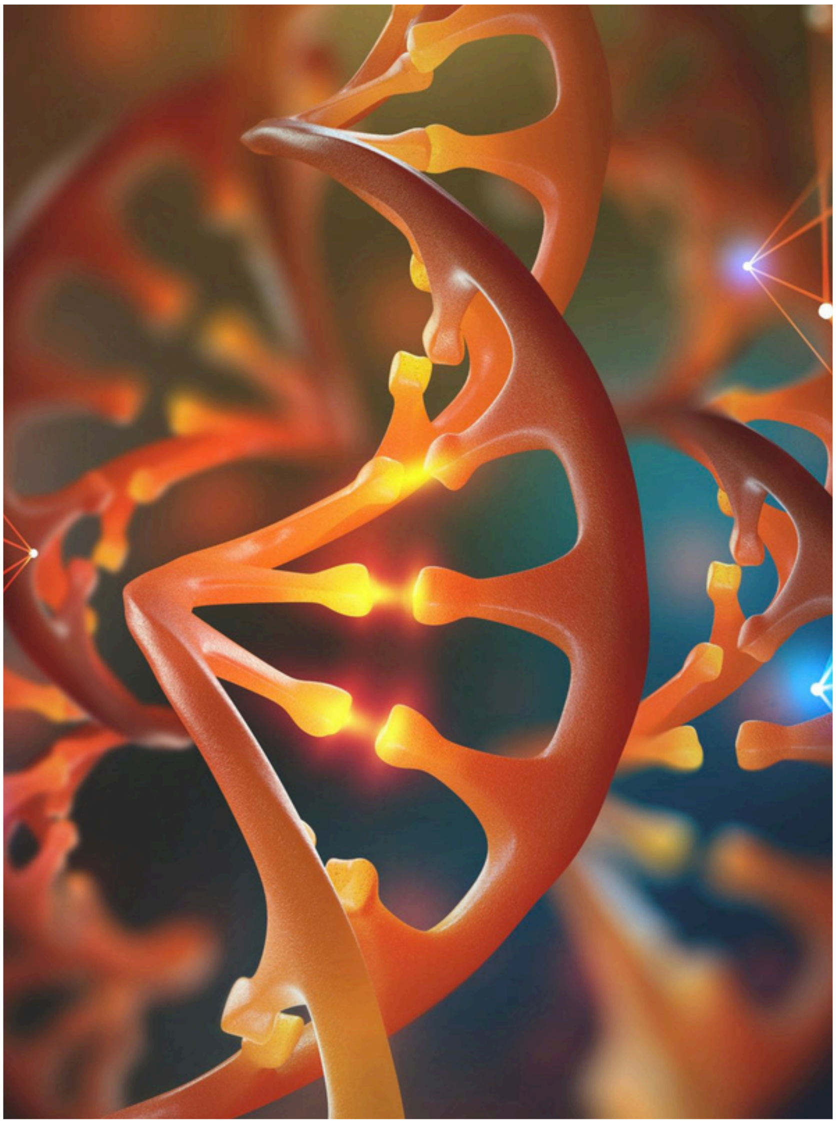
IARJSET

International Advanced Research Journal in Science, Engineering and Technology

A monthly Peer-reviewed (Refereed) journal

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588



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DOI 10.17148/IARJSET

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.311 ⵋ Peer-reviewed & Refereed journal ⵋ Vol. 13, Issue 1, January 2026

DOI: 10.17148/IARJSET.2026.13139

IOT-Based Smart Irrigation System with Real-Time Monitoring and Integrated Weather Forecast

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Abstract: Efficient water management has become a major challenge in modern agriculture due to increasing water scarcity and unpredictable climatic conditions. Conventional irrigation methods operate without real-time feedback from the field, often leading to excessive water usage and reduced crop efficiency. This paper presents the development of an Internet of Things (IoT) based smart irrigation system using an ESP32 microcontroller integrated with environmental and flow sensors. The system continuously monitors soil moisture, ambient temperature, humidity, and rainfall to determine irrigation requirements. A water flow sensor is employed to measure the exact quantity of water delivered during each irrigation cycle. Cloud-based weather information is obtained using the OpenWeather API, while real-time monitoring and control are achieved through the Blynk IoT platform. Irrigation is automated based on soil moisture conditions, with rainfall given the highest priority to prevent unnecessary watering. Experimental evaluation shows that the proposed system significantly reduces water wastage while providing accurate monitoring of irrigation parameters. The solution is low-cost, scalable, and suitable for practical deployment in smart agriculture applications.

Keywords: Internet of Things (IoT), Smart Irrigation System, ESP32 Microcontroller, Soil Moisture Monitoring, Water Flow Measurement, Automated Irrigation, Cloud-Based Agriculture

I. INTRODUCTION

Due to increasing water scarcity, irregular rainfall patterns, and rapidly changing climatic conditions, effective water management has become one of the most critical challenges faced by the agricultural sector. Agriculture consumes a significant portion of global freshwater resources, and inefficient irrigation practices contribute substantially to water wastage. Traditional irrigation methods often rely on manual operation or fixed time-based schedules, supplying water without considering real-time soil and environmental conditions. Such practices frequently result in over-irrigation or under-irrigation, leading to water loss, soil degradation, nutrient leaching, and reduced crop productivity. Over time, these inefficiencies increase operational costs and negatively affect soil fertility and crop yield.

To overcome these limitations, technology-driven approaches—particularly those based on the Internet of Things (IoT)—have gained significant attention. IoT-enabled irrigation systems facilitate continuous monitoring of agricultural fields and enable automated decision-making using real-time data. By integrating sensors, microcontrollers, and wireless communication technologies, these systems collect accurate information on soil moisture, temperature, humidity, and other environmental parameters that directly influence irrigation requirements. The adoption of IoT in agriculture has shown promising results in reducing water wastage, improving crop health, and minimizing the need for constant human supervision.

Simple yet effective technological interventions play an important role in supporting farmers and gardeners in managing water resources efficiently. Continuous monitoring of soil moisture helps identify the actual water needs of plants, ensuring irrigation is performed only when required. Temperature and humidity sensing provide additional environmental context, allowing better understanding of crop water demand under varying climatic conditions. Automatic control of water pumps eliminates manual intervention and ensures timely irrigation based on predefined thresholds. Additionally, remote access through mobile applications enables users to monitor system performance and irrigation status from any location, thereby saving time and reducing labour dependency.

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Timely irrigation is essential for healthy plant growth and for preventing crop stress caused by insufficient or excessive watering. Prolonged water stress can lead to stunted growth, reduced yield, and increased vulnerability to pests and diseases. Early detection of soil dryness ensures that irrigation is provided before crops reach critical stress levels. The proposed system addresses this requirement by using real-time sensor data to assess soil moisture continuously and trigger irrigation only when moisture levels fall below a predefined threshold.

As illustrated in Fig. 1.1, the proposed smart irrigation system integrates IoT technology to provide a reliable and efficient solution for monitoring agricultural parameters and automating irrigation operations. A rule-based automation approach is implemented using an ESP32 microcontroller as the central control unit. The system continuously monitors soil moisture, temperature, and humidity, and activates the water pump only when necessary. A user-friendly mobile interface allows real-time visualization of sensor data and manual control when required. This cost-effective solution demonstrates the effective application of IoT technology in conserving water and supporting sustainable agricultural practices.

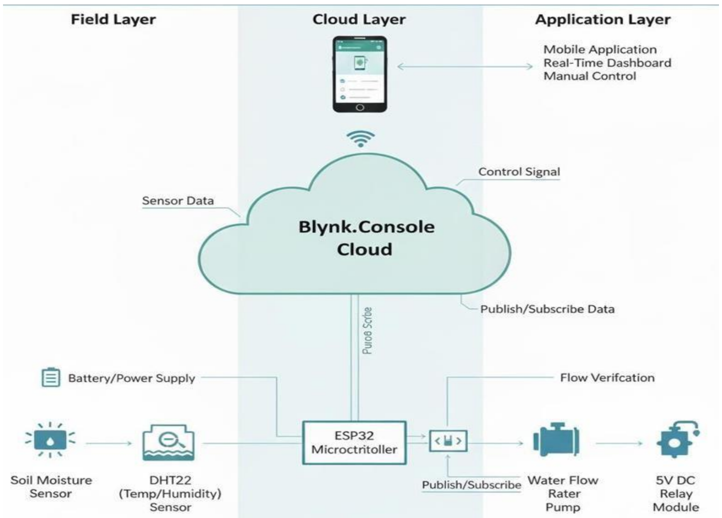

Fig 1.1 Proposed System

II. LITERATURE SURVEY

A literature survey was conducted to review existing research on automated and IoT-based irrigation systems, with the aim of understanding recent developments and identifying limitations that motivate the proposed work. Several studies have explored the application of IoT technologies to automate irrigation and improve water management in agriculture.

Kamaldin et al. (2019) proposed an IoT-based smart irrigation system using soil moisture sensors to automate irrigation and reduce water wastage. The system enabled remote monitoring and minimized human intervention. However, it assumed successful irrigation once the pump was activated and did not include any mechanism to verify actual water delivery or account for environmental factors such as rainfall.

Ghorpade and Patil (2019) presented an automated irrigation system based on soil moisture threshold logic with IoT connectivity. While the system improved water utilization and reduced labour requirements, it relied on fixed threshold values and lacked adaptability to varying field conditions. Additionally, real-time water flow verification was not implemented.

Kumar and Singh (2020) developed an IoT-based smart watering system integrating soil moisture sensing with cloud-based monitoring. Although the system enhanced automation and data visibility, it did not measure the volume of water delivered during irrigation and lacked extensive validation across different soil and environmental conditions.

From the literature, it is evident that most systems emphasize automation and remote monitoring while assuming effective irrigation after pump activation. The proposed system addresses these limitations by incorporating water flow measurement, rainfall detection, and cloud-based monitoring for improved irrigation reliability.

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III. METHODOLOGY

The proposed system employs a modular, pipeline-based methodology that systematically monitors field conditions and automates irrigation decisions using real-time sensor data. The approach prioritizes efficient water usage, reliability, and minimal human intervention while remaining cost-effective and scalable for agricultural deployment. The system integrates soil and environmental sensing, rule-based decision logic, flow verification, cloud communication, and mobile-based monitoring into a unified framework. All processes operate continuously to ensure timely irrigation while preventing over-watering under varying environmental condition results & Discussions

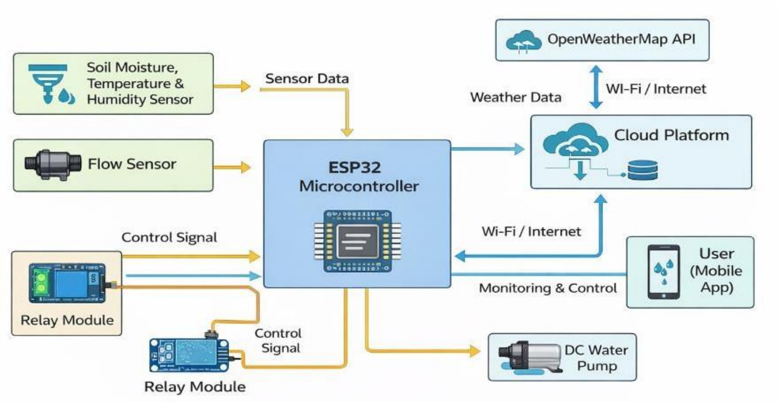

Fig 3.1 Block Diagram

[1]. Sensor Data Acquisition

The methodology begins with continuous acquisition of real-time data from field-deployed sensors. A soil moisture sensor measures the volumetric water content of the soil, while a temperature and humidity sensor captures ambient environmental conditions. A rain sensor detects rainfall events, and a water flow sensor measures the quantity of water delivered during irrigation. These sensors provide the primary inputs to the system and enable accurate assessment of irrigation requirements.

[2]. Data Processing and Threshold Evaluation

The ESP32 microcontroller serves as the central processing unit, periodically reading sensor values and comparing them against predefined and calibrated threshold levels. Soil moisture readings are evaluated to determine whether irrigation is required, while environmental parameters provide contextual awareness. Threshold values are selected based on crop requirements and field conditions, ensuring reliable and repeatable operation.

[1]. **Decision Logic and Irrigation Control**

Based on the evaluated sensor data, a rule-based decision mechanism determines the irrigation action. If the soil moisture level falls below the defined threshold and no rainfall is detected, the ESP32 activates the irrigation process. Rainfall detection is given the highest priority; if rain is present, irrigation is immediately suspended irrespective of soil moisture conditions. This logic prevents unnecessary watering and protects crops from over-irrigation.

[2]. **Pump Actuation and Flow Verification**

When irrigation is triggered, the ESP32 activates a relay module to switch ON the water pump. During pump operation, the water flow sensor generates pulses proportional to the rate of water flow. These pulses are counted and converted into volume units to calculate the total quantity of water delivered. This step provides physical verification of irrigation, ensuring that water delivery is accurately measured rather than assumed.
The system captures real-time sensor data and transforms it into irrigation actions through sequential processing: sensor readings are acquired, analysing and translated into control signals for pump operation. The verified irrigation data is then forwarded to the monitoring module, as illustrated in Fig. 1.

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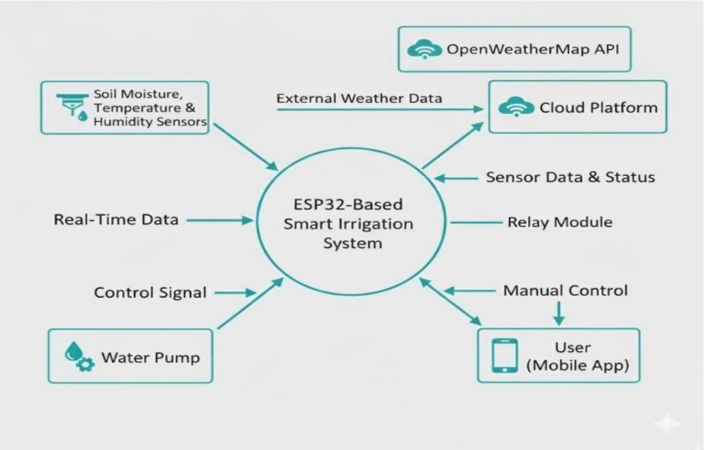

Fig 3.2 Data Flow Diagram – Level 0

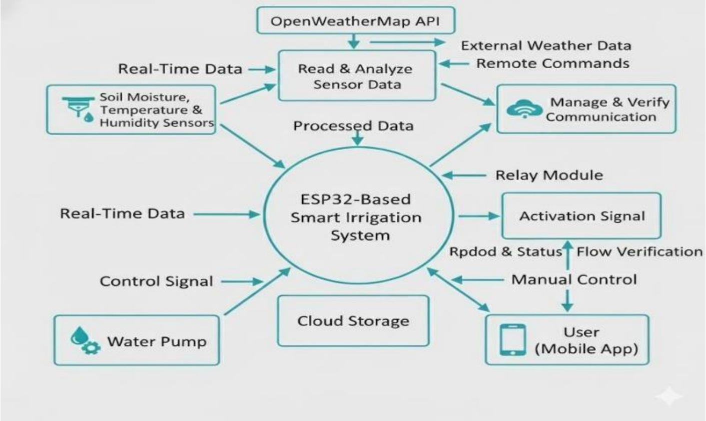

Fig 3.3 Data Flow Diagram – Level 1

IV. SYSTEM IMPLEMENTATION AND PERFORMANCE EVALUATION

The proposed IoT-based smart irrigation system was implemented using an ESP32 microcontroller as the central control unit, integrating sensor modules, cloud services, and a mobile-based monitoring interface. The system combines real-time soil and environmental sensing with weather forecast data to enable intelligent, automated irrigation decisions aimed at efficient water resource management.

4.1 System Implementation

The ESP32 firmware was designed to initialize sensor interfaces, establish Wi-Fi connectivity, and communicate with cloud services. Soil moisture sensing was used to determine the water content of the soil, while temperature and humidity data were acquired using a DHT sensor to provide environmental context. A water flow sensor was integrated to physically verify irrigation by measuring the actual volume of water delivered. In addition, real-time and forecast weather data were retrieved from the OpenWeather API using HTTP requests and parsed using JSON-based processing.

A rule-based decision logic was implemented within the ESP32 to control irrigation. When soil moisture fell below a predefined threshold and no rainfall was predicted, the relay module was activated to switch ON the water pump. Rainfall prediction was given the highest priority, ensuring that irrigation was skipped during forecasted rain events regardless of soil moisture conditions. Flow sensor feedback was continuously monitored to confirm successful water delivery during pump operation.

The system communicated with the Blynk IoT cloud platform to transmit sensor readings, pump status, water usage data, and weather information. A mobile dashboard provided real-time visualization of system parameters and allowed users to manually control the pump when required. This modular design ensured real-time operation, scalability, and ease of maintenance.

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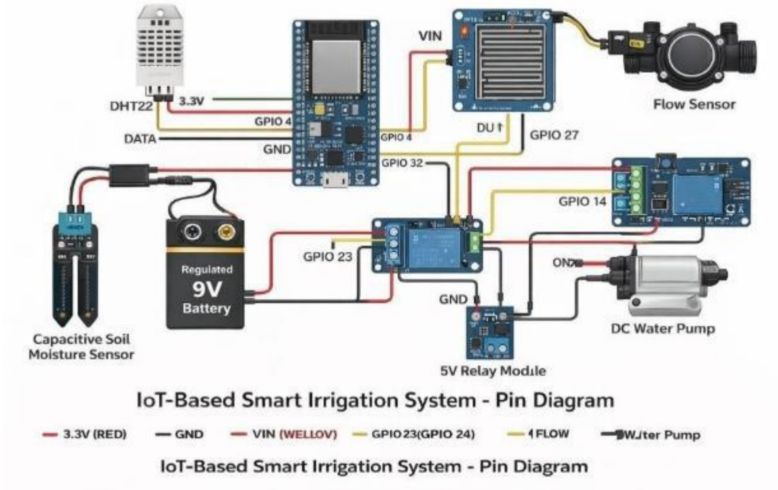

Fig 4.1 ESP32 Pin Configuration and Sensor–Actuator Interfacing Diagram

4.2 Performance Evaluation and Results

The system was evaluated under varying soil moisture levels, environmental conditions, and weather forecast scenarios to assess its reliability, responsiveness, and irrigation accuracy. Performance metrics included pump response behavior, system response time, water flow verification, and reduction of unnecessary irrigation events.
Experimental observations confirmed that the pump was activated and deactivated correctly based on sensor thresholds and weather forecasts. The response time between condition detection and pump actuation was minimal, enabling effective real-time irrigation control. Integration of weather forecast data significantly improved decision accuracy by preventing irrigation during predicted rainfall, resulting in improved water usage efficiency.
An irrigation decision matrix, analogous to a confusion matrix, was used to evaluate system decisions. High decision accuracy was observed, with correct pump activation during dry soil conditions (True Positives) and correct pump suppression during adequate moisture or rainfall prediction (True Negatives). False irrigation events were minimal, indicating reliable differentiation between irrigation and non-irrigation conditions.
Water flow verification further enhanced system reliability by confirming physical irrigation whenever the pump was ON and detecting dry-run or failure conditions immediately. Scenario-based testing—including dry soil, wet soil, rainfall forecast, manual override, and pump-without-flow cases—demonstrated that observed system behavior closely matched expected outcomes.

4.3 Overall System Behaviour Analysis

The system was tested under multiple scenarios:

Scenario	Expected Behaviour	Observed Result
Dry soil, no rain	Pump ON	Correct
Wet soil	Pump OFF	Correct
Rain forecast	Pump OFF	Correct
Manual override	Pump ON/OFF	Correct
Pump ON, no flow	Alert condition	Correct

The observed results closely matched expected outcomes, proving the system's consistency and correctness.

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5. RESULTS AND DISCUSSION

The results validate that combining real-time sensor data with predictive weather information enables smarter irrigation decisions compared to sensor-only approaches. The inclusion of flow verification ensures that irrigation decisions are not only logical but also physically validated. Overall, the system demonstrated stable cloud connectivity, accurate monitoring, reduced water wastage, and reliable operation.

The proposed implementation proves to be a robust, cost-effective, and scalable smart irrigation solution suitable for real-world agricultural deployment.

Fig 5.1 Prototype Model

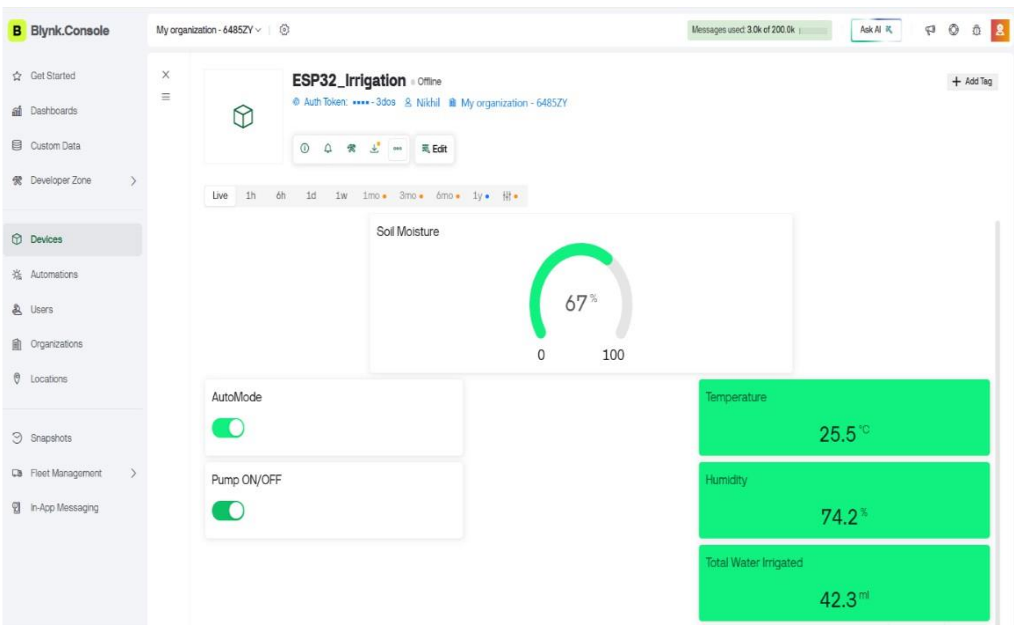

Fig 5.2 Real-Time Dashboard Monitoring

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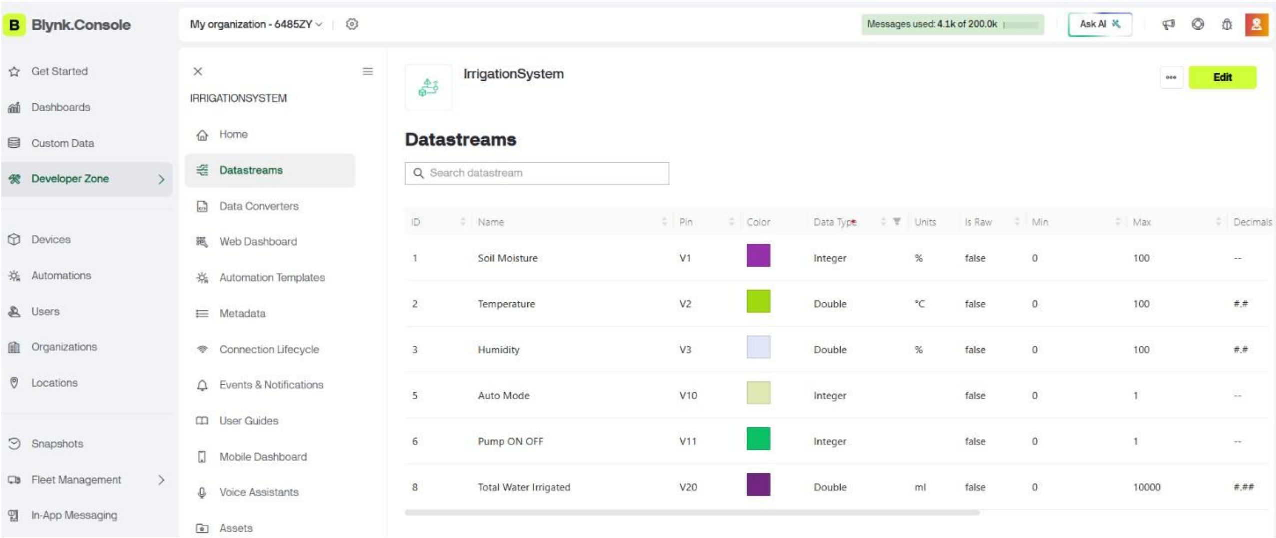

Fig 5.3 Parameters

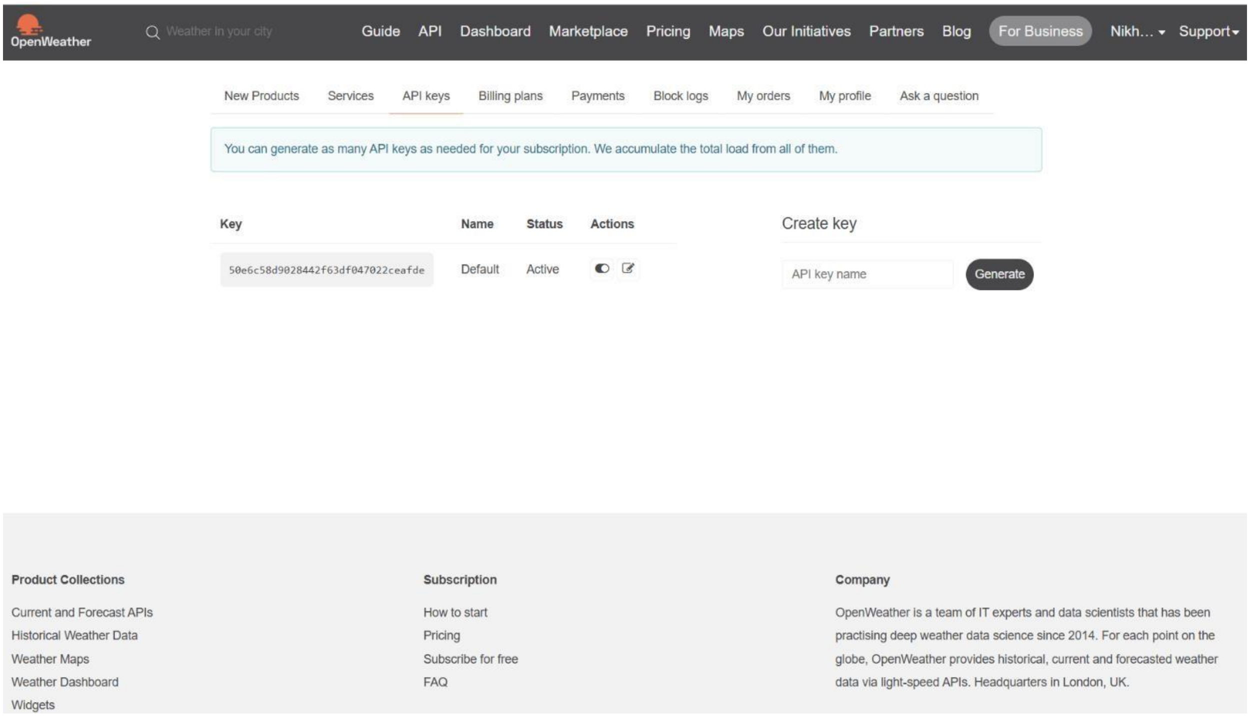

Fig 5.4 Open-Weather API-Key Integration

6. CONCLUSION

This research work successfully demonstrated the design and implementation of an IoT-based smart irrigation system using an ESP32 microcontroller integrated with multiple environmental sensors and cloud services. The system effectively automates irrigation by continuously monitoring soil moisture conditions and prioritizing rainfall detection to prevent unnecessary watering. The inclusion of a water flow sensor provides physical verification of irrigation, ensuring that water delivery is accurately measured rather than assumed, which addresses a major limitation observed in many existing irrigation systems.

The experimental results confirm that the proposed system significantly reduces water wastage while maintaining optimal soil moisture levels for crops. Real-time visualization through the Blynk IoT platform enhances transparency and usability, allowing users to remotely monitor irrigation status and environmental conditions. The integration of cloud-based weather information further improves decision-making by providing environmental awareness.

Overall, the proposed system offers a reliable, cost-effective, and scalable solution for smart irrigation, making it suitable for adoption in modern agricultural practices and small-to-medium scale farming environments.

6.1 Future Scope

Future enhancements to the proposed system may include the integration of machine learning algorithms for predictive irrigation, solar-powered operation for improved energy efficiency, and advanced data analytics for long-term assessment of water usage and irrigation patterns.

ACKNOWLEDGMENT

I extend my deepest gratitude to **Professor Nidhi Hebbar**, my project guide, for her unwavering guidance and support throughout this endeavour. My sincere thanks also go to the dedicated faculty and staff at the National Institute of Engineering, Mysuru, for their invaluable resources and assistance. I am profoundly thankful to my friends and classmates for their camaraderie and encouragement, as well as to my parents for their steadfast backing. Finally, I acknowledge with appreciation everyone who contributed directly or indirectly to the successful completion of this project.

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Impact Factor 8.311

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Certificate of Publication

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