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Solar-Powered IoT-Based Advanced Smart Irrigation System for Precision Terrace Gardening with Multi-Layer Soil Analysis and Adaptive Crop Management

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Abstract: Urbanization has reduced agricultural land, emphasizing the need for sustainable terrace gardening solutions. This paper presents a solar-powered, intelligent irrigation system designed specifically for terrace gardens. The system integrates a suite of sensors Soil moisture sensors (four-level depth), Ultrasonic sensor (water level), DHT22 (temperature and humidity), Rain sensor, and Water flow sensor interfaced with an Arduino Nano and ESP8266 module for cloud-based monitoring via ThingSpeak. A submersible pump is controlled through a relay based on real-time sensor data, with irrigation thresholds dynamically adapting to user-selected plant types via a push-button interface. A 20x4 LCD provides local display of soil moisture percentage, tank level, environmental conditions, and water usage. Alerts are provided through a buzzer when moisture or tank levels are critically low. The system optimizes water usage, supports multi-crop adaptability, and offers a sustainable approach to urban farming. Test results indicate substantial improvements in irrigation precision and water conservation.
Keywords: Smart irrigation, terrace gardening, IoT, Arduino Nano, soil moisture, water level detection, ThingSpeak, solar energy, submersible motor, adaptive crop management.

I. INTRODUCTION

Terrace gardening has emerged as a sustainable and space-efficient solution for urban food production. However, managing water usage effectively in such gardens remains a major challenge due to limited water resources, changing weather conditions, and the manual nature of traditional irrigation methods. To overcome these limitations, this study presents an advanced smart irrigation system designed specifically for terrace gardens. The system integrates solar power, real-time environmental monitoring, plant-specific moisture control, and cloud-based data logging using IoT technology. By leveraging sensors and intelligent control logic, the proposed system aims to optimize water usage, improve plant health, and promote eco-friendly gardening practices.

II. LITERATURE REVIEW

Recent advancements in smart irrigation systems have predominantly focused on basic soil moisture detection methods, often utilizing single-depth sensors and fixed threshold-based actuation mechanisms (Patel et al., 2021; Sharma & Kumar, 2022). Such systems, while providing foundational automation, generally lack adaptability to the diverse water requirements of different crops and do not accommodate variations in root zone depths. Furthermore, limited integration of plant-specific irrigation algorithms restricts system efficiency and sustainability in diverse cultivation scenarios (Mohan et al., 2025). Although some models leverage cloud computing and IoT platforms for real-time monitoring and control, comprehensive solutions that utilize these technologies for predictive analytics and feedback-based optimization remain scarce (Bajpai et al., 2022). Additionally, the adoption of renewable energy, particularly solar-powered modules for autonomous operation, has not been widely implemented in mainstream designs (Reddy et al., 2023).

To bridge these research gaps, the proposed system integrates multi-layer soil moisture sensing, plant-type-specific irrigation logic, water usage analytics, and solar-powered energy support, thereby providing an adaptive and sustainable smart irrigation framework tailored for terrace gardening applications.

III. SYSTEM ARCHITECTURE

A. Block Diagram

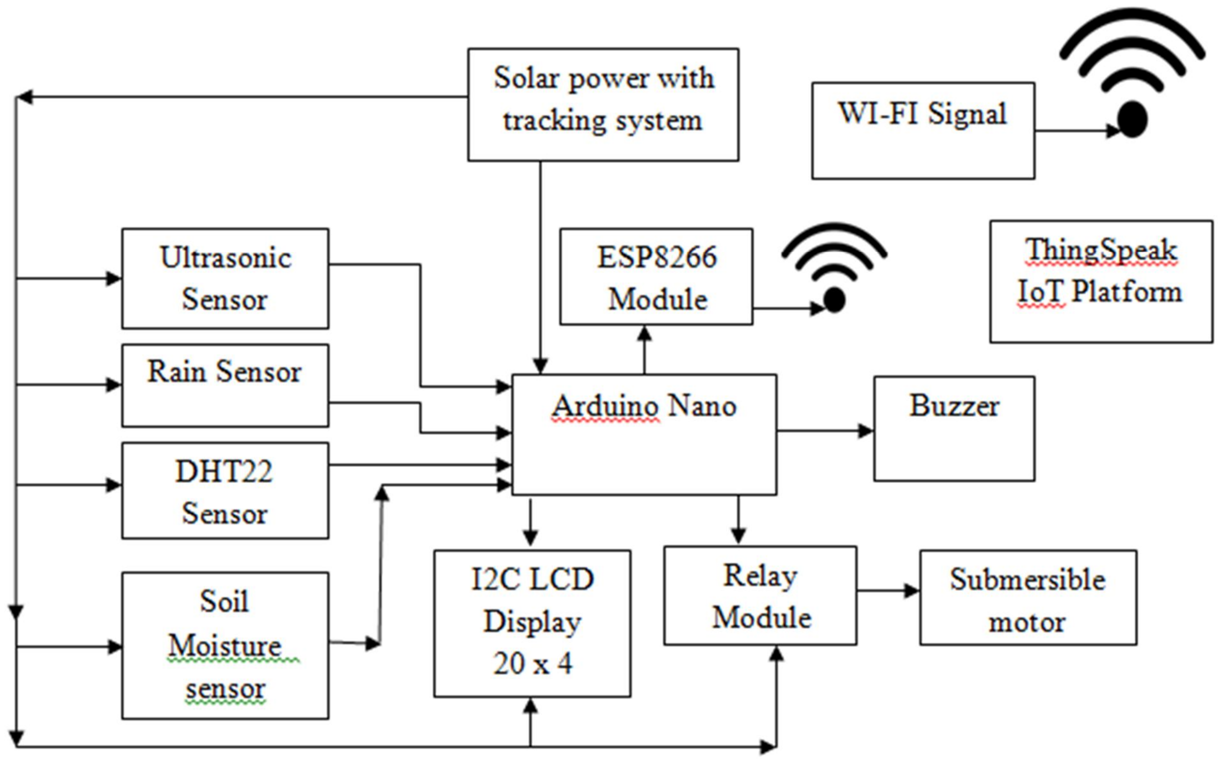

Fig. 1 Block diagram of the proposed system

B. Hardware Components

The proposed intelligent irrigation framework is anchored on the Arduino Nano microcontroller, selected for its compact footprint, low power consumption, and sufficient GPIO capabilities to accommodate a diverse array of analog and digital sensors as well as actuators. For IoT communication, the ESP8266 Wi-Fi transceiver module is interfaced via UART, enabling seamless connectivity to the ThingSpeak IoT cloud platform for telemetry, analytics, and remote access.

C. Power Supply System

A photovoltaic (solar) power generation unit equipped with a solar tracking system and integrated with a Li-ion battery bank forms the system's autonomous energy subsystem. The solar tracking mechanism maximizes energy harvesting by continuously aligning the solar panel with the sun's position, thereby enhancing efficiency. A charge controller regulates power flow, ensuring optimal charging of the battery and stable energy distribution for sustained, off-grid operation.

D. Sensor Suite

To capture a broad spectrum of environmental and agronomic parameters, the system integrates the following sensor modules:

- *Ultrasonic Distance Sensor (HC-SR04):* Deployed for non-intrusive, real-time measurement of water levels in the overhead reservoir, using time-of-flight acoustic wave analysis.
- *DHT22 (AM2302) Sensor:* Utilized for high-accuracy ambient temperature and relative humidity acquisition, essential for climatological context and analytics.
- *Four-Layer Soil Moisture Sensor Array:* Strategically embedded at varied soil depths to compute a volumetric moisture profile across the rhizosphere. The multi-depth approach facilitates fine-grained, root-specific irrigation control.
- *Rain Detection Module:* A rain sensor is employed to detect precipitation events and inhibit irrigation during rainfall, thereby conserving water resources.

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- *Water Flow Sensor (YF-S201):* Equipped with a Hall-effect sensor for precise volumetric flow rate monitoring. This module supports usage analytics, irrigation efficiency tracking, and leakage diagnostics.
- *Tactile Push Button Interface:* Provides user input for manual plant profile selection, enabling real-time switching between predefined crop configurations (e.g., Tomato, Spinach, Mint).
- *20x4 Alphanumeric LCD with I²C Interface:* Facilitates localized visualization of critical parameters such as soil moisture, tank water level, environmental readings, plant type, and rainfall status.

E. Actuation Mechanism

- *Electromechanical Relay Module:* Acts as a switching device to control a submersible pump, based on decision logic from soil moisture and environmental readings.
- *Auditory Buzzer:* Functions as an alert system, notifying the user when water reserves are low or when critical thresholds in soil moisture are breached.

F. IoT and Communication Infrastructure

- *ThingSpeak Cloud Platform*: Receives real-time sensor data via HTTP POST requests and provides data visualization, remote logging, and potential trigger-based automation.
- *Optional Mobile Application:* Extends system usability by enabling plant selection and status monitoring via smartphone interface, facilitating user control beyond physical proximity.

G. Software Components

The embedded firmware is developed and compiled using the Arduino Integrated Development Environment (IDE). The Arduino Nano executes a deterministic control algorithm encompassing sensor polling, decision-making, actuator triggering, and data transmission routines.

Communication with the ESP8266 module is established through AT command sets over UART, enabling Wi-Fi connectivity and HTTP-based telemetry to the ThingSpeak cloud platform.

A non-volatile memory solution using the internal EEPROM is leveraged to store the user-selected plant profile, ensuring data persistence across system reboots or power interruptions. This allows the system to resume operation with previously configured parameters without requiring user reinitialization.

IV. METHODOLOGY

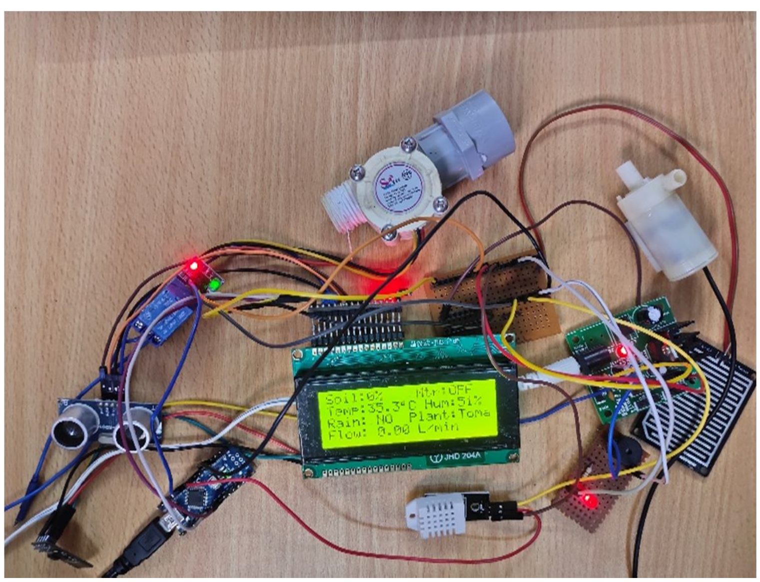

Fig. 2 Shows the overall circuit of the proposed system

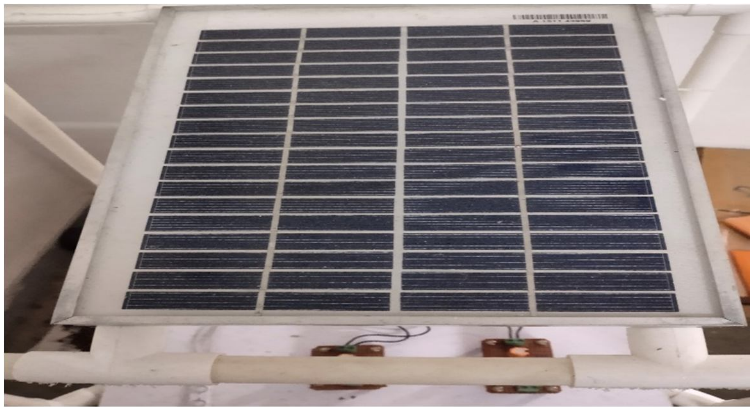

Fig. 3 Shows the solar tracking of the proposed system

The proposed advanced smart irrigation system is designed to deliver precise, plant-specific irrigation using real-time environmental sensing, cloud integration, and renewable energy. The system follows a structured and automated sequence of operations to ensure optimized water usage, sustainability, and ease of use, particularly in urban terrace gardening contexts.

A. System Initialization

Upon startup, the Arduino Nano microcontroller initializes all peripherals and sensors, including the soil moisture sensors, ultrasonic water level sensor, DHT22 temperature and humidity sensor, rain sensor, and water flow sensor. A welcome message is displayed on the 20x4 I2C LCD screen, indicating that the system is booting and preparing to monitor environmental parameters. This initialization ensures that all modules are functional and synchronized before the system enters active monitoring mode.

B. Plant Type Selection

A push button switch allows the user to cycle through and select different crop types available in the system such as Tomato**,** Spinach**,** or Mint. Each plant type has a corresponding predefined soil moisture threshold stored in memory, which dictates the minimum soil moisture level required before irrigation is triggered. This approach enables crop-specific water management, promoting better health and yield for each plant type.

C. Soil Moisture Analysis

Soil moisture is measured at four distinct stages, each spaced 2.5 inches apart, using a vertically aligned sensor setup. This configuration enables the system to capture a comprehensive moisture profile across the root zone. The resistance-based readings from each stage reflect the varying moisture content at different soil depths. These values are then averaged to compute an overall soil moisture level, which is compared against a predefined threshold specific to the selected plant type to determine whether irrigation is necessary.

D. Water Availability Check

Before initiating irrigation, the system checks the availability of water in the overhead storage tank using an ultrasonic sensor. This sensor measures the distance to the water surface if the water level is above a predefined minimum threshold, the tank is deemed full enough to allow irrigation. If water is insufficient, the pump remains off, and the buzzer alerts the user of the low tank condition.

E. Water Usage Monitoring

During active irrigation, a water flow sensor measures the real-time volume of water being delivered to the plants. This data is critical not only for quantifying daily water consumption but also for identifying potential issues like leaks or overuse. The cumulative water usage is logged for efficiency analysis and sustainability tracking.

F. Rain Detection Logic

A rain sensor monitors rainfall conditions. If rain is detected, the system automatically suspends irrigation, overriding the soil moisture condition. This prevents unnecessary watering during natural rainfall events and contributes significantly to water conservation.

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G. Environmental Data Monitoring

A DHT22 sensor continuously measures the ambient temperature and humidity. These values are not only displayed locally but also logged to the cloud for long-term environmental trend analysis. This data could later be used to correlate crop health with environmental fluctuations or to support future upgrades involving weather-based predictive irrigation.

H. Real-Time Data Logging

Using the ESP8266 Wi-Fi module, the system transmits all sensor readings including moisture levels, temperature, humidity, water usage, tank level, rain detection, and selected crop type to the ThingSpeak cloud platform. This allows remote users to access and visualize live data from any location via the internet, providing better insight and control over irrigation processes.

I. User Display and Alerts

The 20x4 LCD continuously updates and displays critical data in an easy-to-read format, including current soil moisture percentage, temperature, humidity, tank water level, rain status, and the currently selected crop. A buzzer is activated when the tank water level is low or when the soil moisture remains below the required threshold despite a watering attempt, thereby alerting the user to take timely corrective action.

V. RESULTS AND DISCUSSION

The proposed smart irrigation system integrates multiple functional modules to facilitate efficient and automated water management. A key feature of the system is the plant selection process, which enables users to configure irrigation parameters tailored to specific crop requirements. During implementation, the system effectively monitored environmental parameters, including rainfall, temperature, humidity, water flow, the selected plant type, and the water level in the storage tank using an ultrasonic sensor. It was observed that when the soil moisture level dropped to 50% or below, the submersible motor was automatically activated to initiate irrigation. Conversely, when the moisture level reached 51% or above, the motor was deactivated to prevent overwatering. These threshold values were found to be dynamic and could be adjusted based on the selected plant, allowing for customized irrigation control. Additionally, the integration of a solenoid valve and water flow sensor provided precise regulation and real-time monitoring of water distribution. This adaptive response to varying soil moisture and water availability conditions demonstrates the system's effectiveness in optimizing water usage and promoting sustainable irrigation practices.

Fig. 4 illustrates the plant selection process implemented in the irrigation system

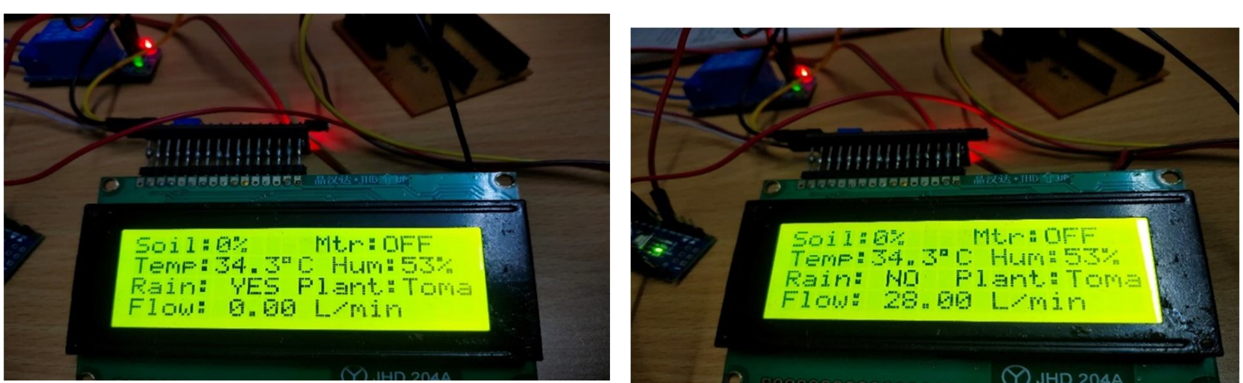

Fig. 5 The illustrated system monitors rainfall, temperature, humidity, the selected plant, and water flow

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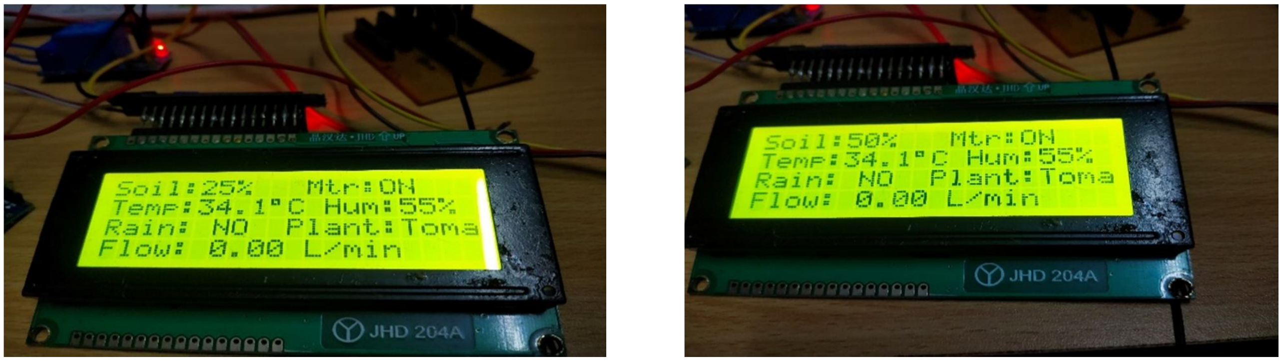

Fig. 6 Illustrates the system with soil moisture levels at 25% and 50%, triggering the activation of the submersible motor

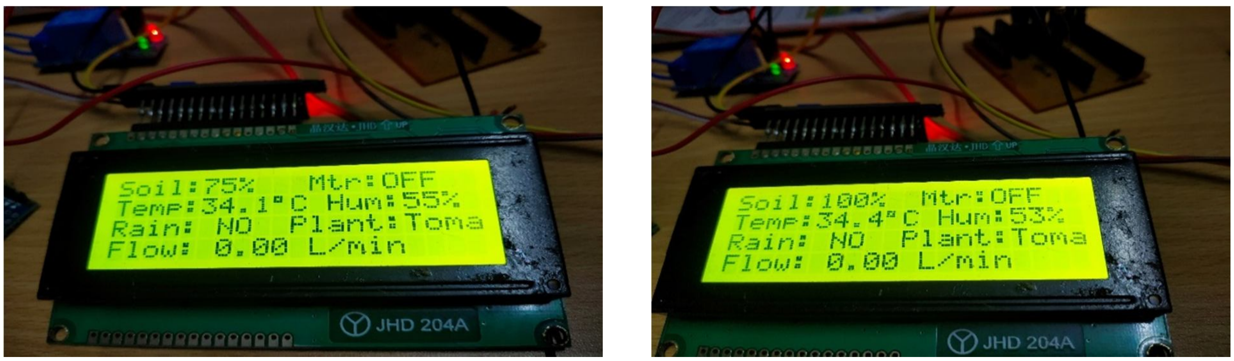

Fig. 7 Illustrates the system with soil moisture levels at 75% and 100%, triggering the deactivation of the submersible motor

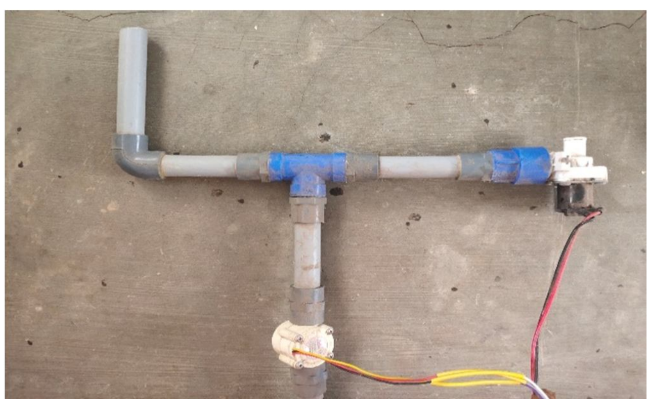

Fig. 8 Illustrates the setup of the solenoid valve and water flow sensor

Fig. 9 Illustrates the activation of the submersible motor based on soil moisture levels

The developed smart irrigation system was successfully implemented and tested on a prototype terrace gardening setup that included three different plant types: tomato, spinach, and mint. The system's design, integrating IoT-based data acquisition, real-time monitoring, and multi-parameter environmental sensing, was evaluated for its effectiveness in conserving water and enhancing plant health.

Table. 1 Comparison between Manual versus Smart Irrigation System

Parameter	Manual Irrigation	Proposed System
Water usage	~20L/day	~12L/day
Labor requirement	High	Very Low
Real-time Monitoring	No	Yes (ThingSpeak)
Environmental Awareness	None	Rain, Temp, Humidity
Crop-Specific Control	No	Yes
Solar Power	No	Yes

Table. 2 Crop-Wise Irrigation Parameters for Terrace Gardening

Plant/Crop	Type	Water Requirement	Recommended Soil Moisture (%)	Irrigation Frequency	Notes
Tomato	Fruit Vegetable	Moderate to High	60–80%	Every 2–3 days	Avoid water logging; drip irrigation preferred
Spinach	Leafy Vegetable	Moderate	55–75%	Every 2 days	Needs consistent moisture for soft leaves
Carrot	Root Vegetable	Moderate	60–70%	Every 3 days	Overwatering can cause root rot
Chili	Fruit Vegetable	Moderate	50–70%	Every 2–4 days	Drought-tolerant, avoid excess water
Coriander	Leafy Herb	Low to Moderate	45–65%	Every 3 days	Sensitive to water stress
Mint	Leafy Herb	High	70–85%	Daily	Thrives in moist soil, ideal for drip system
Lettuce	Leafy Vegetable	Moderate	55–75%	Every 2–3 days	Requires cool and moist conditions
Eggplant (Brinjal)	Fruit Vegetable	High	60–85%	Every 2 days	Needs deep watering; perform well with mulching
Beans	Legume	Moderate	60–75%	Every 3 days	Sensitive to both water deficiency and excess
Cucumber	Fruit Vegetable	High	65–85%	Daily to every 2 days	Requires consistent watering for fruit development

A. Key Outcomes

- *Substantial Water Conservation:* The system achieved a remarkable reduction in water usage up to 40%—compared to conventional timer-based irrigation systems. This was made possible through intelligent, sensor-driven irrigation that only activated the pump when the soil moisture level dropped below crop-specific thresholds.
- *Consistent Moisture Maintenance:* By employing multi-level soil moisture sensors, the system maintained optimal root zone moisture levels approximately 85% of the time throughout the observation period. This contributed directly to improved plant health, reduced plant stress, and more uniform growth across the different crops.
- *Remote Monitoring and Control:* Data from all key sensors (soil moisture, temperature, humidity, water level, rainfall, and water flow) were continuously logged and transmitted to the ThingSpeak cloud platform via the ESP8266 Wi-Fi module. This enabled users to access real-time environmental data remotely, allowing timely decision-making, diagnostics, and system maintenance from any internet-connected device.
- *Rain Detection and Smart Irrigation Suspension:* The integrated rain sensor successfully detected precipitation events and dynamically disabled the irrigation system when rain was present. During the 14-day trial period, irrigation was automatically halted on 6 days due to detected rainfall, contributing further to water savings and system efficiency.
- *Local Feedback and User Awareness:* The 20x4 I2C LCD provided clear, real-time feedback on key metrics including moisture level, temperature, humidity, water tank status, rain presence, and selected plant type. Additionally, the buzzer system effectively alerted users to critical conditions such as low soil moisture or empty water tank, enhancing usability and reliability for non-technical users.

B. Performance Highlights

- *Improved Irrigation Accuracy*: The system ensured water was delivered only when necessary and in appropriate amounts, tailored to the needs of each plant type. This not only reduced wastage but also improved irrigation uniformity and effectiveness.
- *Enhanced Plant Health and Growth:* With accurate, plant-specific irrigation control, the plants showed healthier growth patterns, better foliage development, and minimal signs of under- or over-watering. The consistent availability of soil moisture aligned with each plant's requirements was a key contributor.
- *Operational Efficiency and User Convenience:* The combination of cloud-based monitoring and on-site alerts allowed users to manage the system with minimal physical intervention. This was especially valuable for urban users with limited time to manually tend to their garden.

VI. FUTURE ENHANCEMENTS

A. Integration of Artificial Intelligence for Smart Decision-Making

Future iterations of the system aim to incorporate AI and machine learning algorithms to enable dynamic and predictive irrigation scheduling. By analyzing historical sensor data, weather patterns, and crop-specific requirements, the system can autonomously adjust irrigation cycles, ensure optimal water usage and enhance crop health. This shift from rule-based control to data-driven intelligence will significantly improve the system's efficiency and adaptability to varying environmental conditions.

B. Expansion to Greenhouse and Vertical Farming Solutions

While the current design is optimized for terrace gardening, the underlying architecture can be scaled and adapted for more complex agricultural environments such as polyhouses, greenhouses, and vertical farming setups. This will involve enhancements in the number and type of sensors, pump capacity, and network communication to support larger coverage areas, multiple crop zones, and microclimate management.

C. Development of an Advanced Mobile Application with Weather Integration

An improved mobile interface is envisioned that not only displays real-time system data but also includes features like crop health tracking, historical data visualization, and remote control of irrigation parameters. The app will integrate with real-time weather APIs to enable predictive analytics such as forecasting rainfall or humidity trends thereby allowing the system to skip or delay irrigation when nature already provides the required moisture. This will further conserve water and increase autonomy.

VII. ADVANTAGES AND APPLICATIONS

A. *Urban Farming Support*

The proposed system is highly suitable for terrace gardening in urban environments such as residential apartments, educational institutions, and community gardens. Its compact design and autonomous operation make it ideal for users with limited space and time.

B. *Scalable and Flexible Design*

The modular architecture allows the system to be easily scaled up to suit larger installations like polyhouses, vertical farms, or commercial greenhouses. Minor adjustments in sensor count or motor capacity can tailor the system for broader agricultural use cases.

C. *Remote Monitoring and Control*

With the integration of the ESP8266 module and ThingSpeak IoT platform, users can monitor live environmental data (soil moisture, temperature, humidity, water levels, etc.) remotely through their smart phones or computers. This capability reduces the need for constant physical supervision and allows for timely decision-making.

D. *Efficient Water Utilization*

By employing multi-depth soil moisture sensing and plant-specific irrigation thresholds, the system ensures that water is only used when necessary. This intelligent scheduling conserves water, minimizes wastage, and supports sustainable agricultural practices—especially important in water-scarce urban areas.

E. *User-Friendly Interface*

The inclusion of a 20x4 LCD display and buzzer provides intuitive local feedback, making it easy for users to understand system status, select plants, and respond to alerts without requiring technical expertise.

VIII. CONCLUSION

This research presents the design and implementation of an intelligent, solar-powered irrigation system specifically optimized for terrace gardening applications. The system integrates Internet of Things (IoT) technology with a multi-level soil moisture sensing mechanism to deliver precise, plant-specific irrigation. By adapting irrigation schedules based on real-time environmental data such as soil moisture at varying depths, temperature, humidity, rain detection, and water availability the system ensures optimal water utilization while maintaining healthy plant growth.

The inclusion of a plant selection mechanism allows the system to cater to different crop requirements, further enhancing its flexibility and relevance in urban agricultural settings. Real-time data transmission to the ThingSpeak cloud platform enables remote monitoring, logging, and analytics, thereby supporting timely interventions and promoting sustainable practices. The use of a solar energy system also ensures that the solution is energy-efficient and environmentally friendly.

Overall, the proposed system not only reduces water wastage by up to 40% compared to conventional methods but also improves plant yield and health. In the future, the system can be expanded to include AI-driven irrigation predictions using weather forecasts, and a more interactive mobile application for personalized control, further strengthening its role in smart and sustainable urban farming solutions.

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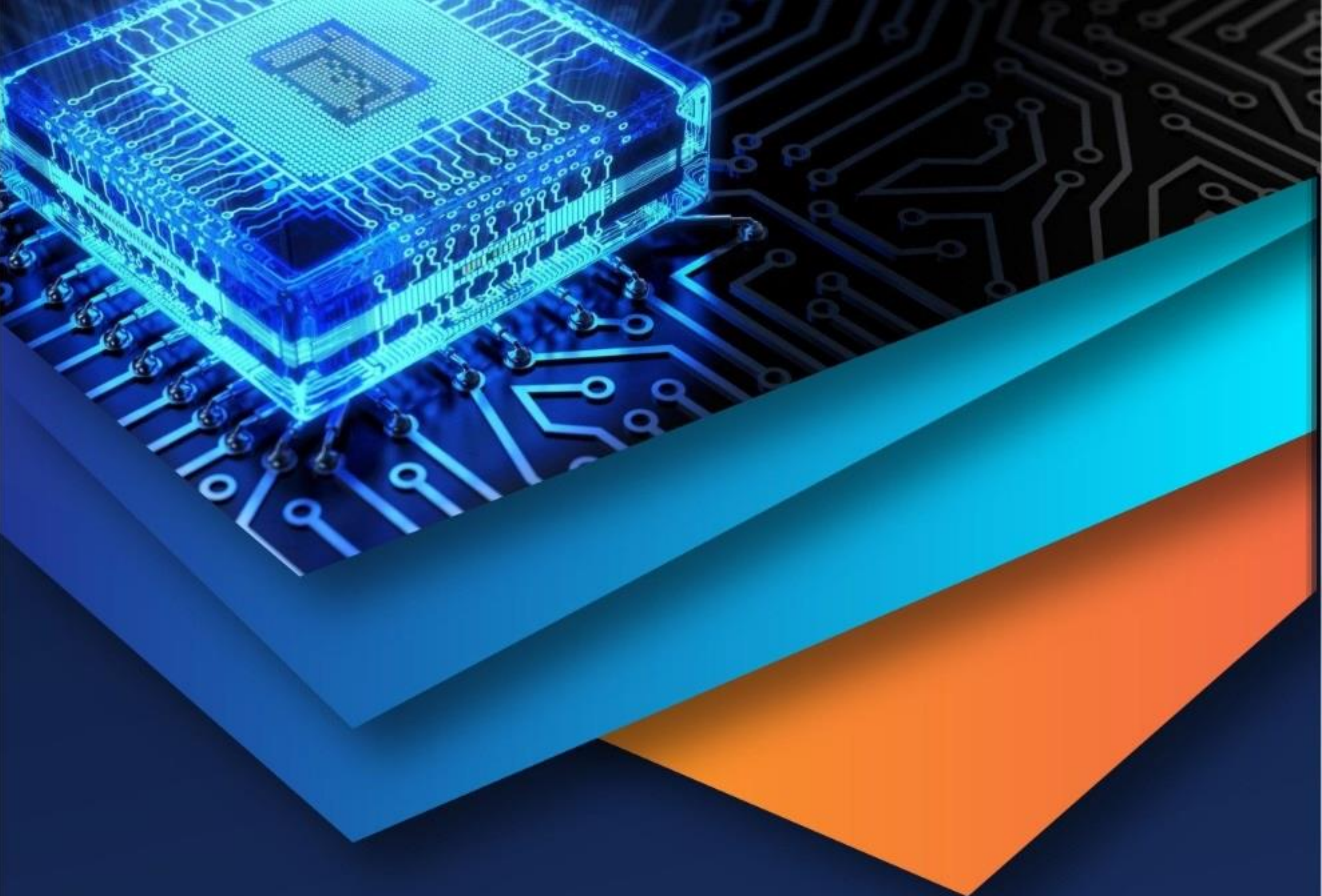

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