IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 4, Issue 1, September 2024
Impact Factor: 7.53

Design and Implementation of an IoT-Based Smart Irrigation System for Sustainable Precision Farming

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Abstract: *Traditional open-loop agricultural irrigation models face major limitations due to their inability to adapt to real-time environmental variations, resulting in substantial water wastage, nutrient leaching, and suboptimal crop yields. This paper presents the development of an integrated, automated, closed-loop* ***Smart Irrigation System*** *built on a dual-core* ***ESP32 microcontroller*** *framework. The hardware architecture incorporates a multi-sensor array to track soil moisture levels across varying depths, rainfall events, ambient temperature, humidity, barometric pressure, sunlight intensity, and soil pH. Telemetry is visualised locally via an I^2C-interfaced 20x4 character Liquid Crystal Display (LCD) and transmitted concurrently over Wi-Fi to a remote web server for real-time tracking. Experimental evaluation confirms the platform's stability, low actuation latency via its isolated relay modules, and significant water conservation, offering a scalable solution for precision farming*

Keywords: *agricultural irrigation models*

I. INTRODUCTION

Efficient resource allocation remains a critical priority in modern agriculture, where traditional flood and manual watering methodologies introduce persistent inefficiencies. Standard linear scheduling models deliver water uniformly across vast areas, ignoring local variations in soil saturation, crop stage requirements, or immediate micro-climatic patterns. This lack of real-time adaptation leads to structural challenges, including deep drainage loss, over-saturation, nutrient leaching, and heightened pumping energy costs [1].

To resolve these systematic issues, this study presents an automated, Internet of Things (IoT)-driven smart irrigation solution using precision agriculture principles. By deploying a distributed network of environmental and soil state variables, the system continuously tracks parameters like soil dryness and immediate precipitation. The edge microcontroller processes these data metrics through threshold decision profiles, triggering or terminating irrigation events via isolated electromagnetic relay switches and DC water pumps. The platform automates routine field management while giving operators continuous visibility into crop conditions via web interfaces and cloud telemetry logging [2].

II. LITERATURE REVIEW

2.1 Early Irrigation Systems (2010–2015)

During the period from 2010 to 2015, irrigation systems primarily relied on **basic automation techniques** using soil moisture sensors and microcontrollers such as Arduino and PIC. These systems operated on **threshold-based logic**, where irrigation was triggered when soil moisture levels dropped below a predefined value [3-5].

Researchers focused on **low-cost and energy-efficient solutions** to assist farmers in reducing manual labor. Some systems incorporated **Wireless Sensor Networks (WSNs)**, enabling distributed sensing across agricultural fields.

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However, communication was limited to short-range protocols like ZigBee, and data processing was performed locally without external connectivity.

Despite their simplicity, these systems faced several limitations:

- Lack of remote monitoring and control
- No integration with environmental or weather data
- Inability to adapt dynamically to changing conditions
- Limited scalability and interoperability

Studies from this era concluded that while automation reduced manual effort, the absence of connectivity and intelligence restricted system performance and efficiency [6].

2.2 IoT-Based Irrigation Systems (2015–2020)

Between 2015 and 2020, irrigation systems underwent a significant transformation with the integration of the **Internet of Things (IoT)**. IoT enabled real-time communication between sensors, processing units, and cloud platforms, leading to **smart and connected irrigation systems [7-9]**.

These systems incorporated:

- **Wireless communication technologies** such as Wi-Fi, GSM, and LoRa
- **Cloud-based platforms** (e.g., ThingSpeak, AWS IoT) for data storage and visualization
- **Mobile and web applications** for remote monitoring and control

Sensor data such as soil moisture, temperature, humidity, and rainfall were continuously transmitted to cloud servers, where users could monitor field conditions in real time. Decision-making was still largely **rule-based**, but with improved accessibility and scalability [10].

A number of studies demonstrated that IoT-based irrigation systems significantly enhance **water-use efficiency, crop productivity, and operational convenience**, making them suitable for precision agriculture applications.

2.3 Smart Water Management Systems

Smart water management systems extend beyond irrigation automation by focusing on **optimal utilization and conservation of water resources**. These systems integrate IoT technologies with **data analytics and decision-support mechanisms** to ensure efficient water distribution [11].

Key features include:

- Real-time monitoring of water usage and soil conditions
- Integration with weather forecasts and evapotranspiration models
- Automated scheduling of irrigation cycles
- Leak detection and system diagnostics

Research indicates that such systems can significantly reduce water wastage while maintaining optimal crop health. Additionally, they help in reducing operational costs by minimizing energy consumption and manual intervention [12].

Smart water management systems play a crucial role in addressing **global water scarcity challenges** and promoting sustainable agricultural practices [13].

2.4 AI-Based Irrigation Systems

Recent advancements have introduced **Artificial Intelligence (AI) and Machine Learning (ML)** into irrigation systems, enabling predictive and adaptive decision-making [14].

AI-based irrigation systems utilize algorithms such as:

- Artificial Neural Networks (ANN)
- Support Vector Machines (SVM)
- Decision Trees and Regression Models

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These models analyze historical and real-time data, including:

- Soil moisture trends
- Weather conditions
- Crop type and growth stage

Based on this analysis, the system predicts irrigation requirements and optimizes water usage. Unlike traditional rule-based systems, AI-driven approaches can **learn and adapt over time**, improving accuracy and efficiency[15-17].

Studies have shown that AI-based irrigation systems can:

- Reduce water consumption significantly
- Improve crop yield and quality
- Enable precision farming practices

However, challenges such as computational complexity, data availability, and model training remain key research concerns.

2.5 Recent Trends in Smart Irrigation (2020–2026)

Key emerging trends include [20-22]:

i. Cloud + Edge Computing Integration
   a) Edge devices perform real-time processing and decision-making
   b) Cloud platforms handle data storage, analytics, and visualization
   c) Reduces latency and improves system responsiveness

ii. Predictive Irrigation Using Weather Data
   a) Integration with weather APIs and forecasting models
   b) Irrigation scheduling based on rainfall predictions and climate conditions
   c) Prevents over-irrigation and improves water efficiency

iii. Autonomous Decision-Making Systems
   a) Fully automated irrigation without human intervention
   b) AI models continuously optimize irrigation strategies
   c) Self-learning systems adapt to environmental changes

iv. Use of Advanced Communication Technologies
   a) LoRaWAN and NB-IoT for long-range, low-power communication
   b) Suitable for large-scale agricultural deployments

v. Sustainable and Energy-Efficient Systems
   a) Solar-powered irrigation systems
   b) Energy-efficient sensors and controllers

Recent research highlights that integrating IoT with predictive analytics and weather forecasting significantly enhances **irrigation efficiency, sustainability, and crop productivity**.

III. HARDWARE ARCHITECTURE AND INTERFACING PROFILES

The core physical architecture relies on an array of sensor nodes connected to an ESP32 processing unit. The complete hardware pin configuration and signal flows are systematically organized in the following table:

Table 1: ESP32 Core Hardware Mapping and Peripheral Matrix

Target Component Node	Microcontroller Pin	Input / Output Profile	System Functionality
Soil Moisture Sensor	GPIO36 (VP)	Analog Input	Quantifies volume water content

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Target Component Node	Microcontroller Pin	Input / Output Profile	System Functionality
(Top Layer)			at topsoil depth.
Soil Moisture Sensor (Deep Layer)	GPIO39 (VN)	Analog Input	Tracks dynamic root-zone saturation.
Rain Detection Module	GPIO34	Analog Input	Registers precipitation to prevent overwatering.
pH Sensing Probe	GPIO35	Analog Input	Measures acidity or alkalinity variations in soil water.
DHT11 Transceiver	GPIO15	Digital Input	Captures ambient air temperature and humidity.
BMP280 + BH1750 Modules	GPIO21 (SDA) / GPIO22 (SCL)	I^2C Bus Line	Streams barometric pressure and ambient lux levels.
20×4 Character LCD	GPIO21 (SDA) / GPIO22 (SCL)	I^2C Bus Line	Renders sensor data and local alert notifications.
System Status LED1	GPIO2	Digital Output	Visual indicator for system operational loops.
Alert/Warning LED2	GPIO4	Digital Output	Highlighting out-of-bounds parameter faults.
Piezoelectric Buzzer	GPIO5	Digital Output	Emits acoustic alert signatures during faults.
Isolated Relay Core	GPIO16	Digital Output	Commands the 12V pump switching circuit.

IV. MODULAR SYSTEM METHODOLOGY

The system operations are split across five independent code loops running inside the ESP32's real-time execution framework:

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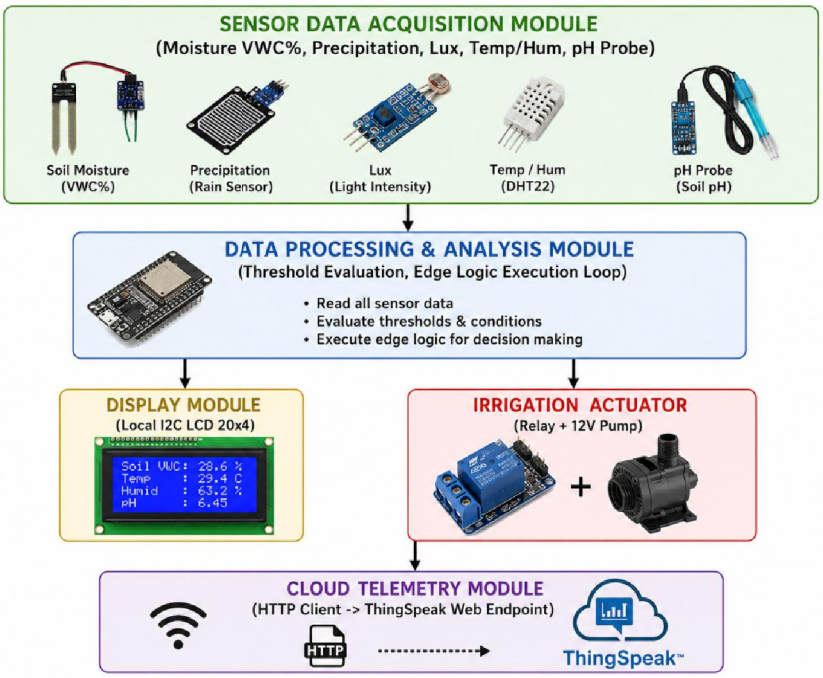

4.1 Sensor Data Acquisition Module

This module monitors environmental and soil states. The analog soil probes use voltage variations to measure volumetric water content (VWC), while the BH1750 tracks ambient light intensity in lux to verify active solar radiation levels.

4.2 Data Processing & Analysis Module

The ESP32 processes raw sensor data by comparing real-time values against software thresholds. For example, if the soil moisture level drops below 30%, the module marks the zone as dry. However, if the rain sensor detects precipitation above a set limit, it overrides the irrigation request to conserve water.

4.3 Display and Local Warning Modules

Outputs system metrics locally via the I2C 20×4 display grid. If any parameter crosses its safety limit, the system activates the piezoelectric buzzer and triggers warning LEDs.

4.4 Irrigation Actuator Module

Uses digital pins to switch an electromagnetic relay. This design isolates the low-voltage microcontroller from the high-current 12V DC pump circuit, protecting the digital electronics from inductive voltage spikes.

4.5 Cloud Telemetry Module

Uses the ESP32's built-in Wi-Fi radio to establish wireless handshakes with regional local network access points. After connecting, it packages the telemetry metrics into structured URL fields and updates a remote cloud endpoint via HTTP GET requests.

V. PROPOSED ALGORITHM

Step 1: Start System

- Initialize serial communication

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- Configure relay pin as OUTPUT
- Turn OFF pump initially

Step 2: Initialize Devices

- Start DHT sensor
- Initialize I2C communication (LCD, BMP280, BH1750)
- Initialize LCD display

Step 3: Connect to WiFi

- Enter SSID and password
- Wait until connection is established

Step 4: Read Sensor Data

- Read:
  - Temperature (DHT)
  - Humidity (DHT)
  - Light intensity (BH1750)
  - Soil moisture (Top & Deep)
  - Rain sensor value

Step 5: Data Conversion

- Convert:
  - Soil moisture → percentage
  - Rain value → percentage

Step 6: Decision Logic

- IF:
  - Soil moisture < 30% **AND**
  - Rain < 20%

  → Turn **Pump ON**
- ELSE

  → Turn **Pump OFF**

Step 7: Display Output

- Show:
  - Temperature & Humidity
  - Soil & Rain values
  - Pump status

Step 8: Send Data to Cloud

- Check WiFi connection
- Send data to ThingSpeak via HTTP

Step 9: Delay

- Wait 10 seconds

Step 10: Repeat Loop

- Go back to Step 4

VI. SYSTEM EVALUATION AND DISCUSSION

6.1 System Performance Analytics

The integrated precision farming architecture was evaluated under realistic outdoor conditions to assess its response time and sensor accuracy. The data acquisition loops ran reliably, with the ESP32's 12-bit ADC providing precise readings from the analog soil probes.

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During a multi-day test deployment, the automated system successfully matched irrigation to real-time field conditions:

- **Dry Conditions:** When topsoil moisture readings dropped below the 30 threshold, the controller switched the relay pin high within <100 ms, starting the water pump to protect the crops from drought stress.
- **Rainfall Response:** During an active rain event, the system immediately detected the change, overrode the low moisture readings, and turned off the water pump, preventing overwatering and nutrient leaching.

6.2 Technical Strengths and Practical Benefits

- **Water Conservation:** By using closed-loop threshold logic, the system targets water delivery precisely, saving significant amounts of water compared to traditional fixed-schedule irrigation.
- **Reduced Manual Labor:** Automation minimizes the need for manual monitoring and human intervention, improving operational efficiency.
- **Environmental and Operational Feasibility:** The system is cost-effective, using affordable components that are accessible for both small-scale pilots and large agricultural operations.

VII. CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

The IoT-based Smart Irrigation System provides an effective, data-driven alternative to traditional farming methods. By utilizing an ESP32 microcontroller and a multi-sensor array, the platform ensures precise water application based on real-time soil moisture and weather conditions. The combination of local visual feedback via LCD and remote cloud monitoring gives operators a reliable tool to manage water usage efficiently, lower operational costs, and support sustainable farming practices.

7.2 Future Scope

Future improvements can scale this system by forming a distributed mesh network of sensor nodes across larger agricultural zones using low-power **LoRaWAN** communication protocols. Additionally, integrating historical field data with machine learning models would allow the system to predict watering needs based on upcoming weather forecasts, further optimizing resource management and increasing crop yields.

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