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IoT-Based Grain Quality Monitoring System with Real-Time Environmental Analysis and Predictive Insights

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***Abstract*—Grain storage losses remain a critical challenge in developing countries due to inadequate monitoring of environmental conditions such as temperature, humidity, moisture content, and pest activity. Traditional storage practices rely on manual inspection and lack real-time visibility, leading to delayed interventions and significant post-harvest losses. This paper presents an IoT-based Grain Quality Monitoring System designed to provide continuous, real-time assessment of storage conditions using low-cost sensors and cloud connectivity. The proposed system integrates temperature, humidity, moisture, gas, and motion sensors with a microcontroller-based architecture to monitor grain storage environments effectively. Sensor data are transmitted wirelessly to a cloud platform for visualization, historical analysis, and alert generation. In addition, machine learning techniques are employed to predict grain shelf life and assist in grain-type identification, enabling proactive decision-making for improved storage management. The system is designed to be portable, affordable, and user-friendly, making it suitable for small-scale farmers and decentralized storage facilities. Experimental evaluation demonstrates reliable real-time monitoring, early detection of unfavorable storage conditions, and improved decision support through predictive analysis. The proposed solution offers a scalable and practical approach to reducing post-harvest grain losses and enhancing food security through intelligent storage monitoring.**

***Index Terms*—Internet of Things (IoT), Grain Quality Monitoring, Smart Agriculture, Sensor Networks, Machine Learning, Post-Harvest Management.**

I. INTRODUCTION

Grain storage is a critical stage in the agricultural supply chain, as it directly influences food security, farmer income, and market stability. In many developing regions, a significant portion of harvested grains is lost during storage due to unfavourable environmental conditions such as high temperature, excess humidity, moisture accumulation, pest infestation, and poor ventilation. These factors accelerate microbial growth, insect activity, and chemical degradation, resulting in reduced grain quality and economic losses. According to various agricultural studies, post-harvest losses in cereals can exceed 20–30% when scientific storage practices are not followed.

Traditional grain storage methods largely depend on manual inspection and periodic checks, which are often inaccurate, labour-intensive, and incapable of providing early warnings. Farmers are usually unable to detect gradual changes in storage conditions until visible spoilage occurs, by which time corrective action becomes ineffective. Additionally, most conventional monitoring solutions are either expensive, centralized, or unsuitable for small-scale and rural storage facilities, limiting their adoption.

Recent advancements in the Internet of Things (IoT) have enabled the development of low-cost, sensor-based monitoring systems capable of collecting real-time environmental data from distributed locations. IoT-based systems facilitate continuous monitoring, remote access, and automated alerts, allowing timely interventions to maintain optimal storage conditions. Parameters such as temperature, humidity, moisture content, gas concentration, and pest activity can be monitored continuously, providing actionable insights into grain health and storage safety.

Alongside IoT, machine learning techniques have gained attention in agricultural applications for predictive analysis and decision support. By analyzing historical and real-time sensor data, machine learning models can estimate grain shelf life, detect abnormal storage patterns, and assist in grain-type identification. Such predictive capabilities transform grain storage management from a reactive process into a proactive and intelligent system.

In this context, this paper proposes an IoT-based Grain Quality Monitoring System that integrates multi-sensor data acquisition, cloud-based visualization, and machine learning–driven analysis. The system is designed to be portable, affordable, and user-friendly, making it suitable for small-scale farmers and decentralized storage environments. By enabling real-time monitoring, early detection of adverse conditions, and predictive insights, the proposed solution aims to reduce post-harvest losses and improve the overall efficiency of grain storage management.

II. LITERATURE SURVEY

The application of Internet of Things (IoT) technologies in agricultural storage systems has gained significant attention in recent years due to the growing need to reduce post-harvest losses and improve food security. Several studies have explored sensor-based monitoring solutions to track environmental parameters affecting grain quality during storage, such as temperature, humidity, moisture content, and gas concentration.

Early research in grain storage monitoring primarily focused on basic environmental sensing. IoT-based systems were proposed to continuously measure temperature and humidity inside storage facilities, enabling real-time data logging and remote visualization. These systems demonstrated that continuous monitoring could help maintain optimal storage conditions and prevent spoilage caused by excessive moisture and heat. However, many of these approaches were limited to data monitoring and lacked intelligent decision-making capabilities.

Subsequent studies extended IoT-based grain monitoring by integrating cloud platforms and wireless communication technologies. These systems enabled farmers to access real-time data through web dashboards or mobile applications and receive alerts when storage conditions exceeded predefined thresholds. While such solutions improved accessibility and responsiveness, they largely relied on rule-based alerts and did not incorporate predictive analytics or long-term trend analysis.

Machine learning techniques have been increasingly investigated to enhance grain storage management. Several researchers applied predictive models to estimate grain shelf life and assess quality degradation based on historical environmental data. Weather forecasting and environmental trend analysis using machine learning algorithms were shown to improve storage planning and reduce spoilage risks. However, most implementations focused on isolated prediction tasks and were not fully integrated with real-time IoT monitoring systems.

Recent works have explored the combined use of IoT and artificial intelligence for grain quality assessment. These systems integrated multiple sensors with machine learning models to detect anomalies, predict storage outcomes, and improve decision support. Some studies also investigated pest detection and gas monitoring to identify early signs of infestation or fermentation. Although these approaches demonstrated promising results, many solutions were designed for large-scale silos or industrial storage facilities, making them unsuitable for small-scale farmers due to high cost, power consumption, or system complexity.

In addition, several existing systems depend on GSM-based communication or proprietary platforms, leading to recurring operational costs and limited scalability. Others lack portability or user-friendly interfaces, which restricts their adoption in rural and decentralized storage environments.

From the reviewed literature, it is evident that while IoT-based monitoring and machine learning-based prediction have been studied independently and in limited combinations, there remains a gap in developing a unified, low-cost, portable grain quality monitoring system that integrates real-time multi-sensor monitoring, cloud-based visualization, and predictive analytics in a single framework. Addressing this gap is essential to provide small-scale farmers with an affordable and intelligent solution for proactive grain storage management.

III. PROPOSED SYSTEM AND ARCHITECTURE

The proposed IoT-based Grain Quality Monitoring System is designed to provide continuous, real-time assessment of storage conditions affecting grain quality. The system integrates multi-sensor data acquisition, wireless communication, cloud-based data management, and machine learning–based analysis into a unified and scalable framework. The primary objective is to enable early detection of adverse storage conditions and support proactive decision-making for improved grain preservation.

A. System Overview

The system consists of four major functional layers:

a) Sensing Layer
b) Processing and Control Layer
c) Communication and Cloud Layer
d) Analytics and User Interface Layer

Each layer plays a specific role in monitoring, processing, transmitting, and analyzing grain storage data to ensure reliability and usability in real-world agricultural environments.

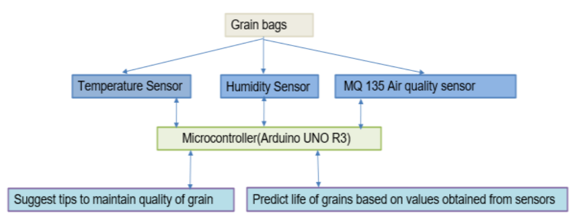

Fig. 1. Flow Diagram and Working Mechanism.

a) Sensing Layer:

The sensing layer is responsible for capturing critical environmental parameters that directly influence grain quality. A set of low-cost sensors is deployed inside the storage environment to monitor:

- Temperature and Humidity: to detect conditions that promote microbial growth and spoilage.
- Moisture Content: to assess grain dryness and prevent mold formation.
- Gas Concentration: to identify the presence of hazardous or fermentation-related gases.
- Pest and Rodent Activity: to enable early detection of infestation through motion sensing.

These sensors continuously collect data at regular intervals, ensuring comprehensive coverage of storage conditions.

b) Processing and Control Layer:

A microcontroller-based unit acts as the core processing element of the system. It performs real-time sensor data acquisition, preprocessing, and local decision logic. The controller aggregates sensor readings, filters noise, and formats the data for transmission. A user input interface allows selection of grain type, enabling grain-specific analysis and recommendations.

An on-device display module provides real-time visualization of key parameters, allowing farmers to access storage conditions locally without requiring internet connectivity.

c) Communication and Cloud Layer:

To enable remote monitoring and data logging, the system employs a wireless communication module that transmits sensor data to a cloud-based IoT platform. The cloud layer performs the following functions:

- Real-time data storage and visualization
- Historical trend analysis
- Threshold-based alert generation
- Secure remote access through web or mobile dashboards

This architecture allows farmers and storage operators to monitor grain conditions from any location and receive timely alerts when parameters exceed safe limits.

d) Analytics and Machine Learning Layer:

To enhance decision-making, machine learning techniques are integrated into the system. Historical and real-time sensor data are analyzed to:

- Predict grain shelf life based on environmental trends
- Identify abnormal storage patterns
- Assist in grain-type identification using image-based analysis
- Machine learning models are trained using labeled datasets and validated to ensure reliable predictions. By combining predictive analytics with real-time monitoring, the system shifts grain storage management from a reactive to a proactive approach.

IV. METHODOLOGY

The methodology of the proposed IoT-based Grain Quality Monitoring System focuses on systematic data acquisition, real-time monitoring, cloud-based processing, and predictive analysis using machine learning techniques. The workflow is designed to ensure reliable sensing, efficient data handling, and meaningful decision support for grain storage management.

a) Data Acquisition
Environmental data are continuously collected using a network of sensors deployed within the grain storage environment. Each sensor measures a specific parameter critical to grain preservation, including temperature, relative humidity, moisture content, gas concentration, and pest or rodent activity. Sensor readings are sampled at predefined intervals to capture both short-term fluctuations and long-term trends affecting grain quality.
The raw sensor data are acquired by the microcontroller, which performs initial validation to ensure data integrity. Noise reduction and basic preprocessing are applied to eliminate erroneous readings caused by sensor drift or transient disturbances.

b) Local Processing and Monitoring Logic
The microcontroller serves as the local control unit, coordinating sensor inputs and executing monitoring logic. Threshold values are defined for each parameter based on safe storage conditions. When a parameter exceeds its allowable range, the system flags the condition locally and prepares the data for immediate transmission to the cloud platform.
A grain-type selection mechanism allows the system to apply grain-specific thresholds and recommendations. This ensures that monitoring and alerts are tailored to the storage requirements of different grains.

c) Data Transmission and Cloud Integration
Processed sensor data are transmitted wirelessly to a cloud-based IoT platform using a Wi-Fi communication module. The cloud platform performs real-time data logging and visualization, enabling users to monitor current storage conditions through dashboards and graphical representations.
Historical data are stored securely to support trend analysis and long-term evaluation of storage performance. Alert mechanisms are implemented to notify users when critical conditions are detected, enabling timely corrective actions.

d) Machine Learning–Based Analysis
Machine learning techniques are employed to enhance the analytical capabilities of the system. Historical sensor data are used to train predictive models that estimate grain shelf life and identify abnormal storage patterns. Data preprocessing steps include normalization, feature selection, and labelling based on environmental conditions and grain type.
In addition, image-based analysis is utilized for grain-type identification and potential pest detection. Trained models analyze visual input to assist in classification and anomaly detection. The integration of machine learning enables predictive insights that go beyond simple threshold-based monitoring.

e) Decision Support and User Interaction
The results of real-time monitoring and predictive analysis are presented to users through an intuitive interface. Visual indicators, alerts, and recommendations help users understand storage conditions and take preventive measures. By combining real-time sensing with predictive analytics, the system supports proactive grain management rather than reactive responses.

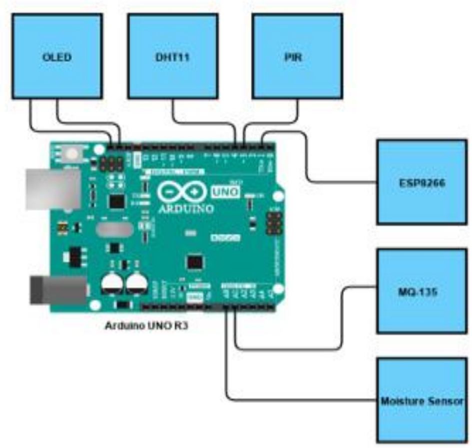

Fig. 2. Circuit Overview

V. APPLICATION - INTERFACE MODULE

The performance of the proposed IoT-based Grain Quality Monitoring System was evaluated through real-time deployment and continuous monitoring of grain storage conditions. The system was tested under varying environmental scenarios to assess its reliability, responsiveness, and usefulness in practical storage environments.

a) Real-Time Monitoring Performance

The system successfully monitored critical environmental parameters, including temperature, humidity, moisture content, gas concentration, and pest activity, in real time. Sensor readings were captured at regular intervals and transmitted to the cloud platform without significant latency. The collected data were visualized through graphical dashboards, enabling users to observe instantaneous values as well as long-term trends.

Temperature and humidity variations were accurately detected, allowing early identification of conditions conducive to spoilage or microbial growth. Moisture monitoring proved effective in identifying unsafe storage conditions that could lead to mold formation. Gas sensing further enhanced safety by indicating abnormal gas buildup within the storage environment.

Figs. 4-6 shows the variation of environmental parameters over time is analyzed using graphical representation for better understanding of storage conditions.

Fig. 3. ThingSpeak Temp v/s Time

Fig. 4. ThingSpeak Humidity v/s Time

Fig. 5. ThingSpeak Moisture v/s Time

b) Machine Learning–Based Predictive Analysis

Machine learning techniques are used to analyze collected data and predict future environmental conditions. Regression models are developed using Python libraries such as sklearn to forecast temperature and other parameters for the next 15 days.

The prediction of environmental conditions helps in estimating grain shelf life and enables proactive decision-making for maintaining optimal storage conditions.

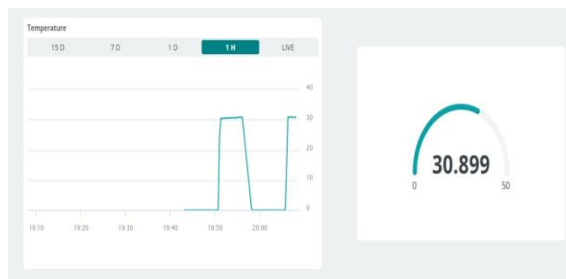

Fig. 6. Temperature Prediction

Fig. 7. Humidity Prediction

Fig. 8. Moisture Prediction

c) Practical Applicability and Discussion

Fig. 9. Logitech Webcam Used for Image Capture

Fig. 10. Grain Type Detection – Wheat

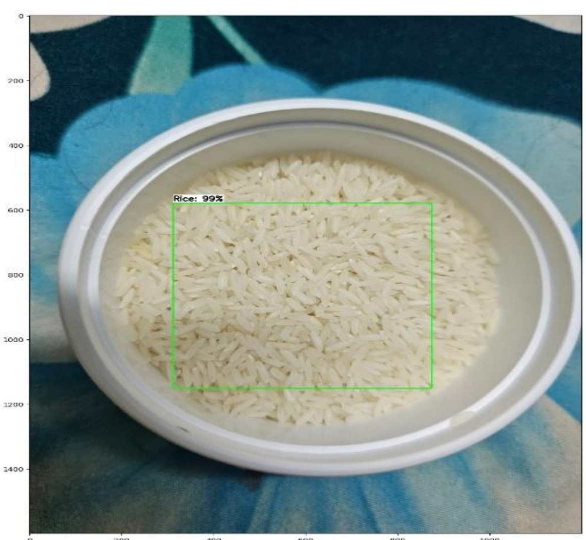

Fig. 11. Grain Type Detection – Rice

Fig. 12. Grain Type Detection – Ragi

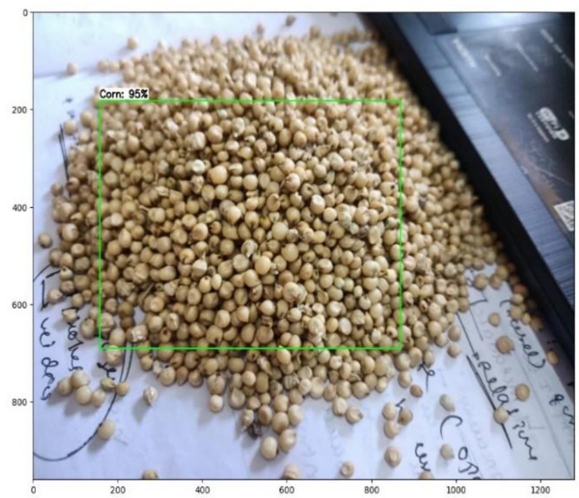

Fig. 13. Grain Type Detection – Corn

The system incorporates grain type detection using a Raspberry Pi 3B integrated with a webcam for capturing images of different grains. The captured images are processed using TensorFlow-based object detection models to identify and classify grain types such as rice, wheat, ragi, and corn.

The dataset used for training consists of labeled images of different grain types. These images are collected and preprocessed to ensure accurate model training and validation.

A suitable machine learning model is selected and trained using TensorFlow. The trained model is then converted into TensorFlow Lite format for efficient deployment on the Raspberry Pi system.

The detection system identifies the grain type based on the input image and provides corresponding outputs, which are used by the system to generate relevant predictions and recommendations for storage conditions.

VI. RESULT

The system generates a report based on the collected sensor data and analysis. The report includes parameters such as temperature, humidity, and moisture level along with condition status and predicted grain shelf life. This enables users to understand the current storage conditions and take necessary actions to maintain grain quality.

The generated output report is shown in Fig. 14.

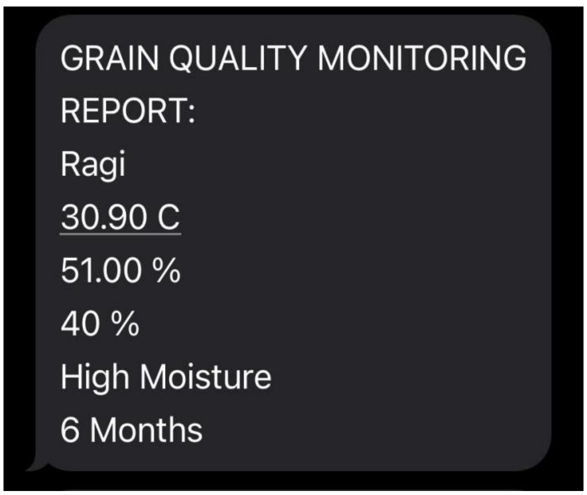

Fig. 14. Report Generation

The developed system successfully monitors grain storage conditions in real time using multiple sensors for temperature, humidity, moisture, gas concentration, and pest activity. The collected data is transmitted through the NodeMCU ESP8266 module to the ThingSpeak server, where it is stored and visualized for continuous monitoring. The graphical representation of sensor data enables effective analysis of environmental variations affecting grain quality.

The system also implements machine learning techniques to predict future environmental conditions and estimate grain shelf life based on parameters such as temperature, humidity, and moisture. The prediction results provide useful insights for maintaining optimal storage conditions.

In addition, the system generates a report that includes sensor readings, condition status, and predicted shelf life, allowing users to understand the current state of grain storage. Alerts and recommendations are provided to notify users about critical conditions such as high moisture or temperature fluctuations.

The integration of IoT and machine learning improves decision-making and enables timely actions to prevent spoilage and pest infestation. Overall, the system demonstrates an effective and cost-efficient solution for enhancing grain quality monitoring and reducing post-harvest losses.

VII. CONCLUSION

This paper presented an IoT-based Grain Quality Monitoring System designed to address the challenges of post-harvest grain storage through real-time environmental monitoring and predictive analysis. By integrating multiple sensors with wireless communication and cloud-based data management, the system enables continuous monitoring of critical parameters such as temperature, humidity, moisture content, gas concentration, and pest activity. The incorporation of machine learning techniques further enhances the system by providing predictive insights, including grain shelf-life estimation and grain-type identification.

Experimental evaluation demonstrates that the proposed system is capable of reliably detecting unfavourable storage conditions and generating timely alerts, allowing proactive interventions to preserve grain quality. The low-cost, portable, and scalable architecture makes the system particularly suitable for small-scale farmers and decentralized storage facilities. Overall, the proposed approach contributes to reducing post-harvest losses, improving storage efficiency, and supporting informed decision-making in grain storage management.

Although the proposed system delivers effective real-time monitoring and predictive capabilities, several enhancements can be considered for future development. The accuracy of predictive models can be improved by incorporating larger datasets, additional grain varieties, and adaptive learning techniques. Integration of advanced sensors for precise moisture and gas analysis can further improve storage condition assessment.

Future work may also focus on automating corrective actions such as ventilation or environmental control based on system recommendations. The inclusion of low-power wide-area communication technologies could extend system deployment to remote locations with limited connectivity. Additionally, integrating mobile-based decision support systems and multilingual user interfaces would enhance accessibility and adoption among farmers. These extensions can further strengthen the role of intelligent IoT-based solutions in sustainable agricultural storage management. capabilities.

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