Design and Implementation of an IoT-Based Smart Garden System for Efficient Water Management in Residential Environments

Dr. M. Rathamani

Assistant Professor, PG Department of Computer Science, N.G.M College, Pollachi, Coimbatore, Tamil Nadu-642001, India

Abstract

Water scarcity and inefficient irrigation practices have become major concerns in residential and urban environments. Traditional irrigation systems often rely on fixed schedules that fail to consider real-time environmental conditions, leading to excessive water consumption and poor plant health management. This paper presents the design and implementation of an Internet of Things (IoT)-based smart garden system aimed at improving irrigation efficiency and reducing water wastage in residential gardens. The proposed system integrates soil moisture sensors, temperature and humidity sensors, rain detection modules, and an ESP32 microcontroller for real-time environmental monitoring and adaptive irrigation control. The system utilizes MQTT communication for cloud connectivity and enables remote monitoring through mobile and web applications. Experimental evaluation conducted over a 12-week period demonstrated an average water saving of 39.5% compared to traditional timer-based irrigation methods while maintaining optimal soil moisture stability and improving plant health conditions. The proposed solution offers a low-cost, scalable, and energy-efficient approach suitable for sustainable residential gardening applications.

Keywords— Internet of Things, smart irrigation, water management, ESP32, MQTT, embedded systems, sustainable gardening, precision agriculture

I. Introduction

Water is an essential natural resource required for agriculture, landscaping, and residential gardening. However, increasing urbanization and climate variability have intensified water scarcity problems worldwide. Residential outdoor water usage, particularly garden irrigation, contributes significantly to household water consumption. Conventional irrigation systems such as manual watering and timer-based sprinklers often irrigate plants without considering soil moisture conditions, weather changes, or rainfall events. Consequently, these systems result in over-irrigation, water wastage, nutrient leaching, and unhealthy plant growth.

Recent advancements in Internet of Things (IoT) technologies have enabled intelligent and automated resource management systems. IoT-based irrigation systems employ environmental sensors, embedded processors, cloud communication, and data analytics to monitor soil and weather conditions in real time. Such systems can optimize irrigation schedules dynamically, thereby reducing water usage while ensuring healthy plant growth.

This research proposes a smart garden system using IoT technology for automated irrigation management in residential environments. The system continuously monitors soil moisture, temperature, humidity, and rainfall conditions and automatically activates irrigation only when required. The proposed solution also provides remote monitoring and control capabilities through cloud connectivity and mobile applications.

II. Research Objectives

The objectives of the proposed research are as follows:

1. To design a low-cost and scalable IoT-based smart irrigation architecture for residential gardens.
2. To implement adaptive irrigation algorithms using real-time environmental data.
3. To reduce water wastage and improve irrigation efficiency.
4. To enable remote monitoring and control using cloud-based applications.
5. To evaluate system performance in terms of water savings and soil moisture stability.

III. Literature Review

Several researchers have explored IoT-enabled irrigation systems for agricultural and residential applications. Nayyar and Puri developed a smart farming system using Arduino and cloud computing technologies for monitoring environmental parameters. Suresh et al. proposed an IoT-based irrigation platform capable of automated watering using soil moisture sensors. Vaishali et al. introduced a mobile-integrated irrigation management system for remote irrigation control.

Most existing systems focus primarily on agricultural fields and often involve expensive infrastructure or limited environmental adaptability. In contrast, the proposed system targets residential gardens with an emphasis on affordability, modularity, and real-time adaptive irrigation.

IV. System Architecture

The proposed IoT-based smart garden system consists of three major layers:

1. Perception Layer
2. Network Layer
3. Application Layer

A. Perception Layer

The perception layer includes multiple environmental sensors responsible for collecting real-time data from the garden environment.

Sensors Used

- Capacitive Soil Moisture Sensor
- DHT22 Temperature and Humidity Sensor
- Rain Detection Sensor
- Light Intensity Sensor

The soil moisture sensor continuously measures moisture content in the soil, while the DHT22 sensor monitors ambient temperature and humidity. The rain sensor detects precipitation to avoid unnecessary irrigation during rainfall conditions.

B. Network Layer

The network layer consists of the ESP32 microcontroller integrated with WiFi communication capabilities. Sensor readings are processed locally and transmitted to the cloud server using the MQTT protocol.

Advantages of MQTT

- Lightweight communication protocol

- Low bandwidth usage
- Reliable publish-subscribe messaging
- Suitable for IoT environments
- Supports real-time monitoring

C. Application Layer

The application layer includes:

- Cloud database server
- Web dashboard
- Mobile application
- Historical data analytics

Users can monitor sensor readings, irrigation status, and water usage remotely using the application interface.

The block diagram in fig 1 illustrates the operational flow of the proposed IoT-based smart garden system. Environmental sensors continuously collect real-time data related to soil moisture, temperature, humidity, and rainfall conditions. These sensor readings are processed by the ESP32 microcontroller, which acts as the central control unit.

Based on predefined threshold conditions, the controller activates the relay module to control the water pump and solenoid valve for irrigation. Simultaneously, the ESP32 transmits sensor data to the MQTT cloud server through WiFi connectivity, enabling remote monitoring and control through mobile and web-based applications.

IoT-Based Smart Garden System

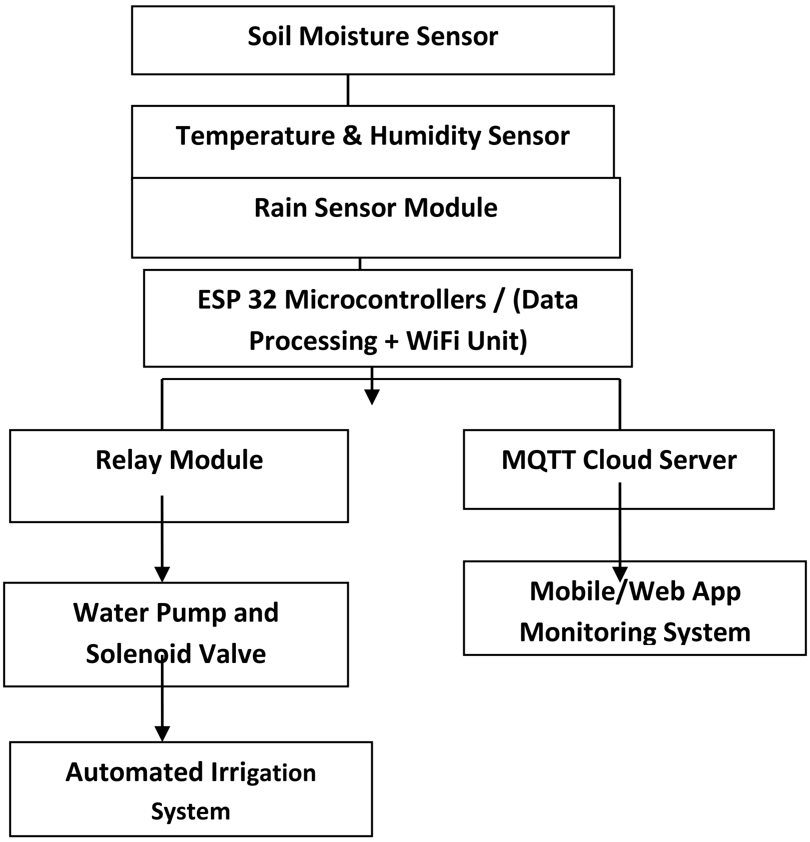

Fig. 1. **Block diagram of the proposed IoT-based smart garden irrigation system.**

V. Hardware Components

The following hardware components are needed to do this proposed work.

Component	Specification	Function	Component
ESP32-WROOM-32	Dual-core 240 MHz, WiFi/BLE	Main controller	ESP32-WROOM-32
Soil Moisture Sensor	Analog capacitive sensor	Moisture measurement	Soil Moisture Sensor
DHT22 Sensor	Temperature and humidity sensing	Environmental monitoring	DHT22 Sensor
Rain Sensor	Digital/analog output	Rainfall detection	Rain Sensor
Relay Module	5V switching module	Pump and valve control	Relay Module
12V Solenoid Valve	Normally closed valve	Water flow regulation	12V Solenoid Valve
Water Pump	12V DC pump	Irrigation water supply	Water Pump

VI. Irrigation Control Algorithm

The irrigation process is controlled using adaptive threshold-based logic.

The moisture threshold is dynamically calculated as:

$$\theta_{th} = \theta_{base} \times K_p \times K_s$$

Where:

- (θ_{base}) = baseline moisture threshold
- (K_p) = plant coefficient
- (K_s) = seasonal adjustment factor

The irrigation duration is determined using:

$$t_{irr} = \frac{(\theta_{target} - \theta_{current}) \times V_{soil}}{Q_{flow} \times \eta}$$

Where:

- (θ_{target}) = target moisture level
- ($\theta_{current}$) = current soil moisture
- (V_{soil}) = soil volume
- (Q_{flow}) = water flow rate
- (η) = irrigation efficiency

The controller activates irrigation only when soil moisture drops below the predefined threshold and rainfall is not detected.

VII. Firmware Implementation

The ESP32 firmware is designed using an event-driven architecture. Sensor readings are periodically collected and transmitted to the MQTT broker.

```
#define MQTT_BROKER "mqtt.smartgarden.io"
#define SENSOR_INTERVAL 900000
#define MOISTURE_PIN 34
#define VALVE_PIN 25
typedef struct {
   float soilMoisture;
   float temperature;
   float humidity;
   bool rainDetected;
   uint32_t timestamp;
} SensorData_t;
void publishSensorData(SensorData_t* data) {
   char payload[256];
   sprintf(payload,
   "{\"moisture\":%.2f,\"temp\":%.2f,\"humidity\":%.2f,\"rain\":%d}",
   data->soilMoisture,
   data->temperature,
   data->humidity,
   data->rainDetected);
   mqttClient.publish("garden/sensors", payload);
}
```

VIII. Experimental Setup

The system was deployed in a residential garden with an area of 50 m² over a period of 12 weeks during summer conditions. A conventional timer-based irrigation system was maintained as the control setup for comparison.

Experimental Parameters

- Irrigation Area: 50 m²
- Evaluation Period: 12 weeks
- Sensor Sampling Interval: 15 minutes
- Average Daily Temperature: 30–36°C

IX. Results and Analysis

A. Water Consumption Analysis

The proposed IoT system demonstrated significant reduction in water consumption compared to conventional timer-based irrigation.

Week	Timer-Based (L)	IoT System (L)

1	210	142
2	210	98
3	210	128
4	210	145
5	210	112
6	210	131
7	210	89
8	210	125
9	210	156
10	210	118
11	210	134
12	210	148

Average Water Savings

The proposed system achieved:

- Average water savings: 39.5%
- Total water saved: 1,044 liters

B. Soil Moisture Stability

The proposed IoT-based system maintained soil moisture within the optimal range of 60–80% with significantly lower fluctuations compared to conventional irrigation methods.

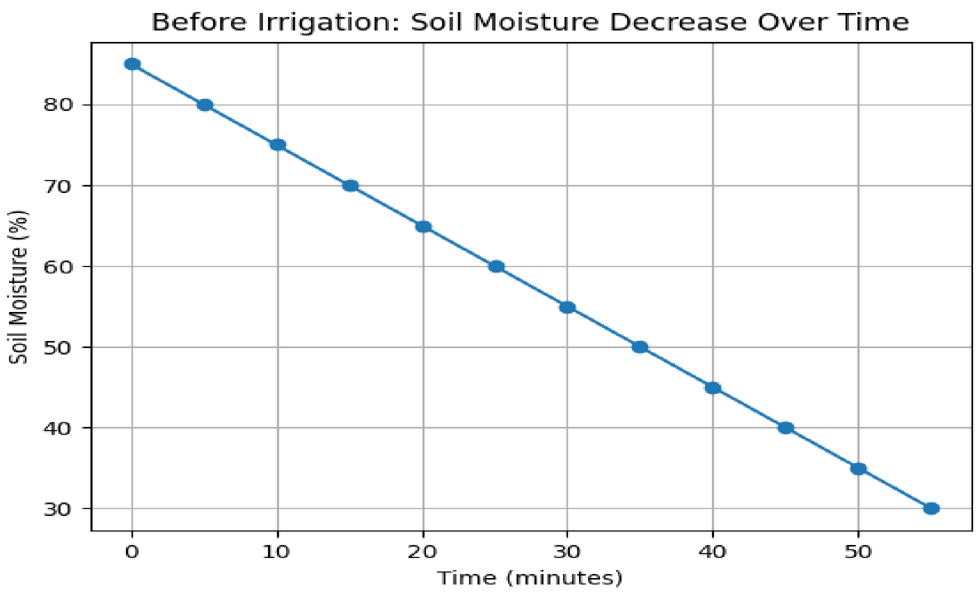

Figure 2. Soil Moisture Decrease before Irrigation

The graph illustrates the gradual reduction of soil moisture before irrigation activation. Moisture decreases steadily due to evaporation and plant water absorption until the threshold level is reached.

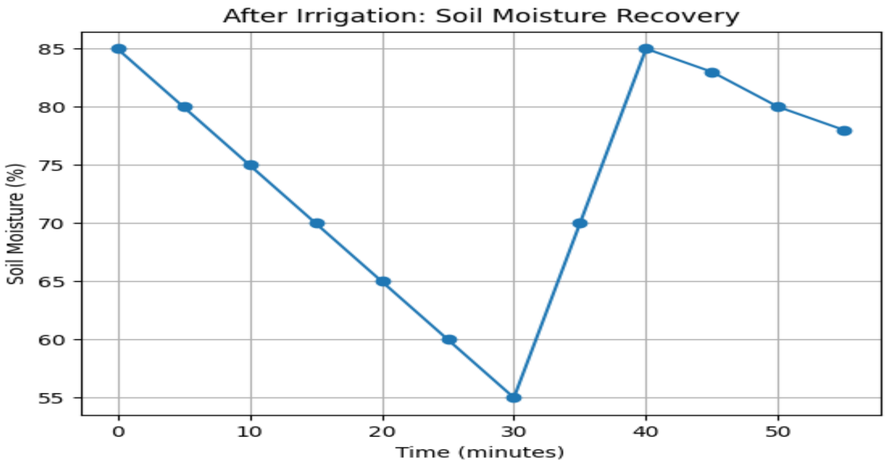

Figure 3. Soil Moisture Recovery after Irrigation

The graph demonstrates rapid recovery of soil moisture after automatic irrigation activation by the IoT controller. This confirms the responsiveness and effectiveness of the adaptive irrigation algorithm.

Metric	**Timer-Based**	**IoT System**
Weekly Water Usage (L)	210	127
Moisture Variance (%)	±18.7	±5.2
Plant Health Index	6.8/10	8.4/10
Over-Watering Events	14	2

The results indicate that the proposed system improves irrigation precision and maintains stable soil conditions for healthy plant growth.

X. Cost Analysis

The proposed IoT-based smart garden system is designed to be affordable for residential deployment in India.

A. Hardware Cost Estimation

Component	**Estimated Cost (INR)**
ESP32 Development Board	₹700 – ₹1,000
Soil Moisture Sensor	₹250 – ₹450
DHT22 Sensor	₹300 – ₹500
Rain Sensor Module	₹150 – ₹250
Solenoid Valve	₹700 – ₹1,200
Relay Module	₹150 – ₹300
Water Pump	₹500 – ₹1,000
Power Supply & Enclosure	₹800 – ₹1,500
Wiring and Connectors	₹400 – ₹700

Total Estimated Cost

The overall implementation cost ranges between:

₹3,950 – ₹6,900

depending on component quality and installation requirements.

B. Economic Feasibility

Based on observed water savings, the proposed system can recover its implementation cost within approximately 18–24 months through reduced water consumption and maintenance effort.

XI. Advantages of the Proposed System

1. Significant reduction in water wastage
2. Real-time adaptive irrigation control
3. Remote monitoring capability
4. Low-cost and scalable architecture
5. Improved plant health management
6. Reduced over-watering events

XII. Limitations

Despite its advantages, the system has certain limitations:

- Dependence on stable WiFi connectivity
- Sensor calibration requirements
- Environmental wear of outdoor sensors
- Power supply considerations

XIII. Future Enhancements

Future improvements may include:

- Integration of machine learning algorithms
- Weather forecast API integration
- Solar-powered operation
- Multi-zone irrigation support
- AI-based plant disease detection

XIV. Conclusion

This paper presented the design and implementation of an IoT-based smart garden system for efficient residential water management. The proposed system integrates environmental sensors, adaptive irrigation algorithms, cloud communication, and remote monitoring capabilities to optimize irrigation efficiency.

Experimental evaluation demonstrated a 39.5% reduction in water usage and improved soil moisture stability compared to conventional timer-based irrigation systems. The proposed architecture is low-cost, scalable, and suitable for sustainable residential gardening applications.

The system contributes toward smart water conservation practices and demonstrates the potential of IoT technologies in sustainable urban resource management.

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