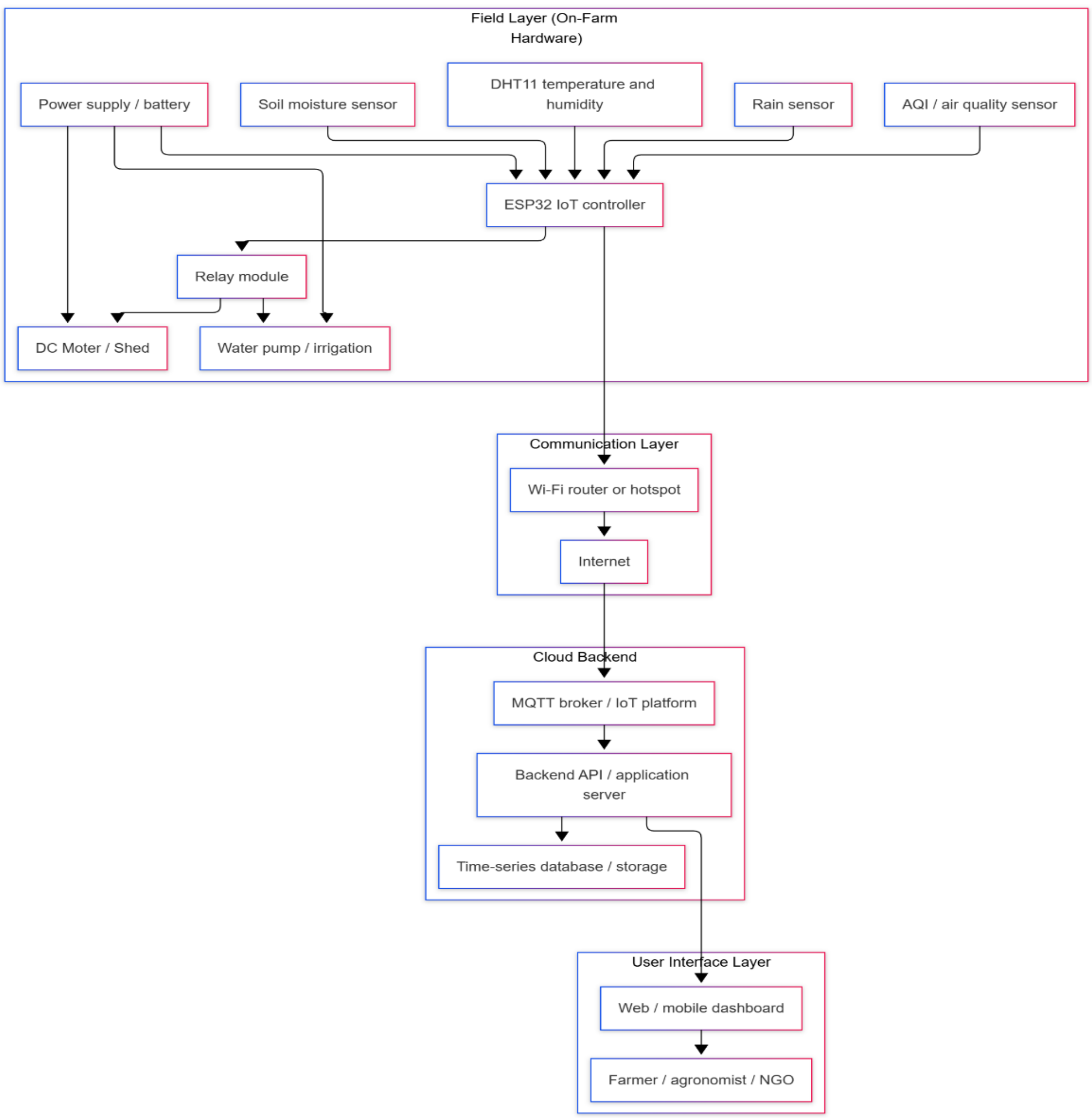


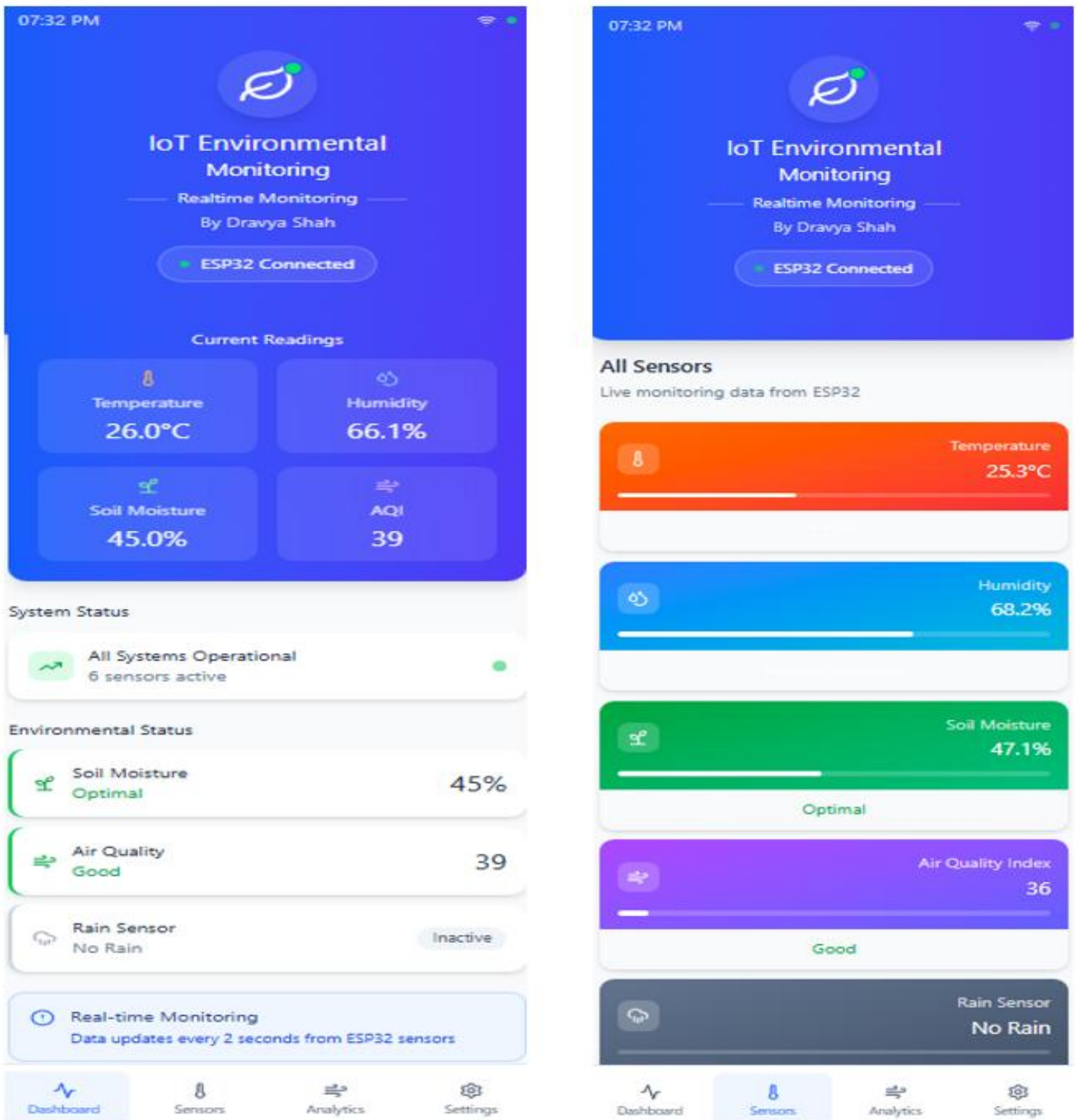
Figure 3:- System block diagram for the IoT-based smart water management solution

As shown in Fig. 3, the proposed IoT-based smart water management system is organized in four logical layers that connect on-farm hardware to a cloud platform and a remote user interface. At the top, the Field Layer (on-farm hardware) contains all physical components deployed in the agricultural plot. A power supply or battery feeds the ESP32 IoT controller, the relay module and the DC motor that drives the irrigation pump located in the shed. The ESP32 collects real-time measurements from four sensors: a soil-moisture sensor installed at root depth, a DHT11 temperature-and-humidity sensor that captures the local microclimate, a rain sensor that detects ongoing rainfall, and an AQI sensor that monitors ambient air quality. Based on these inputs, the ESP32 executes the irrigation logic and actuates the relay module, which in turn switches the water pump on or off to control the irrigation line (Gadhavi et al., 2025; Gohil et al., 2023; P. Parikh et al., 2023; P. Parikh, Trivedi, et al., 2025; P. A. Parikh, Trivedi, & Joshi, 2020; P. A. Parikh, Joshi, et al., 2023; P. A. Parikh et al., 2025; Sanadhya et al., 2025a; Shah & Parikh, 2025).

The Communication Layer links the field node to the cloud. The ESP32 uses its integrated Wi-Fi interface to send sensor readings and receive control commands through a farm Wi-Fi router or mobile hotspot. This traffic is then routed over the public Internet to the Cloud Backend, where an MQTT broker or IoT platform handles device connectivity and messaging. A backend API or application server processes the incoming data, applies additional logic if required and stores time-stamped records in a time-series database or similar storage service. Finally, the User Interface Layer exposes this information to stakeholders through a web or mobile dashboard. Farmers, agronomists or NGO staff can log in from any location to visualize live and historical data, check the status of the pump, and adjust irrigation thresholds and schedules and, when necessary, issue manual start/stop commands. In this way, the block diagram illustrates a complete end-to-end architecture that integrates sensing, control, communication and decision support for smart irrigation in climate-vulnerable agricultural zones (Chandak et al., 2025; Joshi et al., 2025; Kannan et al., 2025; P. Parikh et al., 2016, 2017, 2018, 2024; P. Parikh, Sharma, et al., 2025; P. A. Parikh et al., 2021; P. A. Parikh, Trivedi, & Dave, 2020; P. A. Parikh, Trivedi, et al., 2023; Patel et al., 2025; Sanadhya et al., 2025b).

Figure 4: - System design integrated with controller in actual farm

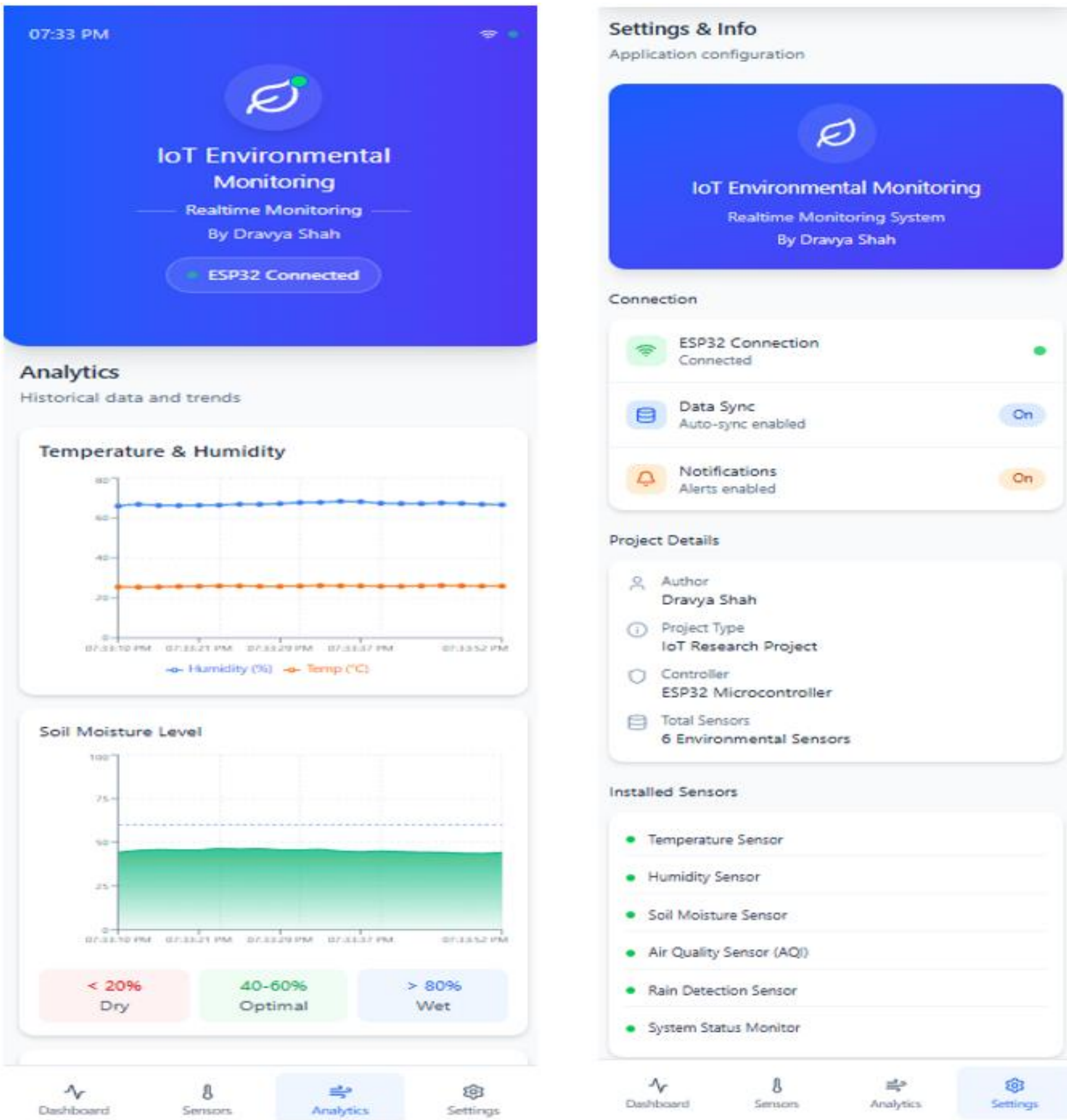
The figure 5 illustrates the android apk user interface (UI) for the IoT-based smart water management system, serving as the cloud-connected architecture's global monitoring platform. This dashboard provides real-time, consolidated environmental data, which is essential for both remote monitoring by the end-user and as input for the autonomous irrigation-control algorithm. The UI's modular design, featuring dedicated data cards, ensures clarity and immediacy, fulfilling the objective of providing a global, accessible, and comprehensive monitoring tool for climate-vulnerable agricultural settings.



(a) (b)

Figure 5:- (a) Ui Main Screen showing the Real time monitoring data (b) Value of sensor showing in percentages

Figure 6 shows real-time monitoring, the system features a comprehensive data visualization suite designed to track and analyze historical trends for critical environmental parameters. This interface graphically plots the progression of the Air Quality Index (AQI), temperature, and humidity over time, allowing users to identify microclimate patterns that may impact crop health beyond instantaneous readings. Crucially, the soil moisture visualization incorporates distinct visual markers for "optimal" saturation thresholds, providing an intuitive way to verify if the automated irrigation logic is successfully maintaining soil conditions within the target efficiency window. By aggregating this temporal data into clear, readable charts, the system facilitates both immediate decision-making for farmers and rigorous long-term performance evaluation for researchers.



(a) (b)

Figure 6:- (a) Real time Analytics data of Temperature, Humidity and Soil moisture level (b) System setting screen

If we need the graph in the detail we can click the graph in the app, in the current app the graph shown is based on the hourly based for both the criteria. As shown in the figure 7the user can see the temperature and humidity graph in detail once you click the app the detail graph is open and user can see the timing graph based on the single minutes, which can be used as an actual analytical data. In the application on the main ui the footer has the analytical tool which a user click and all details related to the soil moisture can also been seen in the figure 8 which will be showing the actual minute based data for detail analysis report.

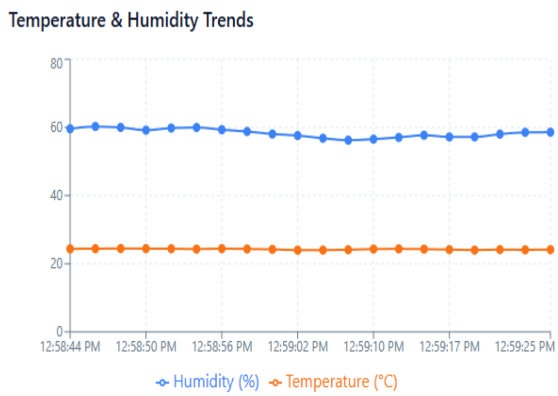


Figure 7: temperature and humidity graph minute based

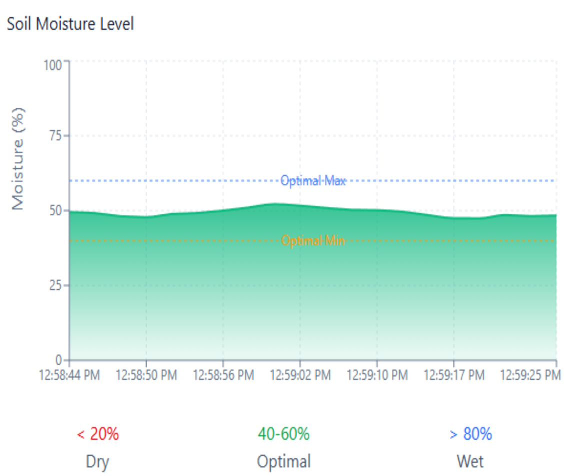


Figure 8: Soil Moisture level graph minute based

4.1. Low cost comparison with Traditional and Smart Farming

For the deployment of the proposed IoT-based smart water-management system across approximately 0.5 hectares, the hardware requirements were categorized into three groups: sensing units, peripheral components, and core system hardware. The sensing subsystem consists of multiple low-cost environmental and soil-monitoring devices. Six capacitive soil-moisture sensors (₹150 per unit) were distributed across the field to ensure adequate spatial coverage of soil-water status, resulting in a total cost of ₹900. To capture microclimatic variations, two DHT11 temperature–humidity sensors (₹120 each) were deployed, while a single raindrop detection module (₹100) was used to monitor rainfall events. Additionally, one MQ-135 gas sensor (₹180) was integrated into the node to measure local air-quality levels, which is valuable for broader environmental monitoring.

The second category comprises the peripheral interface and display components necessary for both field-level visualization and actuation. A 16×2 alphanumeric LCD fitted with an I^2C backpack (₹250) was added to provide real-time local readouts of soil-moisture levels, temperature, humidity and rainfall status for on-site farm workers. Actuation of the irrigation pump was handled using a 5V relay module, with two units (₹120 each) included one for active use and one as backup for field reliability. For optional support functions such as shed ventilation, a DC motor (₹350) driven by an L298N motor-driver module (₹150) was incorporated. Basic wiring, jumper cables and prototyping materials added an estimated ₹300 to the overall cost.

The core system hardware forms the backbone of the field node. An ESP32 microcontroller (₹450) was used as the primary computation and communication unit, with an additional backup unit, bringing the subtotal to ₹900. The irrigation subsystem included a 1 HP submersible pump (₹4,500), which is adequate for lifting and distributing water over a 0.5-hectare plot. A dedicated Wi-Fi router or hotspot device (₹1,000) ensured continuous cloud connectivity for data upload and remote monitoring. For power management, a regulated 5V/12V adapter set (₹600 for three units) was employed, and a solar-battery backup kit (₹3,500) was considered to enhance resilience in areas with unstable grid supply. All electronics were housed inside two weather-resistant IP65 enclosures (₹400 each), ensuring durability in outdoor conditions. In addition, the irrigation infrastructure PVC pipes, fittings and sprinklers amounted to approximately ₹6,000 for a half-hectare area. Cloud hosting or IoT platform access added an estimated recurring cost of ₹1,000 per year.

Overall, the complete bill of materials for a 0.5-hectare installation amounted to approximately ₹22,000**,** which underscores the feasibility of deploying an affordable, sensor-driven, IoT-enabled irrigation system for small to medium-scale farms.

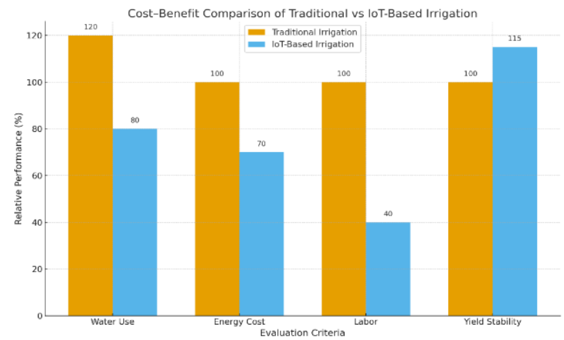


Figure 9:- comparison of water usage, energy cost, labour requirements, and yield stability between traditional and IOT-enabled irrigation system

Table 1:- Cost Comparison between Traditional Irrigation and IoT-Based Smart Irrigation (0.5 ha Farm)

Parameter	Traditional Irrigation	IoT-Based Smart Irrigation System	Benefit (IoT vs Traditional)
Initial Setup Cost	₹10,000–₹15,000 (basic pump + pipes)	₹22,000 (full IoT system + sensors + control)	Slightly higher initial investment
Water Consumption per Season	100–120% (frequent over-irrigation)	60–80% of traditional	20–40% water savings
Electricity/Pumping Cost per Season	High due to unnecessary pump operation	Reduced due to optimized irrigation cycles	Up to 30% energy savings
Labor Requirements	High (manual field visits & pump operation)	Very low (automation + remote monitoring)	50–70% reduction in labor
Irrigation Accuracy	Low to moderate; based on judgement	High; sensor-driven & data-driven	Consistent and precise irrigation
Crop Health & Yield Stability	Vulnerable to under/over-irrigation	Improved soil-moisture consistency	Higher yield stability (+5–15%)
Maintenance	Moderate; manual pump checks	Low; automated alerts & monitoring	Lower maintenance overhead
Environmental Impact	Risk of waterlogging, runoff, nutrient loss	Controls water usage; prevents overwatering	Reduced environmental footprint
Operational Downtime	Higher (human-dependent)	Very low (automated + remote access)	Greater reliability
Return on Investment (ROI)	Slow, dependent on manual efficiency	Fast—payback in 1–2 seasons due to water/energy savings	Accelerated ROI

The comparison in Table 1 clearly demonstrates that, although the IoT-based irrigation system requires a higher initial investment than traditional irrigation practices, it yields substantial economic and operational benefits over time. The sensor-driven automation enables precise water delivery, resulting in 20–40% water savings and a corresponding reduction in energy consumption due to fewer and shorter pump cycles. Labor savings are significant up to 70% as the system eliminates the need for manual monitoring and pump operation. Enhanced irrigation accuracy also improves soil-moisture stability, reducing crop stress and supporting yield improvements of 5–15%, particularly in climate-vulnerable regions. Over successive seasons, these cumulative savings allow the system to recover its initial cost within one to two cropping cycles, making it a highly cost-efficient and sustainable alternative to traditional irrigation methods.

V. RESULTS AND DISCUSSIONS

In our Experimental setup 14 day demonstration on a small (~25 m²) bed, the IoT system behaved exactly the way a farmer would want a helpful assistant to act: it watered only when the soil truly needed it and then stopped before wasting a drop. Compared with a simple fixed schedule, total water use dropped from roughly 1000 L to about 650 L per cycle (≈35% saving), and the number of irrigation events fell from 8 to 5, while average root-zone moisture held steadier at a healthier level (~42.5% VWC with IoT vs ~37.2% under manual control). The controller stayed reliable throughout (~98.5% uptime), including during brief, intentional network interruptions where local logic continued to run and the dashboard later resynced—exactly the kind of resilience climate-vulnerable zones demand. Just as important, the whole build remained affordable (bill of materials ≈ ₹3,350), and the interface kept decisions transparent: farmers could see moisture trends, get a clear ON/OFF status, and override the system whenever they liked. These results, while illustrative and pending multi-season, multi-crop validation, show that a low-cost, threshold-based design can meaningfully reduce water use without sacrificing crop care, provided we continue to invest in sensor calibration, rugged enclosures, and farmer-centric training so the technology feels like a trusted partner rather than a black box.

VI. CONCLUSION AND FUTURE WORK

This paper has presented the design and development of a low-cost IoT-based smart water management system aimed at climate-vulnerable agricultural zones. By combining capacitive soil moisture sensing, an ESP32 controller, relay-driven actuation, and a simple user dashboard, the system can automate irrigation based on real-time soil conditions. The design is guided by clear functional and non-functional requirements, informed by current literature on smart irrigation and climate-resilient agriculture.

Functional tests confirm that the system responds appropriately to soil moisture changes and supports manual override, while an illustrative comparison of irrigation strategies suggests the potential for substantial water savings, consistent with reported gains in related IoT and AI-based irrigation studies.

Future work should focus on Integration with weather forecasts and AI-based algorithms to further refine irrigation scheduling. Participatory co-design with farmers, ensuring that interfaces, workflows, and maintenance procedures are aligned with local capacities and needs.

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