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Real Time Environmental Monitoring using Multiple Sensing Node

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ABSTRACT :

This paper presents the design and implementation of a Wi-Fi-enabled, multi-node environmental sensing system for real-time monitoring of temperature and humidity. Traditional environmental monitoring methods often rely on manual observation or single-point sensors, which limit coverage and responsiveness. The proposed system uses distributed IoT-based sensor nodes connected via Wi-Fi to provide continuous, accurate, and scalable data collection. The system is accessible through web and mobile platforms and includes alert mechanisms to notify users of abnormal conditions. The solution is particularly beneficial in sectors like precision agriculture, storage monitoring, cold chain monitoring, weather monitoring and infrastructure monitoring, where timely environmental data can significantly enhance efficiency, safety, and decision-making.

Keywords: IoT (Internet of Things), Sensor Nodes, ESP32, NodeMCU, Wi-Fi Communication, Environmental Monitoring, DHT11 Sensor, Temperature and Humidity Monitoring.

INTRODUCTION

Environmental challenges are becoming more complex due to extreme weather, pollutants, shifting ecosystems, and climate change, requiring the processing of large volumes of real-time data. Advances in sensor and communication technologies, particularly the Internet of Things (IoT), have enabled on-site monitoring integrated with remote data processing for timely and informed decision-making. This study implements a wireless sensor network for small farm areas using multiple ESP32-based nodes.[4] Each node operates with the ESP-WIFI-MESH protocol, forming a scalable, self-organizing, and autonomous mesh network. The system monitors key plant growth parameters—soil moisture, temperature, relative humidity, and sunlight intensity—using sensors connected to each node.

Agriculture plays a crucial role in the economy of many nations and directly impacts the quality of life of their populations. Effective monitoring and control of storage facilities are essential for both farmers and governments, as they help ensure food security at household and community levels and enable value addition. While some losses occur in the field, the most significant losses typically happen during storage. Effective storage management and maintaining grain quality are essential for achieving high market value and better economic returns. During storage, key factors like temperature, humidity, and light have a major impact on the quality of the grains.[12]As global grain production continues to grow, the need for efficient warehousing is more crucial than ever to ensure profitability and market competitiveness. The integration of IoT technology in grain storage enables real-time monitoring via wireless sensor networks, marking a major advancement in improving storage efficiency and maintaining grain quality Existing monitoring systems are often expensive, slow, and lack proper sealing conditions. This research utilizes advanced technology to deliver an affordable, real-time solution for improving grain storage monitoring, aiming to minimize post-harvest losses and strengthen regional food security.[13]

The proposed project aims to develop a Wi-Fi-based multi-node sensing system for real-time environmental monitoring. By integrating multiple sensor nodes distributed across large-scale environments, the system provides continuous, accurate, and scalable monitoring, with real-time data accessible via web or mobile platforms. This solution not only ensures efficient temperature and humidity control but also enables early detection of unsafe conditions, allowing for prompt corrective action. The system's cost-effectiveness and scalability make it suitable for a variety of applications, from agriculture to industrial monitoring, ultimately enhancing operational efficiency, reducing losses, and improving decision-making processes. Through the implementation of such a system, the project seeks to offer a more reliable, automated, and comprehensive approach to environmental monitoring, aligning with the growing demand for smarter, data-driven solutions in the Internet of Things era.

LITERATURE REVIEW :

Recent advancements in IoT and wireless communication have significantly improved environmental monitoring systems, moving beyond traditional methods like manual inspections and single-point sensors. IoT-based solutions, particularly those using wireless sensor networks (WSNs), enable real-time, scalable, and cost-effective monitoring of key environmental parameters such as temperature, humidity, and pH. Cloud platforms further enhance these systems by providing remote access, data storage, and timely alerts. This section reviews the existing literature on multi-sensor IoT networks and their applications in real-time environmental monitoring, highlighting key trends, challenges, and innovations that inform the development of the proposed system.

A foundational study by (Madushan et al., 2021) [1]explored the project involves developing an IoT sensor node intended for monitoring both humidity and temperature. A key aspect of the design is ensuring cost-efficiency in creating a smart device. To evaluate power efficiency, average current consumption is monitored using a power meter. One of the primary challenges faced is minimizing power usage. To address this, a sleep mode feature is incorporated—where the device remains in sleep mode for 4 minutes and 55 seconds, only becoming active for the final 5 seconds of each cycle. Another significant challenge is achieving a compact design. To fulfill this requirement, the development focused on three core strategies: Designing a double-layer printed circuit board (PCB), Utilizing the space between the NodeMCU module and the PCB, and Employing SolidWorks software for both simulation and assembly modeling.

In a comprehensive review, (Yousuf et al.,2020) [2]examined Edge AI has emerged as a practical alternative to conventional AI approaches by enabling devices to make basic decisions locally, without relying on cloud infrastructure. This results in improved energy efficiency and minimizes the need for constant data transmission. Compact single-board IoT platforms, capable of running lightweight versions of machine learning algorithms and supporting various wireless communication protocols, are gaining popularity for such applications. In this paper, we introduce an energy-efficient IoT platform named iBUG, which integrates several built-in sensors. We also propose an algorithm based on TensorFlow Lite that can accurately estimate CO2 levels using only gas resistance measurements.

According to (K Kour et al.,2022) [3]key challenges and the appropriateness of various methods in hydroponics were examined, along with essential agronomical factors necessary for optimal saffron cultivation. Several IoT-enabled hydroponic models developed by researchers in this field were reviewed. A proposed intelligent hydroponic framework specifically designed for saffron farming was also introduced. According to the literature survey, the primary reasons for the decline in saffron production include poor-quality corms, inadequate water supply, unnoticed nutrient deficiencies, and fungal infections. It was noted that limited research has been conducted on leveraging smart sensors and IoT devices to enhance saffron farming conditions. Among the various IoT-driven models utilizing aeroponic, aquaponic, and hydroponic techniques for saffron growth, 22 models were identified as suitable for comparative analysis. Furthermore, it was discovered that only 25 out of 100 reviewed research papers were exclusively centered on saffron cultivation. The implementation of the proposed smart system will be explored as a part of future work.

Building on previous work (Roostaei et al., 2023)[4] the pilot study investigated various applications of the IoTEC computing architecture aimed at enhancing environmental monitoring by tackling issues such as data latency, high energy usage, and bandwidth expenses. The findings show that integrating diverse sensors and hardware platforms into IoT-based sensor networks, along with edge computing, can effectively minimize energy usage, reduce bandwidth requirements for data transmission, improve response times, and lower overall costs.

A significant contribution by (Xu et al., 2022) [5]demonstrated the Multifeatures Combination Network enhances sensing reliability by integrating perception data from multiple nodes. Unlike traditional cooperative spectrum sensing approaches that rely solely on binary decision outcomes, this method determines the final decision by incorporating the confidence level associated with each node's input. Simulation outcomes indicate that, with four nodes, the Multifeatures Combination Network delivers superior detection performance compared to conventional methods, particularly under challenging sensing conditions. Furthermore, the results confirm the model's strong generalization capability across different modulation schemes. While the proposed network demonstrates competitive and effective performance, it's important to note that computational complexity was not a primary focus in this study.

To conclude, these studies collectively highlight the significant advancements in IoT-based environmental monitoring systems, illustrating their effectiveness in addressing the limitations of traditional methods. The integration of multi-sensor networks, cloud platforms, and real-time data analytics has paved the way for more reliable, scalable, and cost-effective solutions across various industries. Building on these insights, the proposed system aims to further enhance environmental monitoring through a Wi-Fi-based, multi-node approach, addressing the specific challenges of grain storage and similar applications.

Sr. No	Title	Author, Year	Key Findings
1.	Design of Wi-Fi based IoT Sensor Node with Multiple Sensor Types	C.M. Shashika Madushan,M.W.P. Maduranga,P.I. Ishan Madushanka et al., 2021	Cooperative strategies in underwater sensor network protocols
2.	IoT Based Soil Health Monitoring System Using Soil Moisture Sensor and pH Sensor	Mrinalini BariNa, Sitanshu SeNhar Sahub, Rupesh Kumar Sinhac et al., 2023	Arduino-based soil monitoring using moisture and pH sensors
3.	Cooperative Communication Based Protocols for Underwater Wireless Sensors Networks	Muhammad Shoaib Khan 1 , Andrea Petroni 2 and Mauro Biagi et al., 2024	Comprehensive review of cooperative underwater sensor networks across protocol layers.
4.	iBUG: AI Enabled IoT Sensing Platform for Real-time Environmental Monitoring	M. F. Yousuf, T. Siddique and M. S. Mahmud et al., 2022	CO_2 prediction from gas resistance on iBUG using TensorFlow Lite
5.	Smart-Hydroponic-Based Framework for Saffron Cultivation: A Precision Smart Agriculture Perspective	Kanwalpreet Kour , Deepali Gupta , Kamali Gupta et al., 2022	Smart saffron hydroponics using NFT and renewable energy

6.	IoT-based edge computing (IoTEC) for improved environmental monitoring	Javad Roostaei a 1, Yongli Z. Wager a, Weisong Shi et al., 2023	IoTEC-based environmental monitoring with reduced latency and transmission.

Table.1 Literature Review

Feature	Traditional Monitoring	Proposed IoT System
Data Collection	Manual/Single-point	Multi-point, real-time
Accessibility	On-site only	Remote via mobile/web
Alert System	Absent	Real-time threshold alerts
Scalability	Limited	Easily expandable
Cost	Moderate to High	Low to moderate(per node)

Table.2 Comparative Analysis

METHODOLOGY :

2.1 Overview

This methodology presents the design and implementation of a distributed environmental monitoring and alert system using multiple autonomous sensor nodes. These nodes are strategically deployed across designated zones to continuously monitor key environmental parameters such as temperature and humidity. By leveraging a multi-node architecture, the system ensures comprehensive coverage and minimizes the risk of data gaps that often occur in traditional single-point sensing methods.

The system is specifically designed to address the limitations of conventional monitoring approaches, which typically rely on manual inspections or isolated sensors. Such methods can lead to incomplete or delayed data, hindering timely responses to environmental changes.[5] In contrast, the distributed network enables continuous, real-time data collection from various locations, improving the accuracy and reliability of environmental assessments.

To enhance usability and responsiveness, the system incorporates real-time alert mechanisms. These alerts are triggered whenever environmental readings deviate from predefined safety thresholds, promptly notifying users or administrators.[3] This immediate feedback allows for swift corrective actions, reducing the potential impact of adverse environmental conditions.

Overall, this approach offers a scalable and efficient solution for real-time environmental monitoring. It supports proactive environmental management and contributes to the protection of sensitive materials or equipment by enabling timely interventions through automated alerts.

2.2 Data Collection

Fresh rice : Freshly harvested rice is vulnerable to environmental factors like temperature, humidity, and moisture. If not carefully controlled, these conditions can cause spoilage, fungal growth, and loss of quality.

Fig. 1 Fresh rice

Degraded rice : degraded rice is usually caused by extended exposure to high humidity, temperature, or moisture. These conditions lead to fungal contamination, foul odor, and discoloration, making it unfit for consumption.

Fig. 2 Degraded rice

Damp soil : Excess moisture in potted soil can lead to poor aeration and root rot, affecting overall plant health. Prolonged wetness also encourages fungal growth and hampers nutrient absorption by the roots.

Fig. 3 Damp soil

Dry Soil : Dry soil in pots can limit water availability and hinder nutrient uptake, leading to wilting and stunted plant growth. Prolonged dryness also stresses the roots and reduces overall plant resilience.

Fig. 4 Dry Soil

S. No.	Node ID	Temperature (ºC)	Humidity(%)	Alert Triggered
1.	Node 1	27.5	63	No
2.	Node 2	30.2	70	Yes (humidity)
3.	Node 3	25.0	60	No

Table.3 Environmental Reading

Model Architecture

The architectural design of the proposed Multi-Node Environmental Monitoring System emphasizes scalability, robustness, and efficiency, making it suitable for real-time environmental sensing in diverse conditions. This system leverages the ESP32 microcontroller as its core computational unit and integrates it with DHT11 sensors for temperature and humidity measurement and a 16x2 character LCD display via the I2C protocol.

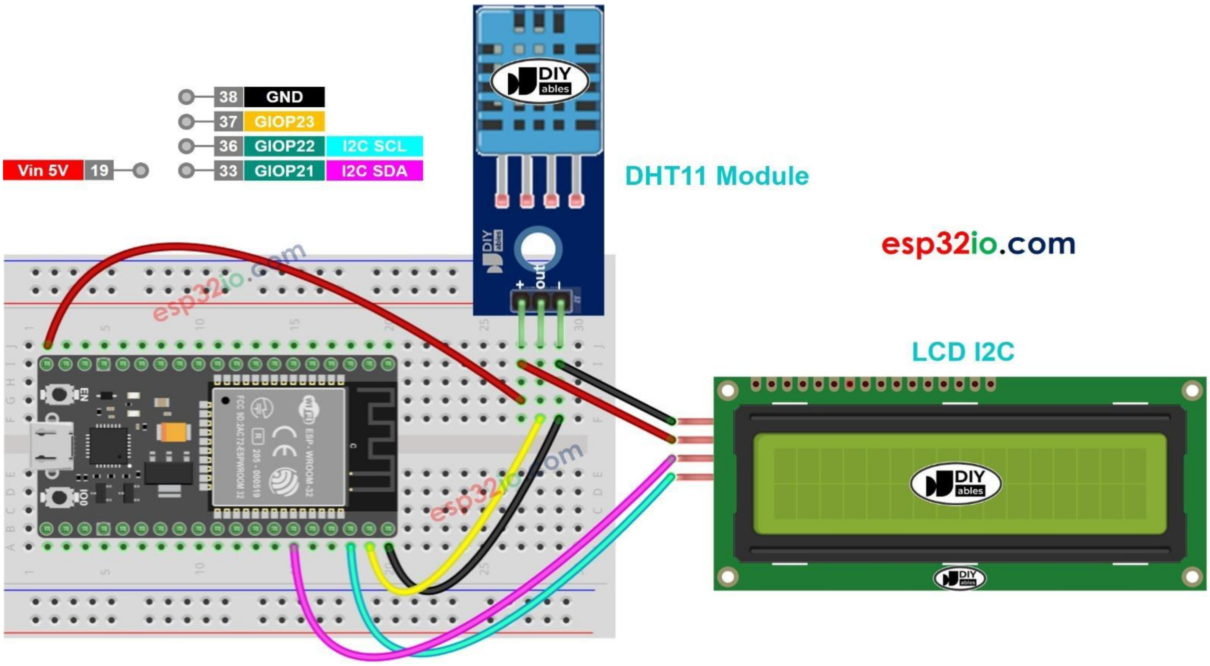

Fig. 5 Circuit Diagram

The entire setup is implemented on a custom-designed Printed Circuit Board (PCB), ensuring enhanced mechanical strength, stable power distribution, and reduced electrical noise—attributes that are critical for long-term field deployments.[7] The architecture supports the deployment of multiple sensor nodes across different zones or storage compartments, where each node operates autonomously while optionally transmitting data to a central system for broader environmental analysis. The architecture is functionally divided into three main components: the input section (responsible for data acquisition), the processing section (which performs data interpretation and communication), and the output section (which provides real-time data visualization).

- **Input Section**

The input stage is built around the DHT11 sensor, a cost-effective digital component capable of measuring both ambient temperature and relative humidity. The DHT11 contains a capacitive humidity sensor and a thermistor for temperature detection. These measurements are internally calibrated and converted into digital signals before being sent to the microcontroller. Each sensor is directly connected to the ESP32 via a dedicated GPIO pin—commonly GPIO23—along with a 5V supply and a common ground. The sampling interval is programmable and typically set to two seconds, allowing near real-time acquisition of environmental data. In a multi-node deployment scenario, several identical sensor nodes can be distributed across a large area, such as different compartments in a grain storage facility, to ensure comprehensive environmental monitoring. The digital nature of the DHT11's output ensures consistency across nodes, thereby enabling accurate spatial comparison of environmental conditions.

- **Processing Section**

The ESP32 microcontroller serves as the processing unit of the system. This dual-core SoC (System on Chip) not only provides powerful local data processing capabilities but also offers built-in Wi-Fi and Bluetooth communication modules, making it ideal for wireless sensor network applications. Upon receiving raw data from the DHT11 sensor, the ESP32 parses, validates, and converts the data into meaningful temperature and humidity values. These readings are then either displayed locally or transmitted to a remote monitoring platform. The ESP32 operates at 3.3V logic levels and is powered through a regulated 5V input distributed across the PCB. The microcontroller is programmed using the Arduino IDE, utilizing relevant libraries such as DHT.h for sensor communication and Wire.h for I2C communication.[8] Timers within the code regulate data sampling intervals and trigger periodic updates to both the display and any networked systems. The system also allows for the implementation of additional features, such as event logging, averaging algorithms, or threshold-based alerts, providing flexibility for a variety of use cases. Its modular code structure makes it easy to scale the system by adding more sensor nodes or enhancing its functionality.

- **Output Section**

The output stage features a 16x2 LCD module equipped with an I2C interface, which displays real-time temperature and humidity values to the user. This LCD communicates with the ESP32 using just two wires—SDA and SCL—connected to GPIO21 and GPIO22, respectively. The simplicity of the I2C interface reduces wiring complexity and preserves GPIO pins for other peripherals. After the ESP32 processes the environmental data, it formats and sends it to the LCD in a human-readable form, typically showing "Temp: XX.0°C" and "Hum: YY%". The display updates every few seconds, synchronizing with the sensor's sampling interval. The LCD includes a contrast control potentiometer and a backlight, enabling visibility in various lighting conditions. In practical applications, this local display allows operators to instantly check environmental conditions without needing network access or external devices. For larger deployments, the ESP32's wireless capabilities can be utilized to transmit the same readings to a cloud-based monitoring platform, ensuring both local and remote accessibility of data.

2.4 Work Flow

The environmental monitoring system operates through a structured and automated workflow that begins with hardware initialization and continues in a loop that includes data acquisition, processing, display, storage, threshold checking, and response mechanisms. The entire process is handled by the ESP32 microcontroller, which acts as the central control unit for orchestrating sensor interactions, data handling, and user interfacing.

The process initiates with the initialization of the ESP32 and the connected sensors. This step involves setting up GPIO pins, establishing communication protocols (I2C for the LCD, digital input for the DHT11 sensor), and loading necessary libraries through the Arduino IDE. Once the system is powered on and initialized, the ESP32 begins the acquisition of environmental data from the DHT11 sensor, which provides temperature and humidity readings at regular intervals. The DHT11 sensor transmits this data over a single digital pin, which the ESP32 reads using the DHT.h library.

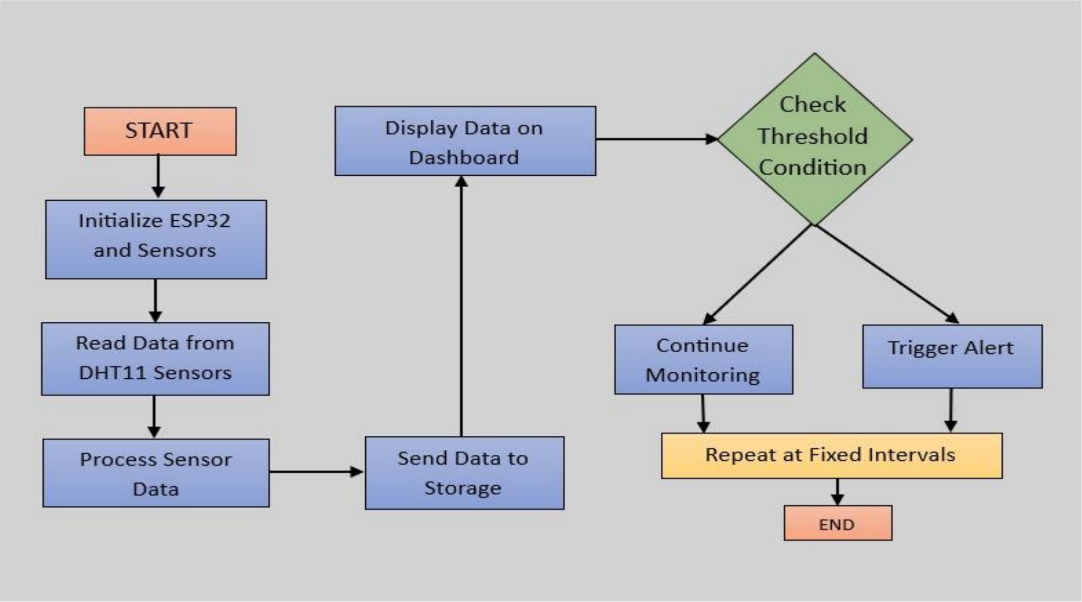

Fig.6 Flowchart

Once the raw data is collected, it is passed to the data processing unit within the ESP32's firmware. This involves converting sensor signals into human-readable values, rounding or formatting the readings, and preparing the data for further handling. Following this, the processed data is sent to two key destinations. First, it is displayed in real time on a 16x2 I2C LCD display, allowing users to monitor environmental conditions locally. Secondly, the data is transmitted to a remote storage platform, such as Blynk or ThingSpeak, using the ESP32's built-in Wi-Fi capabilities. This facilitates real-time cloud storage, remote dashboard visualization, and long-term data logging.

After the data is displayed and stored, the system proceeds to the threshold evaluation stage, where it checks whether the current environmental readings exceed predefined limits. These thresholds, which can be user-configured, represent critical values for temperature or humidity beyond which an alert must be issued. If the sensor readings remain within safe limits, the system simply continues monitoring and repeats the cycle at fixed intervals using a delay or timer-based approach.

If, however, the readings exceed the threshold, the ESP32 triggers an alert mechanism. This could involve activating a buzzer, sending a notification via the IoT dashboard, or flashing a warning on the LCD. Regardless of the outcome—whether continuing normal monitoring or responding to an alert—the system returns to its initial state after a set time interval, creating a looped and continuous monitoring cycle that runs autonomously.

This flow of operations ensures that the system is self-sufficient, responsive to environmental changes, and capable of both local and remote user interaction. The use of a custom PCB enhances system reliability and compactness, while the integration of real-time software platforms extends the monitoring capabilities beyond the immediate physical location, making it suitable for applications like precision agriculture, storage facility monitoring, or smart home systems.

Fig.7 Reading 1

[Sensor 3 is used, spoilage risk is low, ideal for long term storage.]

Fig.8 Reading 2

[Sensor 3 is used, spoilage risk is very high, immediate intervention is needed.]

Fig.9 Reading 3

[Sensor 2 is used, humidity is low, dry soil]

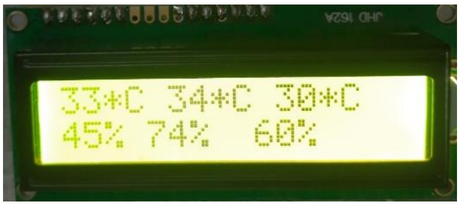

Fig.10 Reading 4

[Sensor 2 is used, humidity is high, damp soil]

EXPERIMENTAL RESULT

The Wi-Fi-based multi-node environmental monitoring system was tested in a controlled grain storage setup to evaluate its accuracy and performance. Sensor nodes recorded temperature and humidity data across different zones to identify spatial variations. The collected data was analyzed to assess the system's reliability, responsiveness, and ability to trigger real-time alerts. Results demonstrate improved monitoring coverage and early detection of unsafe conditions compared to traditional single-point methods.

3.1 Software Interface and Visualization

For real-time monitoring and visualization of environmental parameters, the proposed system leverages ThingsBoard v4.0.0, an open-source IoT platform, as a customized front-end dashboard. While ThingsBoard is widely used in industrial applications, our deployment introduces a domain-specific configuration tailored for grain storage environments, with a focus on spatially distributed sensing.

The dashboard interface has been adapted to visualize temperature and humidity data from three separate nodes (Temperature1–3 and Humidity1–3). Each node represents a distinct zone within a storage facility, allowing zone-wise trend analysis rather than general averages. The use of individual gauge widgets for each sensor offers immediate at-a-glance insight into local conditions, while the line chart below aggregates real-time trends over selectable time intervals, ensuring both micro-level and macro-level situational awareness.

Unlike standard implementations, our system introduces the following customizations:

- Node-specific labeling and color-coded readings for easy anomaly detection.
- A dedicated backend logic that classifies environmental conditions into "safe", "moderate risk", and "critical" categories based on real-time sensor inputs.

- A calibrated response system designed to trigger alerts when critical thresholds are crossed—for instance, temperature >30°C with humidity >50% initiates a spoilage risk notification.
- Integration with the Firebase real-time database (in future versions), enabling cross-platform data access via mobile/web without compromising latency.

The Arduino IDE is used to program the ESP32. Libraries specific to the hardware modules—such as DHT.h for sensor communication and LiquidCrystal_I2C.h for display output—are integrated into the code. The software handles tasks such as initializing the sensors, managing timing intervals, reading sensor data, formatting output strings, and updating the LCD or transmitting data over Wi-Fi. Data logging can be implemented using IoT platforms like Blynk, ThingSpeak, or Firebase, allowing for real-time cloud-based visualization and historical data tracking. These platforms enable mobile alerts, remote dashboards, and integration with web interfaces, enhancing the system's usability and effectiveness.

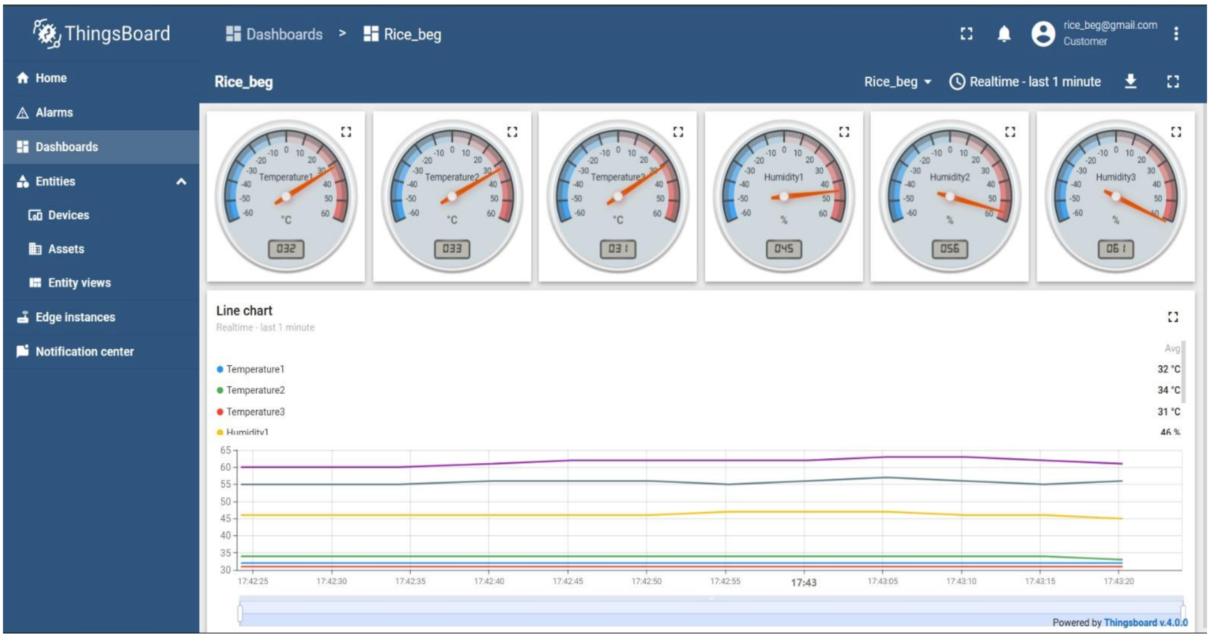

Fig. 11 Plot 1

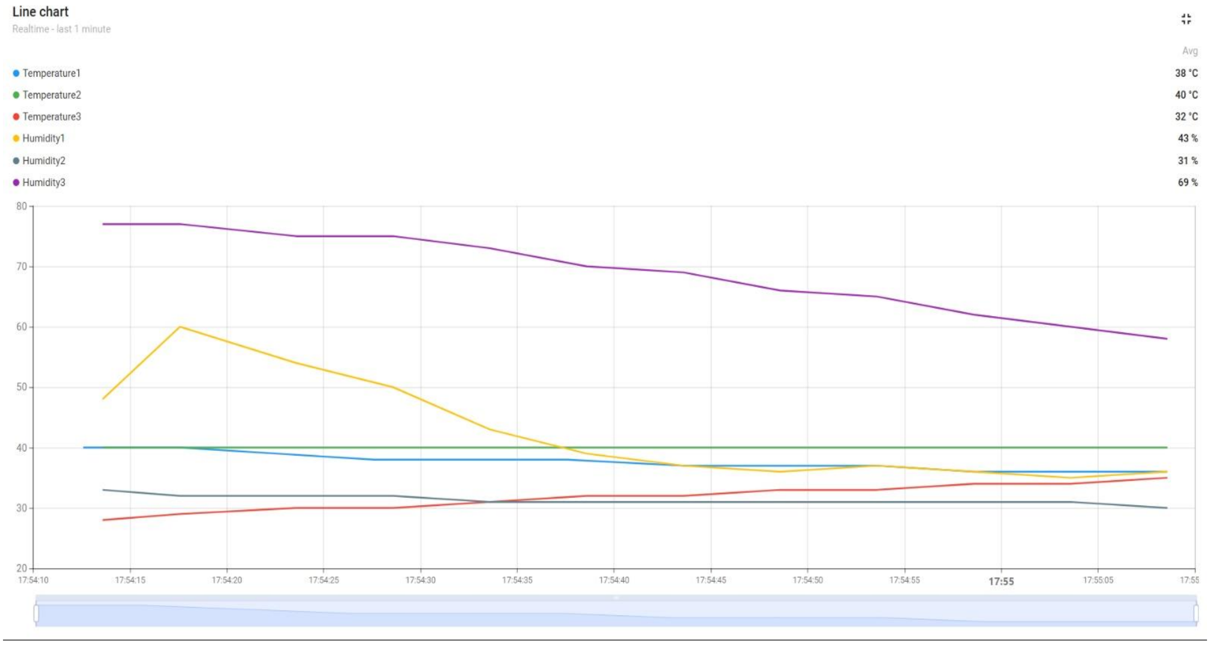

Fig. 12 Plot 2

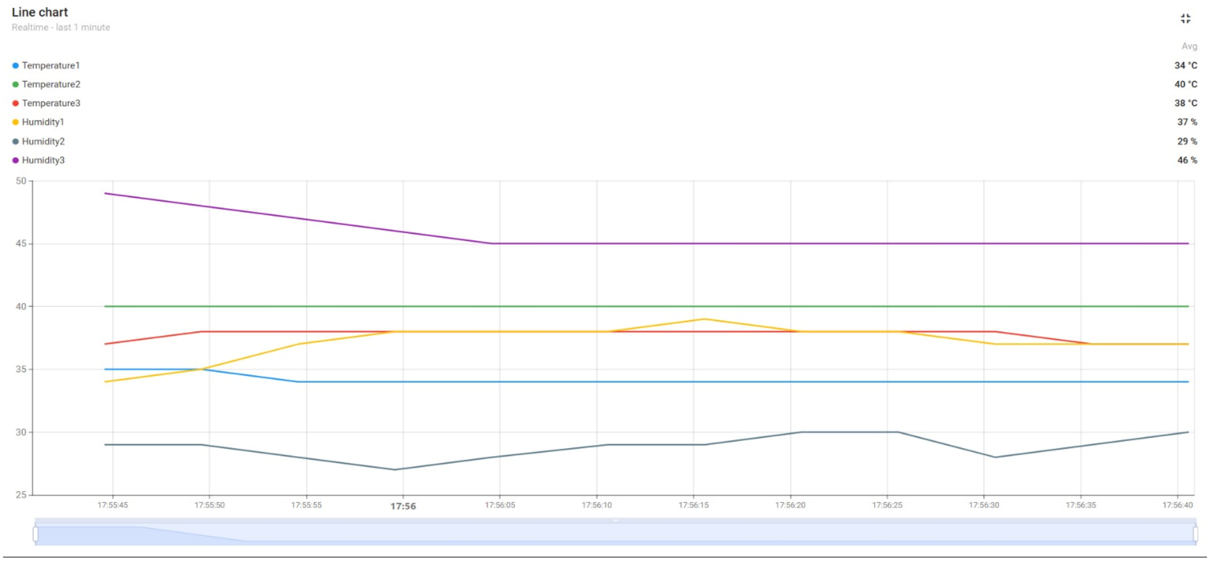

Fig. 13 Plot 3

Fig. 14 Plot 4

The plotted results indicate that the model has effectively learned to distinguish between different cases , as evidenced by the high accuracy metrics and low loss values.

3.2 Model Performance

Temp (°C)	Humidity (%)	Spoilage Risk	Fungal Growth Likelihood	Insect Activity	Storage Recommendation
20–25	40–55	Low	Minimal	Low	Ideal for long-term storage
26–30	56–65	Moderate	Possible	Moderate	Monitor regularly
31–35	66–75	High	Likely	High	Improve ventilation, dehumidify
36–40	76–85	Very High	Very Likely	Very High	Immediate intervention needed
> 40	> 85	Critical	Severe & rapid spoilage	Severe	Not suitable for storage

Table.4 Environmental condition and their impact on rice storage quality

The tabulated data highlights the direct relationship between elevated temperature and humidity levels and the increased risk of rice spoilage and fungal growth.[9] Notably, conditions above 30°C with relative humidity exceeding 70% showed a clear transition from moderate to high spoilage risk.[10] This emphasizes the critical need for continuous monitoring, as even brief exposure to such thresholds can initiate microbial activity. By deploying multi-node sensors, the system effectively captures these fluctuations across storage zones, enabling proactive intervention before irreversible damage occurs.[11] Such granular monitoring is essential for preserving grain quality and minimizing post-harvest losses in large-scale storage facilities.

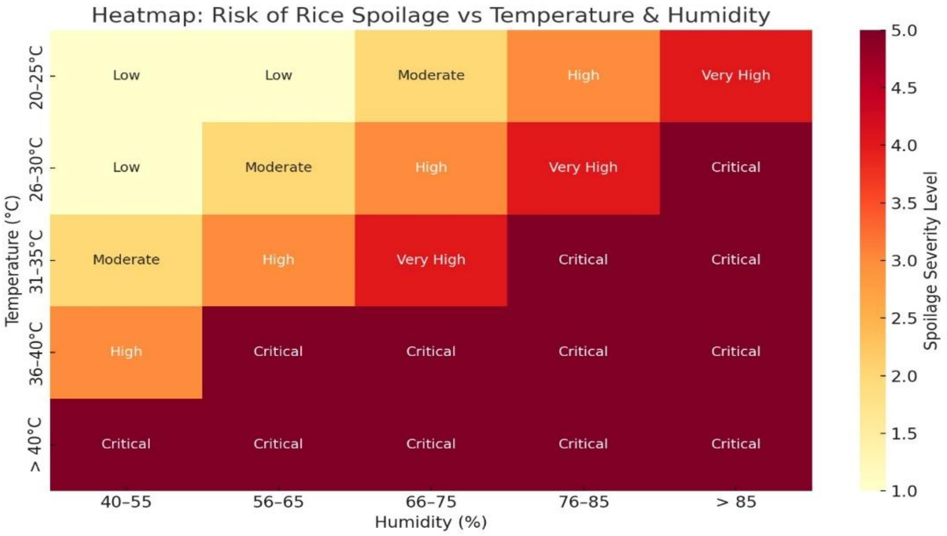

Fig.15 Suggested chart based on data

CONCLUSION

The multi-node environmental monitoring system developed in this study was successfully built and tested, demonstrating its effectiveness in capturing environmental parameters across different locations. Each node was designed to function autonomously, allowing for seamless monitoring without manual intervention. Sensors and controllers integrated into the system were thoroughly evaluated to ensure precision and real-time performance. The collected data showed consistent accuracy and stability, even under varying environmental conditions, confirming the system's reliability.

The architecture supports wireless data transmission, enabling real-time access to environmental information and long-term data storage for future analysis. This capability makes the system suitable for continuous monitoring applications without the need for physical data retrieval.

This system proves to be a practical solution for smart monitoring needs, offering reliable real-time data and seamless wireless communication. It is well-suited for applications like agriculture, storage, and environmental management.

FUTURE SCOPE

The future development of the environmental monitoring system lies in making it more intelligent, autonomous, and globally accessible. One of the most impactful directions is the integration of Artificial Intelligence (AI) and Machine Learning (ML). By using predictive models trained on historical data, the system can forecast spoilage risks or detect anomalies such as sudden spikes in temperature or humidity. With Edge AI, lightweight ML models can be deployed directly on the ESP32, enabling real-time decision-making without cloud dependency. This also allows features like adaptive sampling to conserve power and multi-sensor data correlation to uncover deeper patterns in environmental behavior.

In addition to AI/ML capabilities, the system can be made more sustainable through the use of solar-powered nodes, ensuring continuous operation in off-grid or rural areas. The deployment of LEO satellite communication will further extend its reach, enabling real-time data collection from remote or hard-to-access regions.

Scalability is another promising area, with potential applications in agriculture, industry, and smart cities. By incorporating additional sensors such as CO_2, light intensity, and soil moisture, the system can support precision farming, climate-controlled storage, or urban air quality monitoring.

Together, these advancements will evolve the system into a comprehensive, intelligent, and energy-efficient solution for future environmental monitoring challenges.

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