Design and Development of a Smart Silo Grain Storage Monitoring System

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Abstract
Smart silo grain storage systems combine Internet-of-Things (IoT) sensor networks, targeted biosensing, and data-driven analytics to provide continuous, in-situ monitoring and early warning of spoilage risks in stored cereals and pulses. Recent IoT implementations demonstrate low-cost, real-time monitoring of temperature, relative humidity, and gas concentrations (e.g.,CO_2) to detect conditions that precede insect infestation and fungal growth, enabling automated aeration and stakeholder alerts. Biosensor research, particularly aptamer, immuno and nanomaterial enhanced electrochemical/ optical sensors, has advanced point-of-care detection of key mycotoxins (notably aflatoxin B_1), providing sensitive, rapid, and portable tools that can complement environmental sensing for safety verification. Integration of biosensing with silo-level IoT is emerging as a feasible strategy to couple hazard detection (mycotoxins/pathogens) with environmental triggers, reducing reliance on slow laboratory assays. Meanwhile, AI and machine-learning models (from anomaly-detection frameworks to deep-learning fusion models) have been applied to multi-sensor time series to predict spoilage events and optimize control actions, improving early detection accuracy and reducing false alarms. Deploying these hybrid systems is especially relevant in high-loss contexts such as India, where post-harvest and storage losses remain economically significant; targeted smart monitoring can materially reduce quantitative and qualitative losses when combined with appropriate maintenance and connectivity strategies. Key challenges remain sensor calibration and drift, cost and power constraints in rural deployments, data security, and end-user adoption, but the convergence of IoT, biosensors, and AI offers a scalable pathway to safer, lower-loss grain storage.

Keywords: Smart silo; IoT grain monitoring; biosensors; mycotoxin detection; aflatoxin B_1; anomaly detection; post-harvest losses; real-time monitoring; stored grain safety.

1. Introduction

India loses approximately 10–15% of its stored grains annually because of poor post-harvest management and ineffective monitoring systems (Priyadarsani et al., 2023). Traditional storage structures suffer from uncontrolled temperature, humidity, and pest infestation, leading to both quantitative and qualitative degradation of grains. Consequently, there has been a growing demand for intelligent, automated, and energy-efficient storage technologies that can minimize post-harvest losses while preserving nutritional quality. Smart silo systems utilize digital sensors and Internet of Things (IoT) technologies to monitor environmental parameters in real time, including temperature, relative humidity, gas concentration, and grain moisture (Ajisegiri et al., 2022). These continuous sensing systems can predict spoilage, control aeration, and ensure food safety and security through remote monitoring.

Recent advancements in sensor-driven automation have enabled the use of machine learning models for anomaly detection and spoilage prediction, integrating temperature and gas data to generate early warnings (Wang et al., 2025). IoT-enabled microcontrollers, such as ESP32 and Raspberry Pi, facilitate cloud-based data transmission and analysis, improving decision-making and reducing manual inspection frequency. Such technologies are especially relevant in India, where smart monitoring offers the potential to significantly reduce storage-related losses and improve overall supply chain efficiency (Singh et al., 2022).

Apart from electronic monitoring, research attention has turned toward material and environmental control innovations within silo infrastructure. Self-healing UV light has emerged as a promising approach to prolonging the service life of metal and polymer silo walls. (Guo., et al. 2022) demonstrated UV-triggered polymer network reformation that restores micro-scratches in protective coatings, enhancing corrosion resistance and maintaining barrier integrity under fluctuating storage conditions. Similarly, (Li et al. 2023) fabricated SiO_2/CeO_2 microcapsule coatings capable of self-repair under UV irradiation, showing potential for application in storage facilities exposed to mechanical or environmental wear. The UV light not only improves durability but also reflects or resists microbial accumulation, thereby supporting hygienic storage environments.

In parallel, environmental stabilization using dehumidifier-integrated aeration systems has proven effective in maintaining optimal storage conditions. (Hammami et al. 2016) and subsequent modelling studies revealed that coupling dehumidifiers with forced-air systems prevents condensation and mold growth in high-humidity regions. Desiccant-based dehumidifiers provide low-dew-point air for ventilation, particularly useful during monsoon periods in tropical climates (Dantherm Technical Report, 2023). By integrating such devices with sensor feedback, silo systems can automatically activate dehumidification when relative humidity exceeds safe limits, ensuring moisture uniformity throughout the grain bulk.

The developments of IoT monitoring, self-healing UV-light technologies, and adaptive dehumidification systems represent a new generation of smart silo grain storage systems designed for enhanced reliability, longevity, and food safety. The self-healing smart silo concept, integrating UV light and automated environmental stabilization, demonstrates remarkable potential not only in reducing post-harvest losses but also in advancing sustainable storage practices that align with global food security goals. (Qiang Guo., et al., 2022)

2. Literature Review

2.1. Traditional Grain Storage Challenges

Conventional grain storage systems depend largely on manual inspection methods that are both time-consuming and unreliable. According to (Sushila Priyadarsani et al. 2023), inadequate post-harvest handling and the absence of digital surveillance lead to substantial quantitative and qualitative grain losses in developing nations such as India. Manual inspection cannot continuously monitor the microenvironment inside bulk silos, allowing invisible deterioration to progress before corrective action is taken.

2.2. Moisture imbalance leading to fungal growth

Moisture migration within stored grain is one of the primary factors causing fungal and mycotoxin contamination. (Rajesh Singh et al. 2022) reported that fluctuations in ambient humidity cause localized condensation, creating “hot spots” favorable for mold species such as Aspergillus flavus and Fusarium spp. Similarly, (Abhishek Kumar et al. 2021) emphasized that a 2–3% increase in grain moisture beyond the safe limit rapidly accelerates aflatoxin formation and spoilage, underscoring the need for continuous humidity monitoring.

2.3. Temperature rise causing insect infestation

Temperature gradients in the grain bulk enhance metabolic activity and insect breeding. (Amit Patil et al. 2019) found that grain masses above 30°C significantly boost population growth of Sitophilus oryzae and Tribolium castaneum. (Wei Wang et al. 2025) further noted that uncontrolled temperature variation is a dominant input for spoilage prediction models in smart silos. confirming the necessity of automated thermal regulation.

2.4. Poor aeration resulting in uneven drying and caking:

Lack of proper ventilation leads to moisture pockets and caking near silo walls. (Sami Hammami et al. 2016) experimentally demonstrated that inadequate airflow produces vertical gradients in moisture content, reducing overall aeration efficiency. In practice, this results in uneven drying and partial fermentation zones that compromise both grain quality and storability.

2.5. Lack of real-time data causing delayed interventions

Traditional silos rarely employ integrated sensors for online monitoring. (Emmanuel Ajisegiri et al. 2022) described how the absence of real-time sensing delays the detection of abnormal conditions, often until visible spoilage or odor becomes apparent. Likewise, (Ravindra Singh et al. 2022) highlighted that without IoT-based feedback, corrective measures such as aeration or drying are implemented too late to prevent losses.

2.6. Temperature and Humidity Sensors (DHT22, DHT11, SHT31)

Monitoring temperature and humidity is essential in preventing spoilage and maintaining grain quality during storage. (Mohammad Ali et al. 2021), “Even a 2–3°C rise in temperature can accelerate fungal activity and grain respiration, resulting in rapid deterioration.” Conventional sensors like DHT11 provide basic readings, but the DHT22 and SHT31 offer greater precision and stability under varying moisture conditions. (Wei Chen et al. 2022) reported that “DHT22 sensors show ±0.5°C accuracy and can detect humidity changes as low as 2%, making them ideal for silos exposed to fluctuating climates.” (Ravi Kumar et al. 2023) highlighted that “continuous humidity imbalance above 65% RH leads to condensation pockets, promoting mold colonization.” Integration of IoT-based data logging with DHT22 allows automated alarms and corrective actions through cloud dashboards. The SHT31 sensor, studied by (Ahmed Zhou et al. 2024), demonstrated “faster response time and digital calibration feature suitable for real-time monitoring in sealed environments.” The smart

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temperature-humidity sensing modules enhance grain storage reliability, enabling predictive maintenance, reduced manual inspection, and data-driven decision-making for post-harvest management.

2.7. Role of Anomaly Detection

Anomaly detection algorithms play a critical role in smart grain-storage systems by identifying abnormal patterns in sensor data such as temperature spikes, unexpected gas concentrations, or moisture gradients that may signal spoilage onset, pest infestation, or structural leakage. For instance, (Wei Wang et al. 2025) developed a deep-learning fusion framework combining a 3D DenseNet and 3D CNN-LSTM for grain-storage monitoring: "the grain storage state classification model based on 3D DenseNet efficiently extracts features from three-dimensional grain temperature data" and "the temperature field prediction model based on 3D CNN-LSTM precisely predicts the dynamic changes in the granary's temperature field."
Unsupervised methods such as clustering and autoencoders are particularly suited when labeled anomaly data is scarce. (Mary Adkisson et al. 2021) applied an autoencoder-based model in a smart farming context, explaining that "when it encounters anomalous data, the result will be a high reconstruction loss value, signaling that this data was not like the rest." (Selim Eren Eryilmaz et al. 2023) used a cortical-coding clustering approach for near-real-time agricultural monitoring and found that "incremental and continuous learning is highly beneficial for early and accurate detection in systems with large data streams." Moreover, supervised techniques such as SVM, Random Forest, and K-means clustering remain popular for anomaly classification. In a sensor-data review, (Edwin Omol et al. 2024) note that "Isolation Forest, One-Class SVM, and Autoencoders have emerged as promising approaches to identifying irregular patterns and deviations in sensor data." These algorithms allow smart silo systems to trigger alerts or control actions when deviations exceed threshold-based or learned norms, enabling proactive interventions rather than reactive fixes. By combining anomaly detection with IoT-based sensors and control modules, grain-storage systems can move toward predictive maintenance and continuous quality assurance.

2.8. Stabilization and Control Mechanisms

Ensuring stable operation of a smart silo monitoring system requires not only accurate sensing but also robust environmental and power control mechanisms. One key aspect is automation of aeration and fan systems triggered by real-time sensor feedback. (Liu Jingyun & Li Ping 2021) developed an experimental aeration platform with multivariable control: "The inlet air conditions control error was within ±1°C and 10% for temperature and relative humidity, respectively." The study demonstrates PID/ON-OFF hybrid logic can maintain safe grain conditions by controlling both fan speed and air-inlet humidity.
Automated aeration systems also enable energy savings while maintaining storage quality. In a study on vertical silos, (Carlescu Petru Marian et al. 2022) found that "by eliminating factors that lead to inadequate aeration and introducing an automation system, significant savings in aeration energy consumption can be achieved." Such systems reduce over-aeration, thereby preventing grain cooling when not needed and reducing power consumption.
Another important stabilization mechanism is power management—ensuring uninterrupted monitoring even during outages. While not specific to silos, (Giordano Marco et al. 2023) highlight that "an energy-aware adaptive sampling rate algorithm maximizes sensor sampling rates, ensuring power self-sustainability without risking battery depletion." Applying similar strategies in silo sensor networks (e.g., battery backups, voltage regulators, auto-switching) can enhance the reliability of long-term monitoring systems.
For sterilization and disinfection control, ozone and UV treatments represent automated responses to biological threats. (Lin Jie et al. 2025) review ozone technologies for grain storage: "Modified atmosphere and ozone treatment technologies show significant industrialization potential in replacing traditional chemical fumigants." Similarly, (Bi Jie et al. 2022) report that "ozone application plays an important role in the prevention and control of stored-grain pests." When integrated with sensor-detected increases in CO_2 or fungal markers, such sterilization controls can be triggered automatically to maintain hygienic storage conditions without manual intervention. The smart silo monitoring systems remain reliable, responsive, and capable of maintaining grain quality over extended storage periods.

2.9. IoT and Sensor Networks for Grain Storage

Recent reviews and field studies highlight that low-cost sensor arrays combined with IoT connectivity form the backbone of smart silo systems. (Éric Lutz et al. 2022) reviewed the combined roles of sensors, IoT, and AI for stored-grain monitoring and concluded that multi-parameter sensing (temperature, RH, CO_2, and moisture) plus edge analytics improves early detection of spoilage. Prototype and pilot systems typically pair multiple inexpensive digital sensors (DHT22, SHT31) with microcontrollers (ESP32/Arduino) and low-power wide-area networks (LoRa, NB-IoT) to transmit time-series data to cloud platforms for long-term trending and alerts (Priyadarsani et al., 2023; Narayana et al., 2024).

2.10. Biosensors for Mycotoxin and Microbial Detection

Direct biological hazard detection is a rapidly evolving complement to environmental sensing. Reviews on aptamer and electrochemical approaches report that aptamer-based and nanomaterial-enhanced electrochemical biosensors now achieve low limits of detection for aflatoxin B_1 (AFB_1) in laboratory settings, with rapid response times that suit on-site screening (D. Ciobanu et al., 2023; Y. Li et al., 2024). However, several authors caution that long-term stability, matrix effects from complex grain extracts, and the cost of disposables remain barriers to routine silo deployment (Pérez-Fernández & de la Escosura-Muñiz, 2022; Namanya et al., 2025).

2.11. UV-C and UV-Generated Ozone for Decontamination

Interest in non-chemical disinfestation methods has grown because of residue and resistance concerns. Experimental studies show that UV-C (254 nm) irradiation can inactivate surface microbes and, in some seed studies, stimulate resistance mechanisms; pilot systems that expose grain in thin layers or circulate grain past UV lamps report significant reductions in surface microbial counts (Hidaka & Kubota, 2006; Kamel et al., 2022; Rojas et al., 2025). UV systems that also generate ozone have been trialed for gaseous disinfestation, and reviews note ozone's strong biocidal activity when applied under controlled conditions; industrial scaling requires dose control, worker safety measures, and assessment of potential effects on germination/quality for seed lots (Sitoe et al., 2025; Kumaş, 2025)

Field experiments indicate that dehumidifier-assisted ventilation is particularly valuable in monsoon and tropical regions where ambient air cannot provide drying capacity; modelling work highlights the need to balance airflow, drying rate, and energy use to avoid grain overheating. Controlling interstitial air moisture is central to preventing mold and caking. Both experimental and modelling studies (Hammami et al. group) demonstrate that supplying low-RH air via either mechanical dehumidifiers or desiccant systems combined with controlled aeration reduces grain moisture migration and damp spots more effectively than ambient aeration in humid climates (Hammami et al., 2017). Field experiments indicate that dehumidifier-assisted ventilation is particularly valuable in monsoon and tropical regions where ambient air cannot provide drying capacity; modelling work highlights the need to balance airflow, drying rate, and energy use to avoid grain overheating.

3. Conclusion

The development of smart silo grain storage monitoring systems represents a crucial advancement in post-harvest management and food preservation technology. By integrating multi-sensor networks, IoT communication modules, and intelligent control algorithms, these systems enable continuous, real-time surveillance of key environmental parameters such as temperature, humidity, gas composition, and microbial activity. The addition of biosensors, ultraviolet self-healing coatings, and ozone-based sterilization units enhances the system's capability for microbial control and environmental stabilization, thereby maintaining grain quality and prolonging shelf life.

Artificial intelligence and machine learning-based anomaly detection have further expanded the system's predictive capabilities by identifying deviations in sensor readings that correlate with potential spoilage, leakage, or pest infestation. These data-driven decision frameworks support automated control actions, including dynamic aeration, humidity regulation, and cooling, ensuring optimal storage conditions with minimal manual intervention.

Despite significant progress, human supervision remains vital in system calibration, decision validation, and maintenance. Automated detection algorithms, while highly sensitive, may still generate false positives under fluctuating environmental conditions, requiring expert verification. Hence, the integration of human expertise with automated monitoring fosters a hybrid control model that ensures operational stability and data reliability.

4. Future Prospects

The future of grain-storage monitoring lies in the convergence of IoT, AI, advanced materials, environmental control, and traceability. When smart silos, adaptive dehumidification, self-healing structural systems, and predictive analytics are fully integrated, the outcome is not simply reduced spoilage but a transformative shift in how grain is preserved, moved, and marketed. For countries like India, where post-harvest losses remain high and food-supply resilience is critical, the adoption of such systems could significantly enhance food-security outcomes, reduce losses, and raise grain-value chains.

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