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IoT – based Smart Vertical Farming System to Enhance Agricultural Sustainability

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***Abstract*— In urban and space-constrained settings, vertical farming has become a viable strategy for sustainable food production. Nevertheless, a lot of small-scale agricultural systems still rely on fixed irrigation techniques and human monitoring, which can result in inefficient water use and uneven crop growth conditions. The design and execution of a low-cost Internet of Things (IoT) smart vertical farming system utilizing an ESP32 microcontroller for automated irrigation control and real-time environmental monitoring are presented in this work.**

The proposed system uses several sensors such as soil moisture, temperature, humidity, water level, pH, turbidity and water flow sensors to continuously monitor the environment of cultivation. The device automatically controls the irrigation using a relay driven water pump based on pre-defined moisture threshold levels. Sensor data are transmitted to the Adafruit IO cloud platform for remote monitoring and data logging and to an LCD module for local display. We conducted experimental testing in a soil-based growth system to evaluate irrigation responsiveness, cloud connectivity, and sensing accuracy.

***Keywords*— Internet of Things (IoT), ESP32, Smart irrigation, Indoor farming, Vertical farming, Environmental monitoring, Cloud-based monitoring, Adafruit IO.**

I. INTRODUCTION

Urban and indoor farming are getting more attention as cities deal with limited land and increasing demand for sustainable food production. Vertical farming provides a practical way to grow crops in stacked arrangements while allowing for better control over environmental factors like soil moisture, temperature, and humidity. However, many small and low-cost systems still rely on manual watering and fixed irrigation schedules. This often results in inefficient water use and inconsistent growing condition.

Recent developments in Internet of Things (IoT) technology enable real-time crop monitoring, automated irrigation, and remote farming management, which greatly improve reliability and efficiency. This study designs and tests a low-cost IoT-based monitoring and irrigation control unit for indoor and vertical farming. The system uses an ESP32 controller and a set of environmental sensors that continuously track growing conditions and automatically manage irrigation. Users can access data on a local display and a cloud dashboard.

Initial testing is conducted with a single soil-based growing container to check sensor performance, control response, and cloud connectivity.

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Future work will expand the system to a scalable three-rack vertical farming setup for multi-level deployment and thorough performance evaluation.

II. Motivation

Urban agriculture and indoor cultivation are increasingly required to operate under strict space, water and labour constraints. Although vertical farming provides an effective solution for improving land utilisation, many small-scale and low-cost installations still rely on manual observation and fixed irrigation schedules. Such practices often lead to inconsistent moisture conditions, inefficient water usage and delayed responses to environmental changes.

At the same time, the rapid development of low-power microcontrollers and wireless communication modules enables real-time sensing and automated control at a relatively low cost. However, practical adoption of these technologies in small and modular farming setups is still limited by the lack of reliable and easy-to-deploy control units that can later be extended to multi-rack environments.

The goal of this work is to design and test a compact IoT-based monitoring and irrigation control unit. This unit should work reliably in a straightforward cultivation setup and can be easily expanded to a vertical rack-based farming structure in future projects. By validating the base model in a controlled single-container environment, we can more confidently scale the system to support multi-level vertical farming installations.

III. Literature Review

Said et al. developed an ESP32-based IoT vertical farming system that uses temperature, humidity, and water-level sensors and communicates through an MQTT cloud platform. The system relies on simple rule-based thresholds to control the pump and regulate environmental conditions. Their results showed that the system was able to maintain stable growing conditions, achieved about 96% accuracy in irrigation response, and reduced the need for manual monitoring by nearly 60%. [1]

Reddy et al. proposed a multi-layer vertical farming setup with DHT and soil-moisture sensors, controlled using relay-based automation. They managed irrigation and ventilation through a mix of scheduling and threshold-based decisions. The authors reported that the system improved water use efficiency by 35% and kept the temperature stable within ±1.2 °C, showing reliable environmental stability. [2]

Kumar et al. introduced an Arduino-based aeroponic vertical farming system that uses a timed misting strategy with real-time sensor feedback. The approach aimed to deliver nutrients evenly across all stacked growing units. Their experimental results showed more uniform nutrient spraying and improved plant growth rates by about 18% compared to traditional aeroponic methods. [3]

Patil et al. created a hydroponic monitoring and control platform that uses an ESP32 controller along with pH and electrical conductivity sensors. The system allows for real-time visualization through cloud dashboards and uses feedback-based monitoring for nutrients and environmental conditions. The authors noted over 97% reliability in real-time data transmission, showing the strength of the communication system. [4]

Al-Hammadi et al. introduced a layered IoT sensing system that combines temperature, humidity, and moisture sensors with cloud-based data logging. They controlled irrigation and ventilation using a rules-based approach. The system maintained the desired environmental ranges across multiple rack layers with about 95% accuracy. [5]

Zhang et al. proposed a rack-based vertical farming system that uses distributed sensor nodes and layer-wise closed-loop irrigation control. They used a proportional control algorithm to manage the water pump. Their results showed that this approach reduced moisture differences between the upper and lower growing layers by nearly 41%. This led to more uniform growing conditions. [6]

Singh and Kaur created a smart irrigation system that uses soil moisture sensors and adjusts watering thresholds in real-time. The system changes irrigation schedules based on current soil conditions. Their study found a 38% reduction in total water use while keeping plants healthy. [7]

Rahman et al. introduced a water distribution model for stacked hydroponic racks using ultrasonic and flow sensors. A feedback-driven flow-balancing algorithm was applied to ensure equal water delivery across different cultivation levels. The proposed system achieved about 94% accuracy in providing uniform water distribution. [8]

Lee et al. created an IoT-enabled indoor vertical farming system that pairs environmental sensing with adjustable LED lighting control. The lighting approach used both scheduled operation and sensor-driven changes. Their experiments revealed a 21% increase in biomass yield and a 17% decrease in lighting energy use. [9]

Basha et al. created an Arduino-based automation system that combines soil-moisture and temperature sensors with a DC motor-driven irrigation unit. They made irrigation decisions using a rule-based logic. The system reached about 92% accuracy in controlling irrigation and greatly decreased the need for human involvement. [10]

Sharma et al. proposed a cloud-connected ESP32 monitoring platform that can stream data in real time and generate alerts automatically. The system showed over 98% success in data delivery and offered dependable remote supervision for indoor and vertical farming environments. [11]

Khan et al. created an IoT-based irrigation control system that uses flow sensors and soil-moisture sensors in a closed-loop feedback structure. This method significantly reduced excessive watering, cutting over-irrigation by 43% and reaching about 95% accuracy in irrigation control. [12]

Prakash et al. introduced a water quality monitoring framework for hydroponic vertical farms that uses pH and turbidity sensors. They applied a threshold-based technique to find abnormal nutrient solution conditions. The system reached about 96% accuracy in detecting water quality issues. [13]

Santos et al. introduced a cloud-based framework that combines temperature, humidity, and water-level sensors for real-time visualization and decision support. By centralizing monitoring and analytics, the system cut operational response time by almost 32%. [14]

Gupta and Verma created a modular rack-based vertical farming system that uses IoT sensors and automated pumping units. They used a distributed control strategy to improve scalability and allow for fault isolation. The prototype showed quicker system deployment and better structural stability. [15]

Yadav et al. created a smart farming prototype using the ESP32. It offers local visualization with an LCD display and allows for remote monitoring through cloud dashboards. They used rule-based automation logic, which achieved around 97% accuracy in reporting real-time status and controlling actuators. [16]

Chen et al. proposed a smart vertical farming platform that combines IoT sensing with data-driven optimization of irrigation and environmental settings. A predictive adjustment algorithm used historical sensor data to fine-tune system parameters. This approach led to a 19% improvement in resource use and increased yield stability. [17]

TABLE I. AUTHORS AND THEIR APPROACHES

Ref.	Controller / platform	Vertical structure	Main focus	Control approach	Main limitation
[1]	ESP32	Single vertical unit	Environmental monitoring and irrigation	Threshold based	No layer-wise control
[2]	Microcontroller	Multi-layer setup	Irrigation and ventilation	Schedule + threshold	Limited remote monitoring
[3]	Arduino	Aeroponic vertical stack	Nutrient and mist delivery	Time-based control	No cloud integration
[6]	Distributed nodes	Rack-based system	Layer-wise irrigation	Closed-loop control	Higher hardware complexity
[8]	Controller-based	Stacked hydroponic racks	Water distribution balancing	Feedback-based	Focus limited to water flow
[9]	IoT platform	Indoor vertical farm	Environmental and lighting control	Rule-based and scheduled	Limited irrigation analysis
[15]	IoT nodes	Modular rack structure	Scalable rack deployment	Distributed control	No detailed experimental evaluation
This work	ESP32	Single container (validated), rack-based (proposed)	Integrated monitoring and irrigation	Closed-loop threshold	Rack deployment not yet implemented

V. SYSTEM ARHCITECTURE

Fig 1. System Architecture

VI. METHODOLOGY

A. System Overflow

The proposed IoT-based smart vertical farming system is meant to allow real-time tracking and automatic control of important environmental factors that influence plant growth. It combines various sensors, a microcontroller for processing, and wireless communication tools to ensure effective data collection, analysis, and control actions.

The system uses a layered design that includes:

- Sensing Layer: This part gathers real-time data on environmental conditions like soil moisture, temperature, humidity, and light levels.
- Processing Layer: An ESP32-based control system is used to analyze the data from the sensors and make decisions about how to control the environment.
- Communication Layer: The built-in Wi-Fi module of ESP32 sends the collected data to the cloud platform for remote monitoring and storage.
- Application Layer: This offers a user-friendly interface where users can check the status, receive alerts, and view data visually.

B. Hardware Components and Design

- Dht11: The DHT11 is a basic, low-cost digital temperature and humidity sensor. Widely used by hobbyists and makers, it integrates a capacitive humidity sensor and a thermistor to provide calibrated digital output signals over a single-wire interface

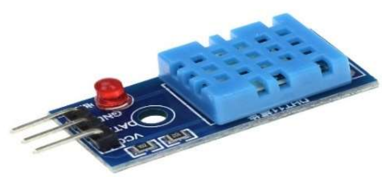

Fig.2 Dht11

- ESP32 : Node MCU is an open source platform based on ESP32 which can connect objects and let data transfer using the Wi-Fi protocol. In addition, by providing some of the most important features of microcontrollers such as GPIO, PWM, ADC, and etc, it can solve many of the project's needs alone.

Fig.3 ESP32

- Moisture Sensor: A resistive soil moisture sensor works by using the relationship between electrical resistance and water content to gauge the moisture levels of the soil.

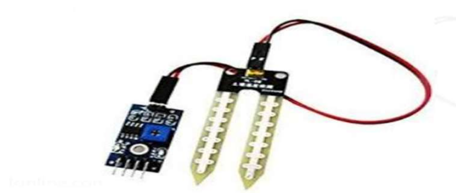

Fig.4 Moisture Sensor

- DC Water Pump : DC powered pumps use direct current from motor, battery, or solar power to move fluid in a variety of ways. Motorized pumps typically operate on 6, 12, 24, or 32 volts of DC power. Solar-powered DC pumps use photovoltaic (PV) panels with solar cells that produce direct current when exposed to sunlight.

Fig.5 DC Water Pump

- 16*2 LCD: A 16x2 LCD means it can display 16 characters per line and there are 2 such lines. In this LCD each character is displayed in 5x7 pixel matrix.

Fig.6 16*2 LCD

C. Data Acquisition and Monitoring

Environmental parameters are continuously monitored using sensors placed throughout the vertical farming system. These sensors collect data at regular intervals, ensuring the information remains both precise and current.

- Soil moisture sensors measure the amount of water available to the plant roots.
- DHT11 sensors monitor the temperature and humidity levels.
- Light sensors assess the intensity of sunlight, which plays a key role in plant growth.
- All the collected data is transmitted to the Arduino controller.

There, the data is processed and verified before any actions are taken

D. Control and Automation Strategy

The system uses a threshold-based method to keep the growing conditions optimal.

- When the soil gets too dry and the moisture level falls below a certain point, the irrigation pump turns on to water the plants.
- If the moisture level goes above the maximum allowed, the pump stops to prevent overwatering.
- When the temperature becomes too high, cooling systems like fans are activated to bring it down.
- If there's too much light, the system sends an alert so someone can take action to address the problem.

This closed-loop control system helps manage water, energy, and other resources in a smart and efficient way.

E. Communication and IoT Integration

The ESP32 allows the DHT11 controller to connect wirelessly to cloud-based IoT platforms. Sensor data is sent to the server regularly, which makes it possible to:

Watch over the system from a phone or computer

Get instant alerts and updates when something happens

Keep an eye on the system continuously without needing to be there in person.

F. Data Logging and Analysis

The system has the ability to log data over time, keeping a record of past environmental conditions. This data can be used to:

Spot patterns in how plants grow under different conditions.

Plan the best times to water crops.
Boost the overall efficiency of farming practices.
By looking at this data, farmers can make smarter choices that help the environment and increase crop yields.

VI. ALGORITHM

A. System Initialization

Initialize sensing modules for soil moisture, temperature, humidity, and light. Set up the LCD interface and establish wireless communication with the IoT cloud platform. Ensure sustainability.

B. Synchronous Data Acquisition and Normalization:

Periodically gather environmental parameters from all sensors and convert raw analog readings into normalized percentage values for consistent processing.

C. Threshold-Based Adaptive Control

Check soil moisture against set lower and upper limits:
- Turn on irrigation when moisture drops below the minimum level.
- Turn off irrigation when moisture goes above the maximum level.

This maintains proper water regulation and prevents overwatering.

D. Real-Time Visualization and State Indication

Update the local display with the current environmental parameters and system status (pump ON/OFF) to provide quick feedback.

E. Cloud Synchronization and Remote Monitoring

Send processed sensor data and actuator status to the IoT platform for remote monitoring and data logging in real time.

F. Continuous Feedback Loop Execution

Repeat the sensing, processing, and actuation cycle at regular time intervals to keep environmental conditions stable.

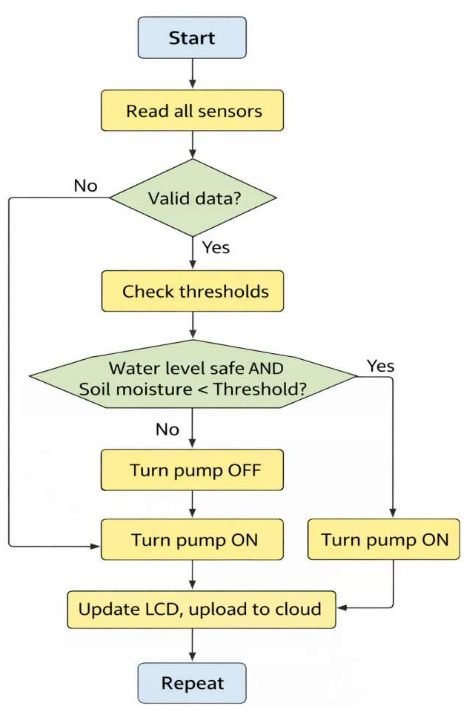

Fig.2 Algorithm Workflow

VII. Results and Performance Analysis

Proposed ESP32 based smart vertical farming system was tested periodically for thirty days in real environmental conditions. The developed prototype was a three-layer hydroponic system with 21 evenly distributed plants per layer. The ESP32 controller was connected to IoT sensors to monitor environmental factors such as temperature, humidity, soil moisture and light intensity in real-time.

The system kept stable environmental conditions for hydroponic farming during the whole experiment. The temperature and humidity recorded were between 26.8°C and 32.4°C and 58% and 72% respectively. The automated irrigation system controlled the water flow based on pre-set moisture parameters, thus reducing water wastage.

The proposed automated irrigation system used only 12.4 litres of water in 30 days compared with 38.7 litres in manual irrigation, saving over 68% of the water. In addition, the crop yield increased by about 22% as compared to traditional manual cultivation techniques.

The ESP32-based monitoring system has achieved an operational uptime of about 98% during continuous testing. Successful transmission of real-time sensor data to the cloud platform Adafruit IO for remote monitoring. The proposed system is suitable for small scale indoor and urban farming applications as it consumes less power around 2.3 W and the cost of implementation is low about ₹ 2,500.

VIII. Future Scope

As a next step, we will deploy the proposed monitoring and irrigation control unit on a three-rack vertical farming structure. Each rack level will operate as an independent cultivation zone. Each rack will have its own soil-moisture sensor and irrigation outlet to allow for monitoring and control on each layer. The future implementation will focus on evaluating moisture uniformity across different rack levels, differences in irrigation response between layers, and the scalability of the sensing, power distribution, and communication systems. Long-term experiments will also be conducted to examine water consumption, system stability, and reliability under continuous multi-rack operation.

IX. Conclusion

As a next step, the proposed monitoring and irrigation control unit will be used on a three-rack vertical farming structure. Each rack level will function as an independent cultivation zone. Each rack will have its own soil-moisture sensor and irrigation outlet to allow for monitoring and control at each layer. The future implementation will look at moisture uniformity across different rack levels, differences in irrigation responses between layers, and how well the sensing, power distribution, and communication systems can grow. Additionally, long-term experiments will be done to examine water use, system stability, and reliability during continuous multi-rack operation.

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