

IoT-Based Smart Storage Systems in Seed Processing

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1. Introduction

Seeds are the most important input in agricultural production, serving as the foundation for successful crop establishment and higher productivity. The quality of seeds directly influences germination, seedling vigor, crop performance, and ultimately the yield potential of agricultural systems. However, maintaining seed quality after harvesting is a major challenge because seeds are living biological materials that continuously undergo physiological changes during storage. Even high-quality seeds produced under ideal field conditions can lose their viability and market value if they are stored under unfavorable environmental conditions.

Seed storage is a critical operation in the seed processing industry, where large quantities of processed seeds are preserved for future planting seasons. During storage, factors such as temperature, relative humidity, seed moisture content, insect infestation, fungal development, and poor ventilation can significantly affect seed longevity. Conventional storage systems generally depend on periodic manual inspection, where workers collect samples and measure storage conditions at fixed intervals. Although this approach is widely practiced, it may fail to detect sudden changes in storage conditions, leading to irreversible quality deterioration.

With the advancement of digital technologies, agriculture is moving toward automation and intelligent management systems. The integration of the Internet of Things (IoT) into seed storage has introduced a new approach where storage environments can be continuously monitored, analyzed, and controlled automatically. IoT-based smart storage systems combine sensors, communication networks, cloud computing, artificial intelligence, and automation technologies to create intelligent storage environments that ensure better preservation of seed quality.

These smart systems are transforming traditional warehouses into technologically advanced facilities capable of making real-time decisions. By reducing human dependency and enabling predictive management, IoT-based storage systems have the potential to minimize post-harvest losses, improve operational efficiency, and ensure the availability of high-quality seeds for sustainable agriculture.

2. Importance of seed storage in modern agriculture

The primary objective of seed storage is to maintain the physiological quality of seeds from harvest until the next

planting season. Proper storage preserves seed germination capacity, genetic purity, physical quality, and resistance to deterioration. In commercial seed industries, maintaining consistent quality throughout storage is essential because seeds are often stored for several months or even years before distribution.

Seeds are highly sensitive to environmental conditions. Temperature and moisture are considered the two most important factors affecting seed deterioration. Increased temperature accelerates metabolic activities within seeds, leading to faster aging and loss of viability. Similarly, high relative humidity causes seeds to absorb moisture from the surrounding environment, increasing respiration rates and creating favorable conditions for fungal growth and insect multiplication.

During bulk storage, heat and moisture may accumulate unevenly inside storage structures, creating localized areas known as "hot spots." These regions become ideal environments for microbial growth and insect activity. Without continuous monitoring, these problems may remain unnoticed until significant damage occurs.

Therefore, modern seed storage requires advanced systems capable of continuously observing environmental conditions and providing timely corrective measures. This requirement has encouraged the development of smart storage technologies based on IoT.

3. Limitations of conventional seed storage systems

Traditional seed storage facilities commonly rely on manual monitoring practices. Warehouse operators periodically inspect storage conditions by measuring temperature, humidity, and seed quality parameters using portable instruments. Although these methods provide basic information, they have several limitations.

Manual monitoring provides data only at specific time intervals and may not capture sudden variations in environmental conditions. For example, a rise in temperature during nighttime or a sudden increase in moisture due to external weather conditions may remain undetected until the next inspection. Similarly, insect infestation or fungal growth may only become visible after significant damage has already occurred. Another limitation of conventional systems is the lack of accurate historical data. Since observations are often recorded manually, maintaining long-term storage records becomes difficult. Without detailed data analysis, it is challenging to predict seed deterioration patterns or optimize storage practices.

Furthermore, large-scale seed warehouses require considerable labor for inspection and management. Frequent physical visits increase operational costs and may not always be practical in remote storage locations. These limitations highlight the need for automated and intelligent storage solutions.

4. Emergence of IoT in seed processing and storage

The Internet of Things (IoT) is an advanced technology that enables physical devices to communicate, collect information, and exchange data through digital networks. In agricultural applications, IoT connects sensors, machines, and management platforms to create automated systems capable of monitoring and controlling farm and post-harvest operations.

In seed processing industries, IoT provides a pathway toward smart storage management by continuously collecting information about storage conditions. Small, energy-efficient sensors placed inside warehouses, storage bins, or silos can monitor critical parameters such as temperature, relative humidity, seed moisture content, carbon dioxide concentration, and air quality.

The collected information is transmitted through wireless communication networks to centralized monitoring platforms. Warehouse managers can access real-time information through computers, tablets, or mobile applications. When storage conditions move beyond acceptable limits, the system can automatically activate corrective measures or send alerts to operators.

Unlike traditional storage systems that respond after problems occur, IoT-based systems support preventive and predictive management. This shift from reactive monitoring to proactive control represents a major advancement in seed storage technology.

5. Working principle of IoT-based smart storage systems

An IoT-based smart storage system operates through continuous data collection, communication, analysis, and automated control. The process begins with strategically placed sensors inside storage facilities. These sensors continuously measure environmental conditions and generate digital information. The collected data are transferred through communication technologies such as Wi-Fi, ZigBee, LoRaWAN (Long Range Wide Area Network), bluetooth, or cellular networks (Fig 1). Depending on the size and location of the storage facility, different communication systems can be selected to ensure reliable data transmission. The information received from sensors is stored and processed using cloud computing platforms. Cloud technology allows large volumes of storage data to be maintained securely while providing access from any location. Users can analyze current conditions, compare

historical trends, and monitor storage performance remotely. Artificial intelligence and machine learning algorithms further improve the efficiency of smart storage systems. These technologies analyze patterns in temperature, moisture, and seed quality changes to predict possible deterioration. Based on predictive analysis, the system can recommend or automatically initiate corrective actions. For example, if temperature inside a seed storage unit increases beyond the recommended level, automated ventilation systems can be activated to remove excess heat. Similarly, humidity control systems can operate when moisture levels become unfavourable. This automatic response helps maintain a stable storage environment.

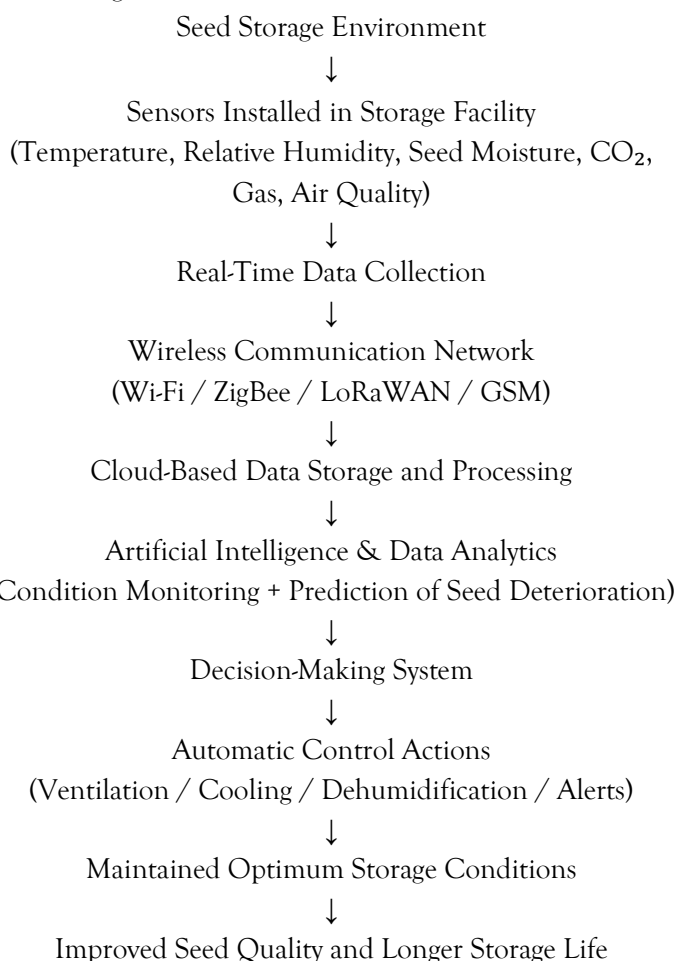


Fig 1: Architecture of an IoT-Based Smart Storage System

6. Major components of IoT-based smart seed storage systems

A smart storage system consists of several integrated components that work together to maintain favorable storage conditions.

6.1 Sensor technology: the foundation of smart storage

Sensors are the most important components of an IoT-based storage system because they provide real-time

information about storage conditions. Temperature sensors monitor heat variations inside storage structures, while humidity sensors measure moisture conditions in the surrounding air. Seed moisture sensors provide information about the actual moisture content of stored seeds, which is directly related to storage stability. Advanced systems may also include carbon dioxide sensors to monitor respiration activity, gas sensors to detect fumigation conditions, and cameras equipped with image processing technology to identify insect activity or physical changes in stored seeds. The use of multiple sensors at different locations improves monitoring accuracy because storage environments are often not uniform. Data collected from different points help identify variations and prevent localized quality deterioration.

6.2 Communication networks and data transmission

Communication systems act as a bridge between sensors and monitoring platforms. Wireless technologies have made IoT implementation easier by reducing installation complexity and improving flexibility. For large seed warehouses and storage silos, long-range communication technologies such as LoRaWAN are particularly useful because they can transmit data over long distances with low energy consumption. In smaller facilities, Wi-Fi and Bluetooth-based systems may provide efficient communication. Reliable communication ensures that storage managers receive accurate and timely information, allowing quick responses to unfavorable conditions.

6.3 Cloud computing and data management

Cloud computing plays an important role in storing and analyzing the large amount of data generated by IoT devices. Instead of maintaining physical storage servers, industries can use cloud platforms to securely manage storage information. Cloud-based systems allow users to access storage conditions remotely and generate reports related to temperature trends, humidity variations, energy consumption, and equipment performance. These digital records also support quality certification and traceability requirements in the seed industry.

7 Artificial intelligences for predictive storage management

Artificial intelligence is making smart storage systems more powerful by enabling prediction and decision-making. Machine learning models can analyze historical storage data and identify relationships between environmental conditions and seed deterioration. For instance, AI-based systems can predict the probability of fungal growth or reduced germination based on temperature and moisture patterns. This allows operators to take preventive action before significant losses occur. The combination of IoT and AI creates an intelligent storage environment capable of learning

from previous conditions and continuously improving management strategies.

8. Benefits of IoT-based smart storage systems

The implementation of IoT technology provides significant advantages for seed industries. Continuous monitoring helps maintain optimum storage conditions, resulting in improved seed viability and longer storage life. Early detection of unfavorable conditions reduces losses caused by moisture, insects, and fungal contamination.

Smart storage systems also reduce labor requirements by minimizing frequent manual inspections. Operators can monitor multiple storage locations remotely through digital platforms, improving management efficiency. Energy consumption can be optimized through automated control systems. Cooling and ventilation equipment operate only when required, reducing unnecessary energy use and operational costs. Another important advantage is improved decision-making. The availability of historical storage data allows industries to analyze performance, identify problems, and develop better storage strategies. Overall, IoT-based storage systems contribute to reduced losses, improved quality control, increased profitability, and sustainable management of seed resources.

9. Challenges in implementing smart storage systems

Although IoT technology offers numerous benefits, several challenges must be addressed for widespread adoption. The initial investment required for installing sensors, communication networks, and automation systems may be high, particularly for small-scale seed processors. Reliable internet connectivity is another important requirement, especially in rural areas where many seed storage facilities are located. Technical knowledge is also necessary for system installation, maintenance, and data interpretation. Sensor accuracy and calibration must be regularly maintained because incorrect measurements can lead to improper storage decisions. Additionally, cybersecurity and data protection are important considerations because smart systems depend on digital communication networks. Future developments focusing on low-cost sensors, renewable energy-powered devices, and user-friendly platforms will help overcome these challenges.

10. Future prospects of IoT in seed storage

The future of seed storage is expected to become increasingly intelligent, automated, and data-driven. Integration of IoT with artificial intelligence, robotics, blockchain, and digital twin technologies will further enhance storage management. Digital twin technology can create virtual models of storage facilities, allowing managers to simulate different storage conditions and optimize operations. Blockchain technology can improve transparency

and traceability throughout the seed supply chain. Solar-powered IoT devices and low-energy wireless sensors will make smart storage systems more affordable and suitable for rural applications. Autonomous monitoring systems using robotics and computer vision may further reduce human

involvement in warehouse management. As agriculture continues to adopt digital solutions, IoT-based smart storage will become an essential technology for maintaining seed quality and reducing post-harvest losses.
