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Review Article

Smart Onion Storage Systems using IoT and Sensor-Based Environmental Monitoring: A Review

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ABSTRACT

Onion is one of the most economically significant horticultural crops, widely consumed and traded globally. However, post-harvest losses in onion storage remain a major challenge, particularly in developing countries such as India, where traditional storage structures often result in 20–40% losses due to sprouting, rotting, microbial infection, and excessive moisture accumulation. These losses not only reduce farmer income but also disturb national market stability. In recent years, the integration of advanced technologies—especially the Internet of Things (IoT) and sensor-based monitoring systems—has emerged as a promising solution for improving onion storage efficiency. This review paper provides a comprehensive analysis of the current state, technological advancements, and future potential of IoT-enabled smart onion storage systems. Within this paper, principal storage conditions such as temperature, relative humidity, airflow, gas accumulation, and weight loss are examined for their critical role in maintaining onion quality and maximizing shelf life. Various sensor technologies, including temperature, humidity, CO_2, ethylene, airflow, and load sensors, are evaluated for their relevance in onion storage environments. The architecture of IoT systems, consisting of microcontrollers, wireless connectivity modules, cloud platforms, and real-time dashboards, is examined to highlight its role in continuous monitoring, automated control, and data-driven decision-making. Furthermore, the review highlights existing research studies, commercial technologies, and case-specific implementations that demonstrate the benefits of IoT-based systems in reducing spoilage, improving environmental stability, and enhancing operational efficiency. Comparative analysis between traditional and smart storage structures reveals that IoT integration significantly enhances storage performance while providing actionable insights through real-time alerts and predictive analytics. Despite the promising outcomes, challenges such as system cost, connectivity issues, maintenance requirements, and user skill limitations must be addressed for large-scale adoption. The paper concludes by emphasizing the potential for future integration of artificial intelligence, renewable energy systems, digital twins, and nano-sensors to develop fully autonomous, climate-resilient onion storage systems.

KEYWORDS: Onion storage, IoT, Sensors, Smart storage system, Environmental monitoring, Post-harvest technology, Smart agriculture, Controlled environment storage

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INTRODUCTION

Onion (*Allium cepa* L.) is one of the most important commercial vegetable crops cultivated and consumed worldwide, playing a vital role in daily cuisine, food processing industries, and the national economies of many countries (FAO, 2019). India is among the world's largest producers of onions, contributing significantly to global supply and export (APEDA, 2022). Due to its year-round demand, onion serves as a crucial component of food security and income stability for millions of farmers (NHRDF, 2020). However, one of the most persistent challenges in the onion value chain is the high level of post-harvest losses during storage. These losses, often ranging from 20–40%, vary depending on the region and storage conditions (ICAR-DOGR, 2020; Bhonde and Chougule, 2019). Such losses affect market availability, seasonal price fluctuations, farmer profitability, and consumer affordability. Onion is a semi-perishable crop that undergoes several physiological and biochemical changes after harvest (Singh et al., 2023; Singh and Kaur, 2024; Singh et al., 2025; Randhawa and Kaur, 2023; Bajaj and Rani, 2025; Kakade et al., 2023). Factors such as temperature, relative humidity, moisture content, air circulation, storage duration, and microbial load significantly influence its quality during storage (Mitra and Devi, 2016; Wills et al., 2014). Poorly controlled environments lead to sprouting, rotting, fungal growth, excessive weight loss, and deterioration of external bulb quality (ICAR-DOGR, 2020). Traditional storage structures—such as the naturally ventilated Kanda Chawl, low-cost thatched roof bamboo storage, and the Patil model—are widely used in rural India due to their low construction and maintenance cost (Patil and Salve, 2015; Kale and Sawant, 2017). While these structures provide basic ventilation through open slats or raised platforms, they lack mechanisms for controlling environmental parameters, making them vulnerable to temperature extremes, monsoon humidity, inadequate airflow, and inconsistent shelf-life outcomes (Bhonde and Chougule, 2019).

With increasing population, climatic variability, and the demand for consistent food supply, the agriculture sector is undergoing a major technological transformation. Smart agriculture integrates digital tools, data analytics, wireless sensing, and automation to enhance production and post-harvest management (Aldrich and Gerhards, 2020). Among these, Internet of Things (IoT) technologies have gained rapid attention for their ability to enable real-time environmental monitoring, remote control, and predictive decision-making (Chandel, et al., 2021). IoT-based storage systems use networks of sensors, microcontrollers, communication modules, and cloud platforms to track variables such as temperature, humidity, gas concentration, and airflow (Sahoo and Panda, 2022). These systems provide real-time data visualization, automated alerts, and analytical insights that traditional storage structures cannot offer (Kumar and Tiwari, 2022).

In the context of onion storage, IoT-based monitoring is highly valuable because onion bulbs are extremely sensitive to microclimatic fluctuations. Even slight deviations from optimal temperature or humidity can trigger sprouting or fungal infection (ICAR-DOGR, 2020). Continuous manual monitoring is impractical and often inaccurate, especially in large storage facilities. Therefore, the integration of IoT and sensor-based monitoring systems presents a feasible, reliable, and cost-effective solution for controlling storage conditions (Ghosh and Roy, 2020). By incorporating sensors such as DS18B20 for temperature, DHT22 for humidity, MQ-series for gas concentration, and load cells for weight measurement, farmers can track environmental conditions with high precision (Rani and Kaur, 2020). These measurements can be transmitted via Wi-Fi, GSM, or LoRaWAN to cloud platforms such as ThingSpeak, Blynk, or Firebase, enabling remote supervision and timely intervention (Singh and Sharma, 2023).

In addition to monitoring, IoT systems enable automated control mechanisms—such as activating exhaust fans when temperatures rise, opening ventilation dampers to reduce humidity, or issuing alerts when CO_2 or ethylene levels increase (El-Masry and Mahmoud, 2019). Such automation reduces labour and minimizes spoilage by maintaining the ideal microclimate inside storage structures. When combined with data analytics and predictive modelling, IoT systems can forecast spoilage trends, detect early signs of disease outbreaks, and evaluate storage performance (Chandel et al., 2021). Globally, several countries use advanced storage technologies such as climate-controlled cold stores, controlled atmosphere storage, and automated warehouses (USDA, 2021). However, these systems are expensive and energy-intensive, making them unsuitable for small and marginal farmers in countries like India (NHRDF, 2020). IoT-based systems, in contrast, offer a scalable and affordable approach that bridges the gap between traditional and high-tech storage. Retrofitting traditional structures with IoT sensors can significantly reduce post-harvest losses without major structural modification (Kumar and Tiwari, 2022).

Despite growing interest, large-scale adoption of IoT-enabled onion storage faces challenges such as poor rural connectivity, sensor cost, lack of technical knowledge, and the need for calibration and maintenance (Rani and Kaur, 2020). Addressing these challenges is essential for achieving widespread adoption and long-term sustainability. This review paper provides a comprehensive understanding of smart onion storage systems using IoT and sensor-based environmental monitoring. It examines physiological aspects of onion storage, critical environmental parameters, sensor technologies, existing smart storage models, limitations, and future prospects such as AI prediction, renewable energy integration, nano-sensors, and digital twins (Aldrich and Gerhards, 2020; Sahoo and Panda, 2022).

FUNDAMENTALS OF ONION STORAGE

Physiological Behaviour of Onions During Storage

Respiration

Onion bulbs remain biologically active after harvest and continue low-level metabolic processes. Respiration involves the oxidation of stored carbohydrates, causing gradual depletion of dry matter (Wills et al., 2014). Factors such as higher temperatures, excessive moisture, and poor ventilation accelerate respiration, leading to faster deterioration (Sahoo and Panda, 2022). Increased respiration also generates metabolic heat and moisture inside storage heaps, often resulting in localized heating and enhanced spoilage in traditional storage structures (ICAR-DOGR, 2020).

Heat Production

Heat generated through respiration accumulates within storage piles, especially when ventilation is insufficient (Benkeblia, 2004). If this heat is not effectively dissipated, internal temperatures rise, creating “hot spots” that favour microbial activity, sprouting, and decay (Kale and Sawant, 2017). In large traditional stores, metabolic heat can be substantial; therefore, adequate airflow and improved structural design are essential to maintain thermal equilibrium (Wills et al., 2014).

Moisture Loss

Moisture loss occurs mainly through transpiration and respiration (Kakade et al., 2023). Excessive moisture loss leads to weight reduction, shrinkage, and lower marketable yield (Mitra and Devi, 2016). High temperatures, low RH, and increased airflow increase transpiration rates and accelerate moisture loss (Thompson et al., 2008). Conversely, high RH encourages microbial infection and sprouting (ICAR-DOGR, 2020). Proper curing and development of dry outer skins are essential to minimize moisture loss during prolonged storage (NHRDF, 2020).

Sprouting

Sprouting is a major physiological challenge in long-term onion storage. It is influenced by bulb maturity, cultivar type, temperature, and hormonal changes (Benkeblia, 2004). In India, temperatures of 25–30°C with moderate RH help suppress sprouting in naturally ventilated systems (ICAR-DOGR, 2020). Storage below 10°C—as used in controlled-atmosphere stores—also inhibits sprouting but is cost-prohibitive for most farmers (Thompson et al., 2008). Elevated CO_2 levels or stress environments can trigger early sprouting and quality loss (Benkeblia, 2004).

Critical Storage Parameters

Temperature

Temperature Range: 25–30°C (Open Storage) For tropical climates such as India, the recommended temperature range for open or naturally ventilated storage is 25–30°C (ICAR-DOGR, 2020). This range balances respiration, suppresses excessive sprouting, and reduces microbial infections. Temperatures above 35°C accelerate dehydration, breakdown, and rotting (Mitra and Devi, 2016), while excessively low temperatures increase condensation and disease incidence (Thompson et al., 2008).

Relative Humidity

A moderate RH of 65–70% provides the best storage outcomes, minimizing water loss while preventing fungal decay (NHRDF, 2020). Low RH (<60%) causes rapid shrinkage (Wills et al., 2014), while high RH (>75%) promotes rotting, neck softening, and sprouting (ICAR-DOGR, 2020). Most natural-ventilation storage systems aim to maintain these levels through airflow and shading.

Airflow Requirements

Ventilation is essential to remove metabolic heat, expel gases, and maintain a uniform microclimate throughout storage (Kale and Sawant, 2017). Traditional systems depend on passive airflow through slatted walls, raised platforms, and open sides (Patil and Salve, 2015). Modern structures use forced ventilation or IoT-controlled fans to optimize airflow and prevent condensation or hot-spot formation (Sahoo and Panda, 2022).

Gas Composition: Ethylene and CO_2 Levels

Ethylene accelerates sprouting and senescence, and even low production in onions can accumulate under poor ventilation (Benkeblia, 2004). CO_2 levels above 5–10% may help inhibit sprouting but can cause internal breakdown if uncontrolled (Thompson et al., 2008). Proper ventilation therefore plays a key role in maintaining suitable gas composition for long-term storage (Wills et al., 2014).

Table 1. Critical Environmental Thresholds for Onion Storage

Parameter	Optimal Range	Impact if Not Controlled
Temperature	25–30°C (open storage)	↑ Sprouting, ↑ Decay, ↑ Respiration
Relative Humidity	65–70%	>70% Causes rot; <60% Causes shrinkage
Airflow	20–40 air changes/hour (traditional)	Hot spots, moisture accumulation
CO_2 Levels	<5%	>10% causes tissue breakdown
Ethylene	<1 ppm	↑ Sprouting rate

TRADITIONAL ONION STORAGE SYSTEMS

Kanda Chawl

Kanda chawl is a widely used, low-cost storage system in Maharashtra characterized by raised platforms made of bamboo or wooden slats, with openings on all sides for natural ventilation (Kale and Sawant, 2017). The structure typically has a thatched or tiled roof for shading and rain protection. Although economical and locally adaptable, it offers limited control over temperature and humidity and is vulnerable to monsoon moisture, pests, and uneven airflow (Patil and Salve, 2015).

Patil Model

The Patil model is an improved version of the traditional chawl, designed with increased height, stronger side ventilation, slatted floors, and reinforced walls (Patil and Salve, 2015). Some variants use GI sheets and elevated platforms to enhance airflow and durability. While this model reduces post-harvest losses compared to open heaps or basic chawls, it still relies completely on natural ventilation and lacks mechanisms to regulate temperature or humidity during extreme climatic conditions (Kale and Sawant, 2017; ICAR-DOGR, 2020).

IOT IN SMART AGRICULTURAL STORAGE SYSTEMS

Concept and Architecture of IoT Systems

The Internet of Things (IoT) is an interconnected ecosystem where physical devices—known as "things"—collect, process, and exchange data through the internet or localized networks. In agricultural storage systems, IoT plays a transformative role by enabling precise, real-time environmental monitoring, automated decision-making, and data-driven storage management (Gubbi et al., 2013). The core components of any IoT system include sensors, actuators, communication modules, gateways, and cloud platforms.

Things and Sensors

"Things" typically refer to sensor-embedded hardware capable of capturing essential environmental variables. In onion storage systems, the most frequently monitored parameters include temperature, relative humidity, carbon dioxide concentration, ethylene levels, and airflow. Sensors such as DHT22 (temperature/RH), MQ-series gas sensors, and ultrasonic airflow sensors play a significant role in quantifying the micro-environment around stored onion bulbs (Banaeian and Omid, 2018). These sensors convert physical measurements into digital data for further processing.

Gateways

Gateways act as intermediaries between field sensors and cloud servers. They perform functions such as protocol translation, local data filtering, and communication management. In agriculture, gateways often operate on low-power microcontrollers or single-board computers and support protocols like MQTT, HTTP, and CoAP for efficient data transmission.

Cloud Computing

The cloud layer provides large-scale data storage, computation, machine learning capabilities, and visualization dashboards accessible to farmers and facility managers. Cloud platforms like AWS IoT, Azure IoT Hub, and ThingSpeak allow real-time analytics, historical data tracking, and automated decision-making (Botta et al., 2016).

IoT Architecture for Onion Storage

A typical IoT architecture for smart onion storage involves four layers: perception layer (sensing), network layer (communication), middleware layer (data processing), and application layer (actionable insights). This multilayer architecture ensures efficient data acquisition, analysis, and control of storage environments (Atzori et al., 2010).

Edge Devices and Sensor Nodes

Edge devices are placed within storage structures to collect crucial environmental data. They include sensor modules linked to microcontrollers that pre-process data before sending it to gateways or cloud servers. Edge computing reduces latency and enables local decision-making—for example, triggering exhaust fans when CO_2 levels rise above acceptable limits. In onion storage, edge devices monitor temperature (25–30°C), relative humidity (65–70%), airflow, and gas composition.

Microcontrollers: Arduino, ESP8266/ESP32, Raspberry Pi

Microcontrollers serve as the processing unit for sensor integration:

- ➢ **Arduino Uno/MEGA:** Widely used for simple sensing tasks due to its robustness and ease of programming (Monk, 2016).
- ➢ **ESP8266/ESP32:** Offer built-in Wi-Fi, low power consumption, and higher processing capability, making them ideal for IoT-based wireless monitoring systems.
- ➢ **Raspberry Pi:** A mini-computer capable of running Python-based analytics, machine learning scripts, and local dashboards. It is used when advanced processing or camera integration is required.

Real-Time Analytics

Analytics tools convert raw sensor data into meaningful insights. Real-time dashboards display storage conditions using graphical interfaces, enabling farmers to track environmental variations and respond promptly. Machine learning algorithms can be integrated to detect anomalies, predict spoilage, and recommend ventilation or cooling adjustments (Kamilaris and Prenafeta-Boldú, 2018). Automated alerts through SMS or mobile apps ensure quick intervention when storage conditions deviate from the optimal range. Collectively, IoT System enhances the precision, reliability, and efficiency of onion storage management.

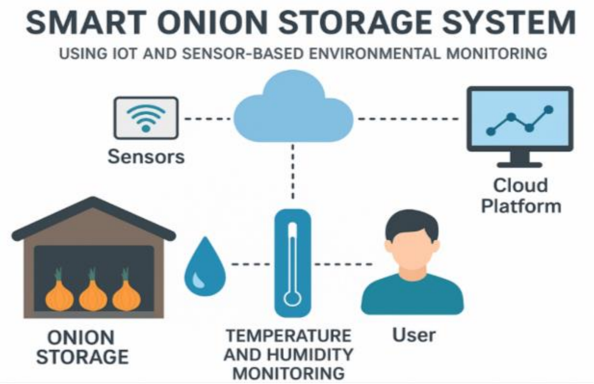

Fig. 1. IoT System (Using IOT Sensor-Based Environmental Monitoring)

Advantages of IoT in Storage

IoT-enabled storage systems provide a wide range of benefits compared to traditional storage structures such as kanda chawls or Patil models. These advantages make IoT a transformative technology for minimizing post-harvest losses in onion supply chains.

Continuous Monitoring

Traditional storage systems rely on manual inspection, which is often inconsistent and prone to human error. IoT solves this limitation by providing 24/7 monitoring of all critical environmental conditions. Parameters such as temperature, humidity, CO_2 concentration, and ethylene levels are recorded continuously, providing a comprehensive dataset for assessing storage performance. Continuous monitoring helps identify micro-environmental fluctuations that are otherwise undetectable manually (Razaque and Amsaad, 2018). This constant flow of information supports improved decision-making, better storage strategies, and enhanced understanding of spoilage patterns over time.

Real-Time Alerts and Decision Support

One of the most impactful benefits of IoT is real-time alerting. When a parameter crosses a threshold—such as RH exceeding 70% or CO_2 reaching harmful levels—the system sends instant notifications via SMS, mobile applications, or email. These alerts enable immediate intervention, preventing severe spoilage or rot development (Dweekat et al., 2017). Additionally, decision support systems powered by AI and IoT assist in adjusting ventilation, modifying airflow rates, or activating cooling systems automatically. This reduces the burden on farmers while ensuring optimal storage conditions.

Minimization of Losses

About 20–40% of onion losses in India occur due to poor storage conditions (NHB, 2022). IoT helps minimize these losses through precise environmental control, early detection of spoilage indicators, and maintenance of optimal physiological conditions for the bulbs. By regulating microclimate parameters, IoT reduces sprouting, shrinkage, fungal growth, and internal heating. Moreover, data-driven insights allow farmers to manage inventory better, optimize stock rotation (FIFO), and estimate potential storage duration more accurately. Long-term datasets also assist policymakers and supply chain operators in forecasting market trends and stabilizing price fluctuations.

SENSOR TECHNOLOGIES FOR ONION STORAGE

Temperature Sensors (DS18B20, DHT22) and Importance of Heat Control

Temperature is a critical determinant of onion storage performance. Physiologically, onion bulbs continue low-rate respiration after harvest, generating metabolic heat that must be dissipated continuously to avoid spoilage, microbial growth, and sprouting. Temperature control is therefore essential in both traditional and IoT-enabled storage systems. In modern smart storage, temperature sensors enable precise monitoring and automated responses to mitigate heat buildup (Thakur and Singh, 2015).

Among the widely used temperature sensors, the DS18B20 is a digital, 1-Wire temperature sensor known for high accuracy (±0.5°C), low power consumption, and robustness. Its digital output reduces noise associated with analog sensors, making it suitable for distributed sensing networks inside large storage warehouses. Its ability to support long cable lengths and multiple-sensor chaining through a single data line makes it ideal for multi-point temperature profiling (Maxim Integrated, 2019). In onion storage, DS18B20 sensors are strategically placed at different heights and depths within storage stacks to detect "hotspots," where overheating often leads to fungal infections or internal rotting.

The DHT22 is another commonly used combined temperature–humidity sensor that offers higher accuracy and a wider operating range than its predecessor, DHT11. Although it measures humidity as well, it is frequently deployed as a temperature monitoring unit due to its low latency, digital interface, and cost-effectiveness (Adafruit, 2020). Heat control is vital because temperatures above 30–32°C significantly accelerate respiration and sprout initiation, while temperatures below 10°C can cause chilling injury unless using controlled atmosphere facilities (Brewster, 2008). Poorly ventilated traditional systems often trap heat, resulting in "cell collapse" disorders. IoT-based systems that integrate temperature sensors with automated fans or alarm mechanisms help maintain stable temperature ranges, thereby reducing storage losses up to 30–40% compared to conventional systems.

Humidity Sensors (DHT11, DHT22, SHT31) and Controlling Moisture Accumulation

Relative humidity (RH) plays a crucial role in onion storage because it directly influences moisture loss, sprouting, microbial activity, and bulb shrinkage. Onions require RH levels of 65–70% for optimal storage. Lower RH accelerates desiccation, while higher RH increases microbial rot and neck softening (Banaeian and Omid, 2018). Thus, humidity sensors are essential for monitoring and controlling moisture accumulation. The DHT11 is a basic digital humidity–temperature sensor with modest accuracy (±5% RH), making it more suitable for preliminary monitoring or small-scale storage units. Due to its limited range and slower response time, it is less effective for high-precision warehouse environments.

The DHT22 offers significantly better accuracy (±2–3% RH) and a wider operational range. It is widely used in IoT-based onion storage systems because of its stability and digital output. When combined with fans, dehumidifiers, or natural ventilation openings, DHT22-based monitoring systems can maintain humidity at optimal levels.The SHT31 is an advanced capacitive humidity sensor known for exceptional accuracy (±2% RH), fast response, long-term stability, and resistance to dust and contaminants (Sensirion, 2019). It is particularly suitable for onion storage structures in dusty environments or where ventilation introduces particulate matter.

Monitoring humidity is essential to prevent moisture condensation inside storage units. Condensation often leads to mold growth, internal decay, and bacterial soft rot. IoT-enabled systems using humidity sensors can detect RH spikes caused by nighttime cooling, poor ventilation, or unexpected weather conditions. Automated alerts or actuator-based mechanisms (e.g., exhaust fans, roof louvers, heating elements) can then correct deviations. Long-term humidity data also help analyze seasonal humidity fluctuations within traditional systems such as kanda chawls and Patil models. Such insights support structural improvements such as increased side ventilation or better roofing materials. Thus, humidity sensors are vital components of smart storage systems, helping maintain the delicate moisture balance required for prolonged onion shelf-life.

Gas Sensors: CO_2, Ethylene, and Ammonia Sensors

Gas sensing is crucial in onion storage because onions continuously release metabolic gases such as carbon dioxide (CO_2), and are sensitive to ethylene, which accelerates sprouting and aging. Poor ventilation or excessive gas buildup can lead to rapid physiological deterioration. IoT-based gas monitoring ensures early detection of harmful gas concentrations and helps maintain optimal air quality inside storage structures (Omid et al., 2020).

CO_2 Sensors

CO_2 concentration is a direct indicator of respiration intensity inside storage piles. High CO_2 levels reflect higher metabolic activity, often caused by temperature rise, insufficient curing, or microbial infection. Infrared-based nondispersive CO_2 sensors (NDIR) provide precise measurements and are widely used in storage warehouses. Research shows that CO_2 levels above 3–5% correlate with increased sprouting and decay (Brewster, 2008). IoT-integrated CO_2 sensors can trigger exhaust fans or open vents to remove accumulated CO_2.

Ethylene Sensors

Ethylene is a plant hormone responsible for ripening, senescence, and sprout stimulation. Although onions are low ethylene producers, ethylene accumulation due to poor airflow or external contamination can significantly shorten storage life. Metal oxide semiconductor (MOS)-based ethylene sensors are increasingly used in postharvest monitoring. Studies show that ethylene concentrations above 0.1–1.0 ppm can induce sprouting and root growth (Saltveit, 1999). IoT-based ethylene monitoring enables early corrective action such as enhanced ventilation.

Ammonia Sensors

Ammonia (NH_3) may be released due to bacterial decomposition or contamination. Elevated ammonia levels indicate microbial deterioration and tissue breakdown. MOS-based NH_3 sensors help detect early rotting before it becomes visible, enabling timely removal of infected bulbs and reducing the risk of spread.

Airflow and Pressure Sensors

Airflow plays a vital role in dissipating metabolic heat, removing excess moisture, and maintaining uniform environmental conditions throughout onion storage structures. Poor airflow distribution often results in "hot spots," moisture accumulation, and increased microbial activity. Therefore, monitoring airflow and pressure differentials is crucial in scientific storage systems (Thompson et al., 2008).

Anemometers

Anemometers measure airflow velocity. In onion storage, they help assess how effectively air moves through ventilation ducts, sidewalls, or slatted floors. Hot-wire anemometers provide high sensitivity and are suitable for detecting low-velocity airflow inside dense storage stacks. Propeller anemometers, on the other hand, are used in large ventilation ducts or fan-driven systems. Continuous airflow monitoring ensures sufficient ventilation for maintaining optimal temperature and humidity.

Differential Pressure Sensors

Pressure sensors measure pressure differences across ventilation zones, indicating whether airflow is evenly distributed. A pressure drop across a storage structure could signal airflow obstruction, blocked vents, or excess load inside the storage unit. In forced-air systems, maintaining an appropriate pressure differential ensures uniform airflow from the bottom to the top of onion piles, preventing localized spoilage.

Weight and Load Sensors

Weight loss is one of the primary indicators of onion storage quality. Onions lose weight due to moisture loss, respiration, and sprouting. Monitoring weight changes helps estimate shrinkage, storage duration, and postharvest losses. Load cells are widely used in modern storage systems for real-time shrinkage monitoring (Timmerman et al., 2014). Load cells measure the weight of bulk onion layers or crates. They provide high precision and continuous measurement, enabling farmers to quantify shrinkage rates. By integrating load cells with IoT platforms, weight data can be logged over time, helping detect abnormal shrinkage patterns caused by high temperature or RH deviations. Weight monitoring also helps evaluate the effectiveness of ventilation strategies. For example, if weight loss is excessively high, humidity levels may be too low, requiring system adjustments. Conversely, stable weights indicate optimal moisture retention.

Light Sensors

Light influences sprouting behavior in many crops, including onions. Although onions are typically stored in dark conditions, accidental exposure to light—through ventilation openings, cracks, or during handling—can stimulate sprouting. Light sensors help detect unwanted illumination that may compromise bulb dormancy.

Light sensors also help assess the efficiency of storage structure design—highlighting areas where light leakage occurs. In modern smart storage units, light sensors can be integrated with automated shutters or light-blocking mechanisms to preserve darkness. Thus, light sensors contribute to sprouting control and overall environmental stability.

Table 2. Sensor Modules Used in Smart Onion Storage

Sensor Type	Example Modules	Parameter Monitored	Importance in Onion Storage
Temperature	DS18B20, DHT22	Bulb temperature, hotspot detection	Controls respiration, sprouting
Humidity	DHT11, DHT22, SHT31	RH inside storage	Prevents moisture condensation, fungal growth
Gas Sensors	MQ-135, MQ-3, NDIR CO_2	Ethylene, CO_2, ammonia	Detects spoilage, microbial activity
Airflow Sensors	Hot-wire anemometers	Airflow speed	Maintains ventilation uniformity
Pressure Sensors	Differential pressure sensors	Ventilation pressure	Ensures proper distribution of air
Weight Sensors	Load cells (HX711)	Shrinkage, weight loss	Real-time crop loss estimation
Light Sensors	LDR/Photoresistors	Light leakage	Prevents sprouting triggered by light exposure

Integration of Multiple Sensors (Networked Sensor Systems, Multi-Parameter Monitoring Units)

Smart onion storage systems rely on the integration of multiple sensors to monitor temperature, humidity, airflow, gas composition, weight, and light simultaneously. A multi-sensor IoT network provides a comprehensive understanding of the storage micro-environment, enabling predictive analytics and automated control. Networked systems typically operate on microcontrollers (ESP32, Raspberry Pi) that aggregate data from various sensors and transmit it to cloud platforms using MQTT or HTTP protocols. Multi-parameter monitoring units can detect complex interactions—for example, high humidity combined with poor airflow leading to mold growth, or rising CO_2 levels associated with temperature spikes.

Sensor fusion techniques combine data from different sensors to generate more accurate predictions and control decisions. For instance, machine learning algorithms can analyze combined temperature–humidity–CO_2 data to predict spoilage likelihood or recommend ventilation adjustments. Thus, multi-sensor integration transforms traditional storage into intelligent, automated storage ecosystems capable of minimizing losses and enhancing supply chain efficiency.

Advanced Smart Storage Mechanisms Using IoT

Automated Ventilation Systems

Automated ventilation systems form a core component of IoT-enabled onion storage, as they help maintain stable temperature and humidity—two critical factors affecting sprouting, microbial growth, and moisture loss. Traditional storage structures depend on passive ventilation, which is highly influenced by weather patterns, inconsistent air movement, and manual operation. IoT-based systems overcome these limitations by integrating sensors, microcontrollers, and actuators to automate airflow control (Thompson et al., 2008).

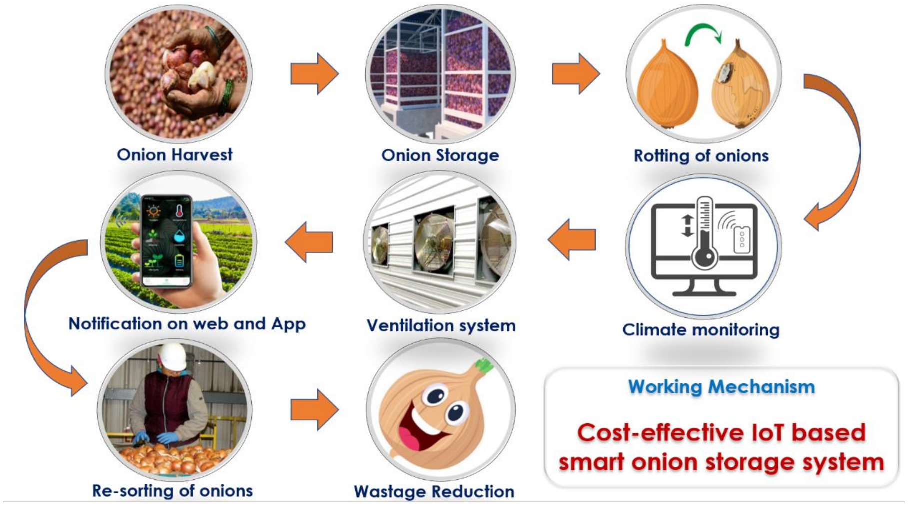

Fig. 2. Sensor Technologies Used in Smart Onion Storage

Fan Activation Based on Temperature and Humidity

In IoT-enabled systems, temperature (DS18B20, DHT22) and humidity sensors (DHT22, SHT31) continuously monitor the storage environment. When these values exceed predefined thresholds—e.g., temperature above 30°C or humidity above 70%—the microcontroller automatically triggers ventilation fans. This dynamic control prevents heat buildup and reduces moisture accumulation, both of which contribute to fungal decay and sprouting (Brewster, 2008). Such automated control minimizes human involvement and ensures that ventilation is activated only when required, resulting in energy savings and better environmental stability. Studies on IoT-based grain and vegetable storage systems show that automated ventilation can reduce spoilage losses by 20–35% (Razaque and Amsaad, 2018).

Smart Dampers and Airflow Optimization

Smart dampers regulate the amount and direction of airflow entering or exiting the storage unit. They can be controlled via servo motors or linear actuators connected to the IoT control system. When CO_2 or humidity spikes are detected, dampers open automatically to increase fresh air inflow. Conversely, they close during adverse outdoor conditions, such as high ambient humidity. Smart dampers provide microclimate zoning, meaning airflow can be optimized for specific sections experiencing higher heat production. This ensures uniform conditions throughout the storage unit—a common weakness of traditional structures like kanda chawl or Patil models. In summary, automated ventilation systems enhance environmental uniformity, reduce spoilage, and support data-driven airflow management.

Real-Time Environmental Control: PID-Based Control Systems and Humidity Management Systems

Real-time environmental control is foundational to maintaining the physiological dormancy and quality of stored onions. IoT-based systems employ advanced algorithms—particularly proportional–integral–derivative (PID) controllers—to regulate temperature, humidity, and airflow with high precision (Åström and Hägglund, 2006).

PID-Based Control Systems

PID controllers continuously calculate the error between desired setpoints and real-time sensor data. Unlike simple ON/OFF control systems, PID controllers adjust fan speed, damper opening, and cooling/heating intensity proportionally, resulting in smoother and more accurate environmental regulation. This is especially important in onion storage where rapid changes in humidity or temperature can lead to condensation, fungal growth, or respiration surges.

For example, if temperature rises gradually, the PID controller increases ventilation speed proportionally rather than switching fans fully ON. This prevents temperature oscillations and maintains a stable microenvironment. Research in controlled-atmosphere vegetable storage has shown PID systems to reduce environmental fluctuation by 40–60% compared to manual control (Danish et al., 2019).

Humidity Management Systems

Humidity is crucial in onion storage because RH outside the 65–70% range leads to either desiccation or microbial spoilage. IoT-based humidity management systems integrate dehumidifiers, evaporative coolers, and ventilation controls. When sensors detect high RH, the system can:

- ➢ Activate exhaust fans

- Open ventilation dampers
- Operate desiccant-based dehumidification units

Conversely, when RH becomes too low, the system may reduce ventilation or initiate evaporative cooling. These IoT-enabled humidity systems are especially important in regions with fluctuating ambient humidity, such as monsoon-prone states in India. Thus, real-time environmental control using PID algorithms significantly enhances efficiency, optimizes energy consumption, and preserves onion quality throughout long storage durations.

Data Logging and Cloud Storage: Thingspeak, Blynk, Firebase and Real-Time Visualization

Data logging is essential for analyzing environmental trends, diagnosing storage problems, and supporting predictive analytics. IoT-based onion storage systems generate continuous streams of data from temperature, humidity, gas, airflow, and weight sensors. This data must be stored, visualized, and interpreted effectively for decision-making (Botta et al., 2016).

Cloud Platforms

Common platforms used include:

- **ThingSpeak** – Enables real-time graphs, MATLAB-based analytics, and API integration.
- **Blynk IoT** – Provides a customizable mobile dashboard with widgets, charts, and control buttons.
- **Firebase** – Offers real-time database synchronization and seamless integration with mobile apps.

Data uploaded to these cloud servers can be accessed remotely by farmers, warehouse managers, or researchers. Cloud logging also ensures long-term data preservation.

Benefits of Data Logging

Trend Analysis

Long-term monitoring reveals seasonal or daily variations such as night-time humidity spikes or midday heating.

Diagnostic Insights

Sudden increases in CO_2 or humidity can indicate rotting bulbs or poor ventilation.

Decision Support

Historical data helps optimize ventilation timings, fan placement, and structural modifications.

Policy and Research Applications

Government agencies and researchers can use data to study regional storage patterns and propose interventions.

Real-Time Visualization

Visualization dashboards help users quickly understand storage conditions. Color-coded alerts, graphs, and heat maps help identify problem zones. Advanced platforms support:

- Predictive charts
- Spoilage-risk indicators
- Data export for statistical analysis

Thus, cloud-based data logging and visualization elevate onion storage management from manual observation to scientific, data-driven control.

Spoilage Prediction and Disease Outbreak Forecasting

Artificial Intelligence (AI) significantly enhances IoT-enabled storage by enabling predictive analytics that can forecast spoilage, detect early signs of disease, and optimize storage operations. AI models use large datasets from sensors—temperature, humidity, CO_2, ethylene, weight loss—to identify patterns associated with deterioration (Kamilaris and Prenafeta-Boldú, 2018).

Spoilage Prediction

AI algorithms such as Random Forest, LSTM (Long Short-Term Memory networks), and Support Vector Machines analyze environmental data to estimate spoilage probability. For example, increased CO_2 combined with rising temperature may indicate early-stage internal rot. Machine learning models can predict how long onions can remain safely stored based on real-time conditions. Studies in potato and onion storage modeling have shown that AI-based spoilage prediction can reduce losses by up to 25–30% by enabling timely corrective measures (Misener et al., 2017).

Disease Outbreak Forecasting

Fungal diseases such as black mold (Aspergillus niger) and bacterial soft rot thrive under high humidity and poor ventilation. AI systems analyze humidity trends, airflow profiles, and historical outbreak data to forecast disease risk.

AI models can:

- Warn users when RH will exceed dangerous levels
- Identify sections of the storage unit vulnerable to infection
- Recommend corrective actions such as increased ventilation or targeted bulb removal

Operational Optimization

AI further supports:

- Automated ventilation planning
- Energy-efficient fan scheduling
- Predictive maintenance of equipment

By integrating AI with IoT systems, onion storage facilities become intelligent, self-learning units capable of adapting to environmental changes and reducing losses.

Smartphone and SMS Alert Systems: Alerts for Abnormal Conditions and Remote Control

Smartphone and SMS-based alert systems significantly enhance the usability and accessibility of IoT-enabled onion storage systems. Many Indian farmers do not continuously monitor digital dashboards, so mobile alerts are essential for timely intervention (Razaque and Amsaad, 2018).

Alerts for Abnormal Conditions

When temperature, humidity, CO_2, or ethylene levels exceed predefined thresholds, the IoT system sends immediate alerts through:

- SMS (GSM modules like SIM800L)
- Mobile notifications (via Blynk, Firebase, or custom apps)

These alerts help farmers respond before significant damage occurs. For example:

- A sudden humidity rise may indicate condensation or rainfall.
- High CO_2 concentration may signal respiration surges or rotting bulbs.
- Light sensor activation may indicate accidental exposure promoting sprouting.

Real-time alerting is critical because onions deteriorate rapidly under adverse conditions, and timely action can prevent cascading spoilage.

Remote Control Options

Many IoT platforms allow remote operation of:

- Ventilation fans
- Dampers
- Humidifiers/dehumidifiers
- Lights or cover mechanisms

Farmers can adjust system settings even when away from the storage site. Remote control reduces labor requirements and ensures rapid correction of environmental deviations.

User-Friendly Interfaces

Mobile dashboards display environmental data in simplified formats—charts, color-coded alerts, icons—making them accessible even for non-technical users. Voice alerts and regional language support further improve usability. Studies on mobile-integrated agricultural IoT systems show increased adoption and improved management efficiency when alerts and remote control are available (Rahman et al., 2020). Thus, smartphone and SMS-based alert systems improve responsiveness, accessibility, and user engagement, making IoT-based onion storage practical and efficient.

Traditional vs. IoT-Based Storage Systems

Traditional onion storage systems (kanda chawl, Patil model, simple heaps) rely on passive design features — slatted floors, raised platforms, and natural ventilation — and manual inspection to manage the microclimate. These low-cost structures are appropriate for smallholders because of minimal capital requirements and simple maintenance. However, they are inherently reactive and weather-dependent: ventilation depends on ambient wind and temperature, there is limited capacity to remove metabolic heat or to disperse gases, and microclimatic heterogeneity (hotspots, humid pockets) commonly develops within piles (Suravi, 2024; Chattha et al., 2020). IoT-based storage transforms the storage environment from passive to actively managed. Networks of distributed sensors continuously monitor temperature, relative humidity, gas concentrations (CO_2, ethylene), airflow and weight; edge controllers implement real-time control logic and actuate fans, dampers, or dehumidifiers as needed. The key differences are proactivity and precision: instead of periodic human checks, IoT systems detect early deviations and either alert managers or automatically correct conditions (Razaque and Amsaad, 2018). This leads to improved environmental uniformity, faster hotspot suppression, and earlier identification and removal of compromised lots. Pilot studies and prototypes in India show IoT retrofits reduce hot-spot formation and fungal outbreaks, extending marketable shelf life by several weeks compared with passive structures.

From an operational perspective, IoT systems also facilitate data logging and traceability — a critical advantage for buffer stocks and export consignments. Cloud dashboards and mobile alerts allow remote supervision and historical trend analysis, enabling better inventory rotation (FIFO), predictive interventions, and evidence for quality assurance during trade.

Table 3. Comparison of Traditional vs. IoT-Based Smart Onion Storage Systems

Parameter	**Traditional Storage (Kanda Chawl, Patil Model)**	**IoT-Based Smart Storage**
Temperature Control	No control; depends on weather	Continuous sensing using DS18B20/DHT22; automated ventilation
Humidity Control	No RH management; high risk of sprouting/rotting	RH monitored with capacitive sensors (SHT31); automated fans/dampers
Airflow	Natural ventilation only	Controlled airflow (smart fans + PID control)
Gas Monitoring	None	Ethylene, CO_2, NH_3 sensors (MQ series, NDIR CO_2)
Sprouting/Roting Prevention	Manual inspection	Real-time alerts + predictive modelling
Data Logging	Not available	Cloud-based dashboards (ThingSpeak, Firebase, Blynk)
Loss Percentage	20–40% losses commonly	Reduced to 8–15% in pilot studies
Cost	Very low construction cost	Moderate initial cost but high ROI

Cost–Benefit Analysis

A realistic cost–benefit analysis must separate initial investment, operational costs, and returns (reduced losses, better prices, extended market window). For traditional systems the initial cost is low: farmer-built kanda chawls and Patil models require locally available materials and minimal technical skill. Operational costs are also low (primarily labor), but these systems suffer from high post-harvest losses and price vulnerability, which translate into opportunity costs for farmers (Suravi, 2024). IoT retrofits typically include sensors (temperature, humidity, gas, weight), microcontrollers (ESP32/Arduino/Raspberry Pi), gateways (GSM/LoRa/Wi-Fi), actuators (fans, dampers), and cloud service subscriptions. A low-cost pilot system for a small storage unit can be implemented for a few hundred to a few thousand USD equivalent (depending on the number/quality of sensors and communication modules), whereas full industrial installations (CA rooms, commercial HVAC, NDIR gas sensors, certified load cells) cost substantially more. Academic prototypes and small pilot projects report attractive payback periods when yield losses avoided are considered: for instance, avoiding even 10–20% spoilage on a medium-sized holding often pays back sensor+actuator costs within 1–2 seasons in higher-value markets (IJARSCT, pilot reports).

Operational costs for IoT systems include energy (fans, dehumidifiers, pumps), network/GSM data, periodic sensor calibration/replacement, and occasional maintenance. Smart control algorithms (PID, demand-based ventilation) and renewable integration (solar power for fans/controllers) can reduce running costs substantially compared with continuous mechanical cooling. In industrial CA/cold storage, energy is the dominant operating expense; in contrast, IoT-enabled ventilation strategies emphasize targeted, intermittent ventilation to minimize energy draw while achieving environmental targets (WUR, CA studies). Return on investment (ROI) for farmers depends on local price spreads (seasonal price differentials), loss reduction achieved, and the ability to access premium markets (exports, processors). Because onions often command significantly better prices off-season, smallholders or cooperatives that can extend shelf life and reduce spoilage stand to capture high marginal profit. In policy contexts where governments procure buffer stocks, meeting quality standards (traceability, low spoilage) opens additional revenue streams. In short, while initial IoT investments are non-trivial, the combination of loss reduction, better market timing and potential premium pricing typically yields positive ROI within a few harvest cycles—especially when systems are scaled across cooperatives rather than single farms. Empirical pilot data and modeling studies support this conclusion, though exact payback periods are context-specific.

Performance Evaluation Metrics

Quantitative evaluation of storage performance requires standardized metrics that capture quality, quantity, and resource use. Three core metrics for onion storage are spoilage percentage, weight loss (shrinkage), and energy consumption; a complete evaluation may also include economic and operational KPIs (e.g., days of safe storage, percentage of lots meeting grade, maintenance downtime).

Spoilage percentage measures the proportion of stored produce rendered unmarketable due to rot, sprouting, or other physiological damage. Literature reports widely varying baseline spoilage for traditional storage, often in the 20–40% range under suboptimal conditions (Suravi, 2024), while well-managed CA or properly ventilated systems can reduce spoilage below 5–10% over comparable storage durations. IoT-assisted ventilation and early detection demonstrably lower spoilage by enabling timely interventions (fan activation, segregation of affected lots). Therefore, spoilage percentage is a primary outcome variable in pilot evaluations and cost-benefit models.

Weight loss (shrinkage) is a direct measure of moisture loss from bulbs and is typically expressed as percent weight lost over storage duration. Weight loss affects marketable yield and is sensitive to RH, temperature and airflow. Studies show forced-air ventilation properly managed can minimize shrinkage compared to static heaps (Chattha et al., 2020). Load-cell networks integrated with IoT platforms provide continuous shrinkage monitoring, enabling managers to correlate weight trajectories with environmental events and optimize interventions. Shrinkage data also feed into inventory valuation and accurate forecasting of saleable volumes.

Energy consumption is critical for comparing active systems (forced ventilation, dehumidification, CA control) and passive systems (natural ventilation). For industrial CA/cold stores, energy use per tonne-month is high, primarily driven by refrigeration compressors. In contrast, IoT-enabled demand-based ventilation uses energy sparingly—fans operate only when sensors indicate need. Energy metrics should therefore capture both instantaneous power draw and integrated energy per unit of storage time (kWh/tonne-month). Optimization algorithms (PID, predictive control) reduce energy use while maintaining environmental targets; several control studies and CA implementations report energy savings vs naive control. In practice, benchmarking a storage solution requires simultaneous monitoring of these metrics, ideally with standardized protocols (sampling frequency, sensor calibration, definition of spoilage thresholds). IoT platforms facilitate this by centralizing data streams and supporting automated KPIs and heat-map visualizations to compare zones, seasons, and interventions. Together, spoilage percentage, weight loss, and energy consumption provide a robust triad for technically and economically assessing storage performance.

Technical Challenges

IoT-based onion storage systems depend heavily on accurate sensing, reliable communication, and consistent data acquisition. However, several technical constraints limit their large-scale adoption. One of the foremost issues is sensor calibration. Temperature, humidity, and gas sensors such as DHT22, SHT31, NDIR-based CO_2 sensors and electrochemical ethylene sensors tend to drift over time due to dust accumulation, fluctuating environmental conditions, and aging of sensing elements. In onion storage environments, where fine dust, moisture, and volatile compounds are present, sensors often experience calibration drift faster than in controlled laboratory settings. Poorly calibrated sensors can result in misleading data, which in turn triggers incorrect ventilation or control responses, undermining the purpose of automation. Studies by Razaque and Amsaad (2018) and Sharma et al. (2021) emphasize that even a ±1°C error in sensor reading can alter spoilage dynamics in stored produce, making calibration accuracy essential.

Data accuracy and noise present another technical obstacle. IoT nodes sometimes generate inconsistent data due to fluctuating voltage supply, low-quality wiring connections, radio interference, or environmental stress such as condensation. Moreover, gas sensors such as MQ-series modules are known to have cross-sensitivity issues, responding to multiple gases at once, complicating interpretation. High-quality industrial sensors exist but increase project cost substantially, reducing feasibility for small farmers. Network issues are also central in limiting system reliability. IoT systems deployed in rural agricultural settings often rely on GSM, Wi-Fi, or LoRaWAN. GSM connectivity in rural zones can be inconsistent, causing data upload failures, delayed alerts, or loss of real-time visibility. Wi-Fi availability is extremely limited in many storage yards, and LoRaWAN gateways are still rarely deployed at scale. Interruptions in communication prevent the system from transmitting environmental data or receiving control commands, reducing its usefulness during critical periods such as sudden temperature rises or humidity spikes. Furthermore, power supply reliability is a recurring technical concern. Frequent power cuts cause system downtime, sensor resets, or controller malfunction. Unstable mains supply can also burn inexpensive sensors or microcontrollers. Solutions such as battery backups and solar integration increase resilience but add complexity. Overall, technical challenges—calibration, data reliability, connectivity issues, and power instability—represent major hurdles limiting the robustness and long-term practicality of IoT-based onion storage systems (Agarwal et al., 2021; Razaque and Amsaad, 2018; ICAR-DOGR Reports, 2022).

Economic Challenges

Economic feasibility remains one of the most significant constraints affecting the adoption of smart onion storage technologies by farmers and cooperatives. Although IoT-based storage systems promise reduction in spoilage, improved quality, and enhanced market timing, their initial investment cost is relatively high. A complete system—including temperature, humidity, gas, and weight sensors, microcontrollers (ESP32, Arduino, Raspberry Pi), gateways (GSM/LoRa), cloud subscriptions, data storage, and automated ventilation units—may cost anywhere between INR 20,000 to 2,00,000 depending on sophistication and scale. For smallholder farmers, who typically store onions in traditional kanda-chawls costing only a few thousand rupees, such investments appear economically daunting (Bhardwaj, 2020; Singh et al., 2022). Beyond installation, operational costs also influence affordability. IoT systems require periodic sensor replacement, calibration, technician visits, GSM data recharge, and occasional repairs to fans or controllers. For farmers with limited cash flow and irregular incomes, these recurring expenses reduce adoption willingness. In contrast, traditional storage structures have almost negligible operational costs aside from manual labor.

Another economic barrier is the need for skilled operators or trained technicians. IoT devices are vulnerable to configuration errors, wiring faults, and software failures. Most rural farmers lack digital literacy or familiarity with troubleshooting microcontrollers or sensor arrays. This creates dependency on external technicians or service providers, which increases maintenance costs and downtime. Although cooperative-level deployments reduce this burden through shared technical staff, individual farmers still find these systems difficult to manage. Moreover, absence of financial incentives such as subsidies, soft loans, or insurance coverage for smart storage systems limits demand. While improved storage substantially increases farmers' potential earnings by enabling off-season sales at higher prices, the delayed return on investment (ROI) discourages adoption among marginal and small farmers. Pilot studies from ICAR and IIT-supported projects indicate ROI periods ranging from 1 to 3 years, which may be acceptable for cooperatives but not for standalone farmers facing seasonal risks. Thus, economic barriers—high initial cost, recurring operational expenses, need for skilled manpower, and limited financial support—remain major challenges preventing widespread deployment of IoT-based smart onion storage systems (Singh et al., 2022; FAO Postharvest Report, 2021).

Field-Level Implementation Challenges

Even when technical and economic barriers are addressed, field-level challenges significantly hinder real-world deployment. One of the most pervasive issues is rural connectivity. Many onion-producing regions in Maharashtra, Madhya Pradesh, Karnataka, and Rajasthan experience intermittent GSM/4G coverage. Poor connectivity prevents real-time data transmission, delays alerts, and disrupts cloud synchronization. LoRaWAN infrastructure—ideal for long-range low-power communication—is not yet widely available, making communication unreliable for remote storage facilities (Patil et al., 2023).

Maintenance challenges also impede sustainability. Rural environments are harsh on electronics: high temperatures, dust accumulation, humidity fluctuations, and occasional rodent damage can degrade sensors and wiring. Most farmers lack tools or expertise for maintenance, causing long downtimes when systems malfunction. IoT nodes exposed to the environment may require protective housings, waterproofing, and regular servicing—all adding complexity and cost. Even simple components like USB cables, relay modules, and connectors fail more frequently in dusty storage environments. Another major barrier is lack of awareness and technical training among farmers. Many farmers are unfamiliar with digital dashboards, cloud systems, or sensor calibration procedures. Improper handling—such as placing sensors too close to fans, burying them in piles, or failing to clean air vents—can lead to misleading readings. Without proper training in interpreting graphs or alerts, farmers may underutilize system capabilities. Thus, extension programs and regular demonstrations are necessary for widespread adoption.

Furthermore, fragmented supply chains make repairing or replacing components difficult in rural areas. Microcontrollers, gas sensors, and differential pressure sensors are not readily available in local markets, resulting in long delays for parts replacement. Lastly, environmental unpredictability—heat waves, monsoon humidity spikes, and voltage fluctuations—compounds the difficulty of implementing stable IoT systems. Smart storage must therefore be adapted to local climate conditions and designed with redundancy. In summary, rural connectivity gaps, maintenance limitations, lack of user training, and environmental stresses create significant field-level challenges that reduce reliability and long-term adoption of IoT-based onion storage systems (Patil et al., 2023; FAO, 2021; ICAR-DOAR Technical Bulletin, 2022).

Predictive Storage Models and Automated Decision-Making

Artificial intelligence (AI) and machine learning (ML) are rapidly maturing into powerful tools for post-harvest management. In smart onion storage, AI enables predictive storage models that combine multi-sensor time-series data (temperature, relative humidity, CO_2/ethylene, airflow, and weight) with historical spoilage records to forecast shelf-life and spoilage risk at the lot or even bulb level. Hybrid ML approaches — for example, ensemble methods (Random Forest, XGBoost) and deep learning models (LSTM for time-series forecasting, CNNs for image-based quality assessment) — have been shown to deliver high accuracy in predicting spoilage events and remaining safe storage time (Rashvand et al., 2025). These models use environmental covariates to estimate respiration-driven deterioration, microbial risk windows, and sprouting probability, enabling proactive interventions before visible deterioration occurs.

Beyond pure prediction, AI supports automated decision-making by translating forecasts into control actions. When an

ML model predicts an imminent risk (e.g., a hotspot that will lead to CO_2 buildup and rot within 24–48 hours), the IoT control layer can automatically enact mitigation — increasing targeted ventilation, opening zonal dampers, scheduling targeted manual inspection, or activating dehumidification. Reinforcement learning (RL) and model predictive control (MPC) frameworks are particularly promising: RL agents can learn optimal ventilation/actuator policies through simulated and real-world interaction, while MPC uses short-horizon optimization on a learned or physics-based model to balance quality preservation against energy cost (papers on control-theory and MPC). These approaches reduce reliance on rigid ON/OFF thresholds and enable nuanced, anticipatory control that improves quality retention while lowering energy use. Integrating machine vision and spectroscopy with AI further enriches predictive power. Hyperspectral or multispectral imaging analyzed by deep networks can detect internal defects or early microbial colonization not visible to the eye, providing labels that improve supervised ML models for shelf-life. Additionally, transfer learning and federated learning architectures allow multisite model training without centralizing sensitive farm data, enhancing robustness across cultivars and climates.

CONCLUSION

The integration of Internet of Things (IoT) technologies into onion storage marks a transformative shift from conventional, manually operated and climate-dependent systems to intelligent, automated, and data-driven storage management. Because onions remain physiologically active after harvest, maintaining optimal microclimatic conditions—temperature, relative humidity, airflow, and gas composition—is crucial to minimize sprouting, microbial growth, and shrinkage. IoT-enabled systems offer continuous and distributed monitoring of these parameters through low-cost sensors, edge devices, and cloud-connected gateways, enabling rapid detection of anomalies, closed-loop control of ventilation and humidity, and real-time data analytics for predictive decision-making. Advancements in recent years, including more accurate environmental and gas sensors, microcontroller platforms like ESP32 and Raspberry Pi, and long-range communication systems such as LoRaWAN, have strengthened the viability of smart storage technologies. Improvements in analytical software, including PID controllers, model predictive control, and machine-learning-based spoilage prediction models, have further expanded the capabilities of automated storage structures. Research and pilot studies—both in India and globally—demonstrate that IoT-based systems significantly reduce hotspots, fungal outbreaks, and overall post-harvest losses when combined with good post-harvest practices. This loss reduction translates into improved marketable yield, better price realization, and greater economic stability for farmers. However, despite promising outcomes, several challenges remain, including the need for cost-effective calibration protocols, robust predictive models suited to diverse agro-climatic conditions, energy-efficient control algorithms, and scalable business models for smallholders and cooperatives. Ultimately, interdisciplinary collaboration across engineering, crop physiology, data science, and extension systems will be essential to fully harness IoT's potential for reducing post-harvest losses and improving the resilience and efficiency of onion storage systems.

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