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RiceShield: AI–IoT-Based Early Pest and Spoilage Prediction for Grain Storage

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Abstract
Post-harvest grain storage often suffers significant losses from unnoticed pest infestations and spoilage. These issues usually start internally and go undetected until serious damage happens. To tackle this problem, we introduce RiceShield, a smart grain protection system using AI and IoT technology. This system predicts and identifies early signs of infestations in stored rice. RiceShield monitors important environmental factors like gas concentration, temperature, humidity, and monitoring by Camera controlled by an ESP32 platform. An increase in carbon dioxide levels is a warning sign of pest activity, while ammonia presence points to spoilage caused by microbial growth. By continuously tracking these conditions and sending timely alerts, the system allows for early action before visible damage occurs. This approach provides a non-invasive, cost- effective, and scalable solution that improves grain safety, reduces post-harvest losses, and supports sustainable agricultural storage methods.

Keywords: *Esp32; Internet of things; Pest detection; Smart grain storage; Spoilage prediction*

1. Introduction

Post-harvest grain storage is a critical component of the agricultural supply chain, directly influencing food quality, safety, and economic sustainability. Rice and other stored grains are highly vulnerable to pest infestation, microbial spoilage, and adverse environmental conditions during storage. These issues often originate inside grain bags and remain unnoticed in the early stages, resulting in significant losses before corrective measures are taken. Conventional storage practices rely on manual inspection and periodic fumigation, which are reactive, labor-intensive, and environmentally hazardous. Hence, there is a growing need for intelligent monitoring systems capable of providing early warnings of storage risks (Ishimwe et al., 2023; Hema et al., 2020) [2,4].

Recent advances in Internet of Things (IoT) technologies have enabled real-time monitoring of storage environments through distributed sensors. IoT-based grain and crop storage systems have demonstrated improved control over temperature and humidity, thereby reducing spoilage risks (Ishimwe et al., 2023; Arun, 2024) [2,3]. However, many existing systems primarily focus on parameter monitoring and alerting, without sufficient emphasis on early-stage pest activity or internal spoilage detection. As a result, hidden infestations often progress undetected until visible damage occurs.

1.1. Related Work on Smart Grain Storage Monitoring

To overcome the limitations of conventional storage practices, recent studies have explored the integration of artificial intelligence and advanced analytics with grain storage monitoring. Deep learning-based frameworks have demonstrated strong potential in predicting storage risks by analyzing multi-sensor data and environmental patterns (Li et al., 2025; Anukiruthika & Jayas, 2025) [1,5]. These approaches emphasize the importance of intelligent data interpretation for proactive storage management. However, the deployment of AI-driven systems in real-world grain storage environments is often constrained by high computational requirements, system complexity, and increased deployment cost. Several researchers have proposed smart monitoring solutions for controlled and

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hermetic grain storage facilities, highlighting the effectiveness of remote supervision and automated control (Bouras et al., 2024) [6]. Earlier works on pest detection in stored grains have shown that pest activity can be inferred using indirect indicators and pattern recognition techniques, rather than relying solely on continuous visual inspection (Santiago et al., 2017) [7]. More recently, IoT systems integrated with artificial intelligence have been recognized as key enablers for precision agriculture, while also acknowledging the practical limitations of real-time image processing at the edge (Senoo et al., 2024) [8].

1.2. Motivation and Contributions of the Proposed System

Motivated by the limitations observed in existing grain storage monitoring systems, this paper presents a smart grain storage solution aimed at early pest and spoilage detection in rice storage environments. The proposed system adopts a zone-based monitoring approach, where a cluster of rice bags is supervised using environmental sensors. Temperature and humidity are monitored using a DHT11 sensor, while gas-based indicators are employed to identify different stages of infestation. A CO_2 sensor is used to detect early pest respiration activity, and an MQ137 sensor identifies ammonia release associated with advanced spoilage. In addition, a camera module captures still images of the storage zone at fixed intervals of two minutes, enabling visual verification without continuous image processing. The originality of the proposed work lies in its multi-parameter sensing strategy combined with zone-level analysis, which enables early detection while maintaining low system complexity and deployment cost. By integrating environmental sensing with periodic image capture and IoT-based alerts, the system provides a practical, scalable, and implementation-friendly solution for smart grain storage applications (Li et al., 2025; Anukiruthika & Jayas, 2025) [1,5].

2. Method

This section describes the methodology adopted for the proposed smart grain storage monitoring system. The method is designed to enable early detection of pest infestation and spoilage in rice storage environments using IoT-based sensing and periodic visual verification. The overall approach combines environmental parameter monitoring, zone-based analysis, and IoT-enabled alerting. Previously established IoT monitoring procedures are adapted from existing literature, while the integration strategy and sensing logic are newly implemented (Ishimwe et al., 2023; Arun, 2024) [2,3]. The system follows a zone-based monitoring approach, where a group of rice bags is considered as a single monitoring unit. Each zone is equipped with a set of sensors to capture localized environmental changes caused by pest activity and spoilage. This approach reduces system complexity while maintaining effective coverage, as demonstrated in earlier grain storage monitoring studies (Hema et al., 2020; Bouras et al., 2024) [4,6].

2.1. System Architecture and Sensor Configuration

The proposed system consists of an ESP32-based controller interfaced with multiple sensors for continuous environmental monitoring. Temperature and humidity are measured using a DHT11 sensor, which provides sufficient resolution for identifying unfavorable storage conditions. Gas-based indicators are employed to detect different stages of infestation. A CO_2 sensor is used to identify early pest respiration activity, while an MQ137 sensor detects ammonia release associated with advanced spoilage and microbial decomposition (Anukiruthika & Jayas, 2025) [5]. To support visual verification, a camera module captures still images of the monitored zone at fixed intervals of two minutes. This periodic image capture avoids continuous video processing and high computational overhead, while still providing visual evidence of external pest activity or bag damage. The images are transmitted via Wi-Fi and can be stored or analyzed offline if required. Similar visual monitoring concepts have been discussed in intelligent inspection and agricultural monitoring systems (Li et al., 2025; Senoo et al., 2024) [1,8]. The collected sensor data are processed locally by the ESP32, and predefined threshold logic is used to identify abnormal storage conditions. When threshold values are exceeded, alerts are generated and transmitted through an IoT communication channel.

2.2. Data Acquisition and Decision Logic

Sensor data are sampled at regular intervals and analyzed using a rule-based decision logic. Temperature and humidity readings are continuously

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compared against predefined safe thresholds. A gradual increase in CO_2 concentration is interpreted as an early indicator of pest respiration, while elevated ammonia levels indicate advanced spoilage conditions *(Santiago et al., 2017)* [7]. When multiple abnormal indicators are detected within a zone, the system categorizes the condition as critical and triggers alert notifications. The zone-based analysis enables differentiation between localized and widespread storage issues, reducing false alarms and improving response accuracy. This method aligns with recent smart grain storage monitoring strategies reported in the literature *(Arun, 2024; Bouras et al., 2024)* [3,6].

Table 1. Experimental Input Parameters for Grain Storage Monitoring

Parameter	Sensor Used	Operating Range	Purpose
Temperature	DHT11	0–50 °C	Detection of abnormal heat rise
Humidity	DHT11	20–90 %RH	Identification of moisture buildup
CO_2 concentration	CO_2 sensor	Relative change	Early pest respiration detection
Ammonia (NH_3)	MQ137	Relative change	Advanced spoilage detection
Image capture interval	Camera module	2 minutes	Visual verification
Monitoring approach	Zone-based	5–10 bags per zone	Localized analysis

2.3.IoT Communication and Alert Mechanism

The ESP32 controller transmits sensor readings and alert messages over a wireless network to a remote monitoring interface. Alerts are generated only when abnormal conditions persist beyond a defined duration, ensuring reliable notification and avoiding unnecessary warnings. The IoT-based communication framework is adapted from established real-time monitoring systems used in agricultural storage applications *(Ishimwe et al., 2023)*[2].

3. Results and Discussion

3.1.Results

The performance of the proposed smart grain storage monitoring system was evaluated through controlled experimental observation and simulation-based validation. The experiments were designed to assess the system's ability to detect abnormal storage conditions related to pest infestation and spoilage using environmental sensing and zone-based analysis. Each monitoring zone consisted of a cluster of rice bags equipped with temperature, humidity, gas, and visual monitoring components.

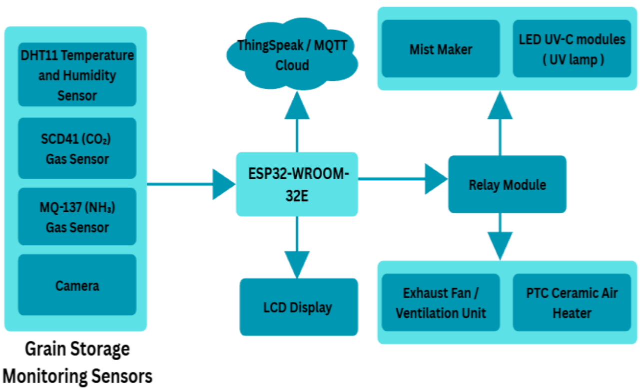

Figure 1 Overall System Architecture of the Proposed Smart Grain Storage Monitoring System

Under normal storage conditions, temperature and humidity values remained within safe limits, and gas sensor readings exhibited stable baseline behavior. When pest-like conditions were simulated, a gradual increase in CO_2 levels was observed, indicating early biological activity within the storage zone. This

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increase occurred before any visible external damage, confirming the effectiveness of gas sensing for early-stage detection. In advanced spoilage scenarios, elevated ammonia levels were detected by the MQ137 sensor, corresponding to microbial decomposition processes.

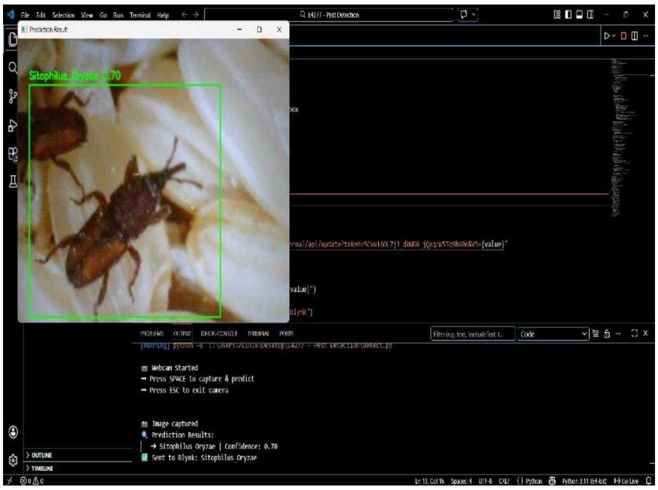

Figure 2. Real-Time Detection of *Sitophilus Oryzae* in Stored Grain

Temperature and humidity variations were also monitored throughout the experiments. A localized rise in temperature and humidity was observed in zones experiencing abnormal gas levels, supporting the correlation between environmental conditions and infestation risk. The zone-based approach enabled effective localization of abnormal conditions without requiring individual sensor deployment for each rice bag. The camera module successfully captured still images of the monitored zones at fixed intervals of two minutes. These images provided visual confirmation of external changes such as bag damage or pest presence, without continuous video streaming. The periodic image capture strategy reduced computational and communication overhead while maintaining sufficient visual evidence for verification. The overall system response, including alert generation, was consistent and reliable across different test conditions. The experimental results demonstrate that the proposed system effectively identifies early and advanced storage risks using multi-parameter sensing combined with zone-based monitoring. The observed increase in CO_2 concentration prior to visible damage highlights the importance of gas-based indicators for early pest detection. This finding aligns with earlier research emphasizing the role of indirect indicators in identifying pest activity in stored grains *(Santiago et al., 2017)* [7].

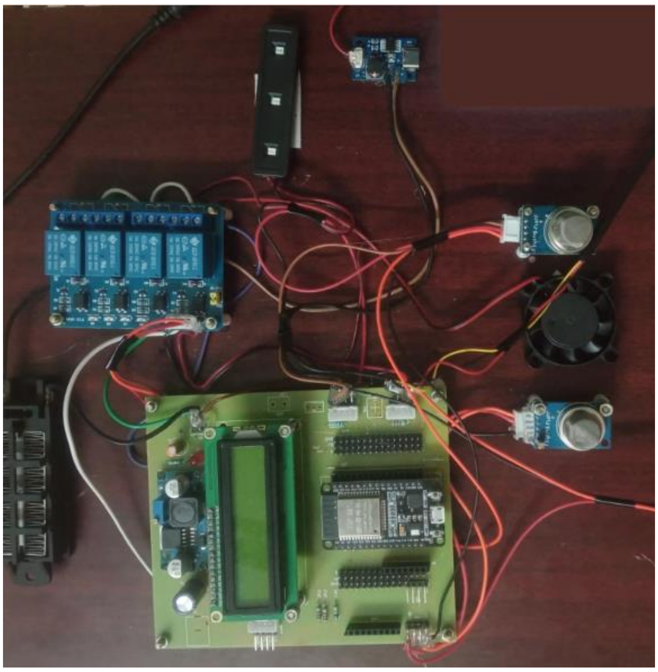

Figure 3 Hardware Implementation

3.2.Discussion

Ammonia detection using the MQ137 sensor proved effective in identifying advanced spoilage conditions, reinforcing the distinction between early infestation and later stages of grain degradation. The combined use of CO_2 and ammonia sensing enabled a layered detection strategy, improving decision reliability compared to single-parameter systems. Similar multi-sensor approaches have been recognized as essential for robust grain storage monitoring *(Anukiruthika & Jayas, 2025)* [5]. The zone-based monitoring approach significantly reduced system complexity while maintaining effective detection accuracy. Instead of deploying sensors on every rice bag, monitoring clusters allowed localized analysis with minimal hardware overhead. This approach is consistent with scalable storage monitoring strategies discussed in recent IoT-based warehouse systems *(Arun, 2024; Bouras et al., 2024)* [3,6]. Periodic image capture complemented sensor-based detection by providing visual verification without the need for

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real-time image processing. This design choice addresses the practical limitations of deploying computationally intensive AI models on low-power edge devices, as highlighted in precision agriculture studies *(Senoo et al., 2024)* [8]. Overall, the results indicate that the proposed system achieves a balance between detection accuracy, system cost, and deployment feasibility.

Conclusion

This study presented a smart grain storage monitoring system designed to address early pest infestation and spoilage challenges in rice storage environments. The results confirm that multi-parameter sensing combined with zone-based analysis can effectively identify abnormal storage conditions before visible damage occurs. Gas-based indicators provided early and late-stage detection capabilities, while temperature and humidity monitoring supported environmental risk assessment. Periodic image capture enhanced verification without increasing system complexity. The findings validate the proposed approach as a practical, scalable, and cost-effective solution for smart grain storage applications, bridging the gap between advanced research frameworks and real-world deployment requirements.

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