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Smart innovations in stored grain protection

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Abstract
Stored grain often spoils or gets infested by pests, causing major food and financial losses around the world. This review highlights how modern technologies—such as IoT sensor networks, electronic noses (e-noses), acoustic sensors, and AI tools—actively improve the way we monitor and manage grain storage. It explains how systems use connected environmental sensors to collect real-time data, send automatic alerts, and detect early signs of spoilage or pest activity through smell and sound patterns. The review also covers how deep learning models classify storage conditions and predict risks before they cause damage. New advances like ultralow-power sensors and blockchain-based traceability tools make these systems even more practical and reliable. Together, these technologies create a smart and connected storage setup that helps prevent losses, reduce chemical use, and improve food safety and security on a large scale.

Keywords: Smart grain storage, IoT sensors, Electronic nose (e-nose), Artificial intelligence (AI), post-harvest loss prevention, real-time monitoring

1. Introduction

Post-harvest grain experiences significant losses globally due to pests, excess moisture, and fungal contamination, with particularly severe impacts in resource-limited regions. These factors compromise food security by causing spoilage before grain reaches end-users. Conventional storage practices, such as manual sampling, visual inspection, and scheduled fumigation are often inadequate for early detection, resulting in delayed responses and widespread damage. However, the advent of advanced technologies has led to the development of intelligent and proactive grain storage systems. Internet of Things (IoT) networks, comprising compact environmental sensors, now continuously monitor key parameters such as temperature, relative humidity, carbon dioxide, and oxygen levels within storage structures. These sensors transmit real-time data wirelessly to centralized platforms, where artificial intelligence (AI) algorithms analyse patterns to identify anomalies; such as elevated CO_2 levels indicative of insect or fungal activity, well before visible signs of deterioration appear (Centaur Analytics, 2025) [2]. Electronic noses (e-noses), equipped with sensor arrays and supported by AI-based pattern recognition, detect volatile organic compounds (VOCs) emitted by infested or deteriorating grain, offering a non-invasive method for early diagnosis (Badgujar *et al*., 2025) [1]. Acoustic sensors further enhance monitoring capabilities by capturing minute vibrations and chewing sounds produced by concealed insect pests within

kernels. When critical thresholds are detected, AI-driven systems promptly notify storage managers via mobile applications or SMS and may activate automated responses such as aeration or temperature control. This integrated framework—combining IoT, advanced sensing technologies, machine learning, and automated interventions—transforms grain storage from a reactive process into a predictive and preventive strategy, significantly reducing post-harvest losses, minimizing chemical usage, and bolstering food security across varying scales of operation. This article systematically reviews these emerging technologies and their integration into next-generation grain storage management.

2. IoT sensor networks for environmental monitoring
2.1. Architecture and components

Wireless Sensor Networks (WSNs) form the core of intelligent grain storage systems. These networks consist of spatially distributed sensor nodes that monitor temperature, humidity, CO_2 concentration, and moisture content within storage facilities (Li *et al*., 2025) [5]. Each node includes sensors, a microcontroller, a wireless communication module (e.g., LoRaWAN, ZigBee), and a power source. Data collected by the nodes is transmitted to a central gateway, which aggregates and uploads it to a cloud-based or local dashboard for real-time visualization and analysis. Artificial Intelligence (AI) models analyse this data to detect anomalies like overheating or CO_2 spikes, indicating early

pest or fungal activity. The system issues automated alerts to managers and can trigger control actions such as ventilation or dehumidification. Advanced setups also integrate gas or acoustic sensors and electronic noses for early infestation detection. These components collectively enable predictive, automated, and traceable grain storage management, reducing losses and enhancing food security in a scalable, cost-effective manner.

2.2. Applications and benefits
Real-time environmental monitoring using IoT-based systems offers significant advantages for stored grain protection. By continuously tracking parameters like temperature, relative humidity, and moisture content, these systems enable early detection of conditions favourable for pest outbreaks or fungal growth. For example, keeping relative humidity below 65% inhibits the reproduction of common storage pests and prevents mold development.

IoT sensors also monitor fluctuations in water potential and temperature, providing actionable understandings that allow timely aeration, drying, or fumigation. Automated alerts ensure that corrective actions are taken before infestations escalate, minimizing losses and reducing dependence on chemicals. The integration of AI enhances decision-making by identifying subtle patterns in environmental changes that may precede spoilage.

Furthermore, such systems improve operational efficiency by allowing remote monitoring and control, reducing the need for manual inspection. Overall, these smart technologies support cost-effective, sustainable, and safer grain storage, which is especially beneficial for low-resource settings and large-scale operations alike.

3. E-nose and Acoustic sensing for hidden pest detection
3.1. Electronic noses (E-noses)
Electronic nose (e-nose) systems use groups of sensors to detect smells specifically, volatile organic compounds (VOCs) that grains release when they are infested or starting to spoil. These systems can quickly and non-destructively identify hidden pests, even when only one or two insects are present per kilogram of grain. They do this by recognizing odour patterns using methods like Principal Component Analysis (PCA), Linear Discriminant Analysis (LDA), Support Vector Machines (SVM), and neural networks (Badgujar et al., 2025) [2].

Benefits
- Detects pest infestations early, before any visible damage appears.
- Works quickly, is easy to carry, and is cheaper than checking samples manually.

Challenges
- Sensor readings may drift over time.
- Sensors need regular calibration to stay accurate.
- Temperature and moisture in the storage environment can affect how well the system works.

3.2. Acoustic detection
Acoustic systems help detect insects inside stored grain by picking up the tiny sounds they make while feeding or moving. Each insect species produces unique sounds,

especially during the larval stage when they chew on grain kernels. These systems use sensitive microphones or vibration sensors placed inside storage structures like bins or silos to listen for these subtle noises.

To make sense of the sounds, the system uses digital signal processing to filter out background noise such as wind, machinery, or human activity. Then, it applies machine learning algorithms to analyze the sound patterns and identify which type of insect is present based on its specific acoustic signature.

This technology is especially useful because it can detect pests that are hidden inside the grain and not visible from the outside. By spotting infestations in the early stages—often before any damage becomes noticeable—it allows timely pest control actions, reducing losses and avoiding the need for chemical treatments.

4. AI & Deep learning for state classification & risk forecasting
4.1. Multi-model deep learning frameworks
Recent advances in deep learning have made it possible to monitor grain storage conditions more accurately and efficiently. A study by Li et al. (2025) [5] used a combination of 3D DenseNet and 3D-CNN-LSTM models to classify different grain storage states, such as normal, aeration-needed, condensation, and mildew-with a high accuracy of 97.4%. These models also predicted temperature changes inside storage units with a mean absolute error (MAE) of just 0.24°C, showing strong precision.

These deep learning models work by analyzing both spatial data (how conditions vary across different areas in a storage facility) and temporal data (how those conditions change over time). The 3D-CNN captures patterns across sensor grids, while the LSTM (Long Short-Term Memory) model understands trends over time. By combining both, the system provides predictive perceptions into potential problems before they become serious, such as spotting conditions that lead to mold growth or overheating.

This kind of smart monitoring helps in automating decisions, like when to aerate, cool, or inspect the grain, leading to better quality preservation, lower losses, and less dependence on manual checks.

4.2. Benefits
1. **Early risk alerts:** Deep learning models can quickly detect warning signs such as condensation, heat buildup, or mildew-prone zones. These early alerts allow storage managers to take action before the grain is damaged, preventing large-scale spoilage.
2. **Operational efficiency:** By accurately forecasting environmental changes, these systems help in making timely decisions—like when to turn on aeration or cooling systems. This proactive control not only protects the grain but also reduces energy use, labor, and dependence on frequent manual inspections.
3. **Emerging trends:** New developments, like ultralow-power electronic nose (e-nose) systems combined with deep learning, are making grain monitoring even more practical. These devices run on very little energy and still provide powerful perceptions, making them ideal for remote or low-resource storage sites (Kim et al., 2024) [4]. Their portability and low maintenance needs

reduce logistical challenges and expand access to advanced grain protection.

5. Integration: Toward an intelligent storage ecosystem
5.1. System architecture
A complete and smart solution for grain storage brings together different technologies to work as one system. It starts with the hardware, which includes IoT sensors that track temperature, humidity, and gas levels, along with electronic noses that detect odours from spoilage and acoustic units that listen for insect activity. All this information is captured in real-time dashboards, where data from different sources is recorded and shown in a clear way. Then, AI-based analytics take over to make sense of the data. The system can spot unusual patterns, like bad smells or hot spots, identify the current condition of the grain—whether it's fresh, damp, or developing mold—and even predict future problems based on trends. When something goes wrong, the system sends instant alerts through mobile messages or SMS and can automatically turn on aeration or other control systems. Finally, to ensure transparency, all temperature readings, pest activity, and actions taken are recorded in secure logs or blockchain systems, making the grain's storage history traceable and tamper-proof.

5.2. Impact and scalability
Smart grain storage systems have a big impact on reducing post-harvest losses. By detecting problems like pests, moisture, or mold early, these technologies helps to stop infestations before they spread that save both grain and money. Precision alerts also mean that chemical treatments like fumigation are only used when truly needed, which lowers the amount of harmful chemicals in the food system and benefits the environment.

Another major advantage is traceability - digital records of storage conditions and actions taken can be shared with buyers, consumers, and regulators to prove the grain was stored safely. These systems are also highly adaptable. Whether it's a small farm using simple sensors in bins or a large warehouse with advanced automation and AI, the same technology can be scaled to fit the need. This flexibility makes smart storage a powerful tool for improving food safety and reducing waste across different regions and storage sizes.

6. Emerging technologies and opportunities
6.1. Ultralow-power sensing
Ultralow-power sensing is a key innovation for making grain monitoring more practical, especially in remote or off-grid areas. New electronic nose (e-nose) systems are now designed to work with very low energy. For example, some devices use a single metal oxide sensor (MOS) that operates in short bursts, or "duty cycles," which keeps power use at just a few micro-watts. Despite their small size and low energy needs, these sensors can still accurately detect odours from spoilage or pests in real time. This makes them ideal for battery-powered or solar-powered storage setups, where energy is limited but reliable monitoring is still needed. Such systems help extend device life, reduce maintenance, and ensure continuous data collection—even in areas without stable electricity—making grain protection more accessible and scalable (Segura-Garcia et al., 2025) [6].

6.2. Drift-resilient machine learning algorithms
One of the biggest challenges in long-term sensor use is sensor drift, where readings slowly become less accurate over time due to wear, dust, or environmental changes. This can lead to false alarms or missed warnings in grain storage monitoring. To solve this, researchers have developed special machine learning methods that can adapt to changing sensor behaviour. One such method is called the Domain-Adaptive Extreme Learning Machine (DAELM). This algorithm can adjust itself when sensor signals begin to drift, without needing frequent manual recalibration. It learns from both past and current data to keep predictions reliable over time. By reducing the need for regular maintenance or sensor replacement, drift-resilient algorithms like DAELM make grain storage systems more stable, cost-effective, and accurate in the long run (Zhang and Zhang, 2015) [7].

6.3. High-Speed Sensor Platforms
New high-speed sensor systems now use tiny electronic noses that can detect smells in just a few milliseconds—almost as fast as animals do. These sensors, built using MEMS-based metal oxide (MOx) technology and fast sampling circuits, can pick up very small changes in odour patterns that happen just milliseconds apart. Some of them can even detect changes happening up to 60 times per second (Dennler et al., 2024) [3]. This makes them perfect for fast-moving environments, like when grains are flowing through pipes or being poured into bins. Because of their speed, these sensors can spot signs of spoilage or insect activity in real time, even while the grain is in motion. This allows for quick actions, such as turning on fans or changing airflow, to protect the grain. These fast sensors help improve on-the-spot grain quality checks and support better decision-making in automated storage and handling systems.

7. Challenges and future thrust areas in smart innovations in stored grain protection
Challenges
1. **High initial costs:** Smart storage systems with IoT, AI, and advanced sensors can be expensive to set up. Many small farmers or rural warehouses may not afford these technologies without support or subsidies.
2. **Sensor accuracy and drift:** Sensors may lose accuracy over time due to dust, humidity, or aging. This "drift" leads to incorrect readings unless sensors are regularly maintained or supported by smart algorithms.
3. **Power supply issues:** Remote storage areas may not have steady electricity. Although some low-power sensors exist, ensuring regular power or battery charging can still be a problem.
4. **Connectivity problems:** IoT systems need internet or network access to send data. Poor connectivity in rural areas can delay real-time alerts and responses.
5. **Data overload and complexity:** Smart systems collect large amounts of data. Making sense of this data and acting on it needs trained staff or smart software, which may not always be available.
6. **Maintenance and calibration:** Smart devices need regular cleaning, updates, and calibration. Without proper care, their performance can drop.
7. **Lack of standardization:** There is no uniform standard

for using smart technologies in grain storage. This can cause confusion and compatibility issues between systems from different suppliers.

8. **Farmer awareness and training:** Many farmers and storage managers are not aware of these technologies or trained to use them, which limits their adoption and benefits.

8. Future thrust areas

1. **Affordable and scalable solutions:** Research should focus on developing low-cost, easy-to-use sensor systems that even small farmers can adopt. Modular systems that can expand as needed are ideal.

2. **Battery-free and solar-powered devices:** Future devices should use solar panels or energy-harvesting methods to run without the need for constant charging or power sources.

3. **AI-based auto-calibrating sensors:** Building smart sensors that adjust themselves to avoid errors from drift or changing environments will improve long-term accuracy.

4. **Offline capabilities and edge computing:** Systems that work without internet by processing data locally (edge computing) can help in remote areas where connectivity is weak or absent.

5. **User-friendly interfaces:** Dashboards, mobile apps, and alert systems should be designed in simple local languages and formats for easy use by farmers and warehouse operators.

6. **Integration with traditional practices:** Combining smart monitoring with traditional grain handling methods will encourage smoother adoption and trust among users.

7. **Blockchain and traceability tools:** Use of blockchain can store a tamper-proof history of storage conditions and pest treatments, which helps improve transparency and trust in food supply chains.

8. **Policy support and government incentives:** Governments and organizations can help by creating policies, giving subsidies, and setting up training programs to encourage the use of smart storage technologies.

9. **Collaboration across sectors:** Scientists, engineers, software developers, and farmers must work together to build practical, farmer-friendly tools that actually solve on-ground problems.

9. Conclusion

The convergence of IoT sensor networks, e-nose and acoustic detection, deep learning analytics, and traceability systems promises a new era in stored grain management. These systems provide early-warning detection, data-driven interventions, and transparent chain-of-custody logs that together reduce post-harvest losses, lower chemical inputs, and boost food safety. However, success depends on addressing sensor drift, affordability, connectivity, and user adoption. Overcoming these hurdles will allow these innovations to revolutionize post-harvest grain protection making a meaningful contribution to global food security.

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