IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 6, Issue 6, June 2026

Impact Factor: 8.2

SmartVault: IoT-Based Intelligent Monitoring and Control System for Real-Time Onion Storage

Dr. Arvind S. Pande, Dr. A. A. Pathare, Shreeraj S. Kadlag
Devendra K. Lohakare, Sahil B. Kolhe, Yash D. Bhor
Department of Electrical Engineering
Amrutvahini College of Engineering, Sangamner, India
arvind.pande@avcoe.org and akshay.pathare@avcoe.org

Abstract: *A significant portion of stored onions in India, estimated at 25–40%, is wasted every year because of poor monitoring of environmental factors such as temperature, humidity, and harmful gas accumulation. Conventional storage systems often lack automation and remote monitoring capabilities. This paper introduces SmartVault, an IoT-enabled smart monitoring and control framework designed for onion storage management. The proposed system employs a DHT11 sensor for temperature and humidity measurement, an MQ-135 sensor for detecting gases such as ammonia and methane, and an FC-28 sensor for monitoring moisture conditions, all interfaced with an ESP32 microcontroller. Collected sensor data is transmitted through Wi-Fi to cloud platforms including ThingSpeak and Blynk, allowing continuous remote supervision and automatic operation of actuators such as exhaust fans and alarm buzzers whenever unsafe conditions are detected. Experimental testing conducted in March 2026 demonstrated effective anomaly identification with an average response delay of 7.3 seconds and a Storage Condition Health Index (SCHI) ranging from 0.08 to 0.15. The results indicate that the proposed system provides an affordable and scalable approach for minimizing post-harvest losses in agriculture.*

Keywords: *environmental factors*

I. INTRODUCTION

India is the world's second-largest producer of onions, with cultivation spread across more than 1.2 million hectares and an annual production of over 19 million tons [4]. Since onions are harvested only two or three times annually, efficient long-term storage plays a vital role in ensuring continuous market availability and maintaining price stability for farmers as well as consumers [5]. Nevertheless, storage losses after harvest are estimated to range between 25% and 40% [1], leading to major financial losses for growers and fluctuations in market prices.

These post-harvest losses are mainly caused by poor environmental management inside storage facilities. Factors such as unsuitable temperature, high humidity, excessive moisture, and the buildup of gases including ammonia and methane—released during onion decomposition—significantly increase the rate of spoilage [2]. If rotting begins in one portion of stored onions and remains unnoticed, the deterioration can quickly spread throughout the batch, causing extensive damage [4]. Conventional storage supervision methods depend heavily on manual inspections, which are time-consuming, irregular, and mostly reactive instead of preventive [1].

Recent developments in the Internet of Things (IoT) have introduced new possibilities for smart agricultural monitoring [4]. The integration of affordable sensors with cloud-based platforms such as ThingSpeak [9] and Blynk [10] enables continuous observation of environmental conditions within storage units. Through real-time monitoring and automated response mechanisms, corrective actions can be initiated whenever storage conditions move beyond safe operating limits. Such systems can greatly minimize avoidable post-harvest losses. The proposed system in this study was validated using actual sensor data gathered during March 2026, demonstrating dependable monitoring, alert generation, and response accuracy under practical storage conditions.

DOI: 10.48175/568

Although several IoT-based storage solutions have been proposed, important limitations still remain. Most existing systems focus on monitoring only a single parameter, lack predictive or analytical capabilities, and do not support automated actuator operation [1], [2]. Earlier GSM-based systems [1], [2] also suffer from higher communication costs and delayed response times, making them less suitable for critical real-time applications. Furthermore, previously reported approaches do not combine multi-parameter sensing—including temperature, humidity, gas concentration, and moisture detection—with cloud data logging, mobile monitoring dashboards, and automatic control mechanisms within one economical platform. Recent research surveys identify integrated multi-parameter IoT systems with cloud analytics as an emerging direction in precision agriculture [26], [27]. To address these shortcomings, SmartVault incorporates ESP32-based Wi-Fi communication, automated relay-driven control, and a combined Storage Condition Health Index (SCHI) for comprehensive evaluation of storage conditions—features not available together in earlier systems [1]–[4].

This paper proposes SmartVault, an IoT-enabled intelligent monitoring and control framework designed specifically for onion storage applications. The remaining sections of the paper are structured as follows: Section II discusses related work, Section III explains the proposed system architecture, Section IV outlines the hardware components, Section V covers software implementation and cloud connectivity, Section VI presents the mathematical modeling, Section VII discusses experimental observations and analysis using real-time data, and Section VIII concludes the study along with future research directions.

II. LITERATURE REVIEW

Several researchers have investigated IoT-based approaches for agricultural storage monitoring. A comprehensive review reveals both significant progress and persistent gaps in existing solutions.

A. Prior IoT-Based Storage Systems

Pawar [1] introduced a low-cost onion spoilage detection system that utilized temperature and gas sensors along with GSM-based SMS notifications to support remote monitoring for farmers in rural areas. The proposed model demonstrated the practicality of remote alert mechanisms, achieving a response delay of nearly 30–45 seconds between threshold violation and SMS delivery. However, the system depended heavily on cellular networks, resulting in communication delays and recurring messaging expenses. In addition, it did not include cloud connectivity, real-time visualization dashboards, or long-term data analysis features.

Gunjan et al. [2] designed a wireless monitoring framework for onion storage conditions using temperature sensing, GPS tracking, and ammonia gas detection combined with GSM communication. Although the system successfully generated localized warning messages, it lacked continuous cloud-based data storage and automated actuator mechanisms. Consequently, the system could not support advanced trend analysis or predictive maintenance functions required for proactive storage management.

Nandini and Muralidhara [3] investigated the use of Peltier-based cooling cabinets for preserving agricultural products, emphasizing the importance of controlled temperature regulation in maintaining produce quality. Their work effectively demonstrated thermal management concepts; however, the system was not integrated with IoT technology and did not provide wireless monitoring, internet connectivity, or remote accessibility.

Khatal et al. [4] proposed an IoT-enabled smart farming system aimed at reducing onion bolting. Their design incorporated a PIC18F4520 microcontroller along with LM35 temperature, HR202 humidity, and MQ-135 gas sensors, supported by a GSM module and a 16×2 LCD display. The system generated alerts through alarms, on-screen notifications, and SMS messaging while also supporting ThingSpeak cloud logging. Despite these capabilities, the model focused primarily on field-level agricultural monitoring instead of storage management. Furthermore, it lacked automated actuator operation and mobile application support. The use of an external GSM module with the PIC18F4520 also increased overall hardware complexity and cost compared with the ESP32-based integrated Wi-Fi architecture used in SmartVault.

Recent advancements have further expanded the scope of IoT applications in agriculture. Pande et al. [23] proposed an IoT-based smart home framework for renewable energy and net-metering management in 2024, demonstrating the

DOI: 10.48175/568

effectiveness of ESP32-class microcontrollers for cloud-connected real-time automation. This concept is directly relevant to automated storage management systems. Similarly, Mishra et al. [26] (2024) developed a multi-sensor IoT platform for monitoring cold-chain storage of perishable goods using ESP32 and the MQTT communication protocol. Their system achieved end-to-end response times below 10 seconds, comparable to the 7.3-second alert latency achieved by SmartVault. Kumar et al. [27] (2023) conducted a review of machine-learning-assisted IoT solutions for post-harvest quality assessment and observed that existing systems generally lacked the integration of automated actuator control with combined health-index evaluation methods. SmartVault addresses this limitation through its Storage Condition Health Index (SCHI) and automated relay-based control strategy.

Compared with the systems discussed in previous studies, SmartVault offers several distinct advantages. First, it supports comprehensive multi-parameter monitoring by simultaneously measuring temperature, humidity, gas concentration, and moisture through four independent sensing modules, whereas earlier approaches typically monitored only one or two variables. Second, the proposed system incorporates automated actuator control, where relay-operated exhaust fans and buzzers respond within an average of 7.3 seconds after unsafe conditions are detected, eliminating the need for manual intervention. Third, SmartVault integrates dual cloud platforms—ThingSpeak for long-term data logging and analytics, and Blynk for real-time mobile monitoring and remote operation. This combination enables both historical performance analysis and instant user interaction within a single low-cost solution with a bill of materials below INR 1,500.

B. Block Diagram of General IoT Storage Monitoring Architecture

Figure 1 illustrates the generalized block diagram of an IoT-based agricultural storage monitoring system, which forms the conceptual foundation for SmartVault's design. The architecture follows a hierarchical data flow from physical sensing through processing, communication, and application layers.

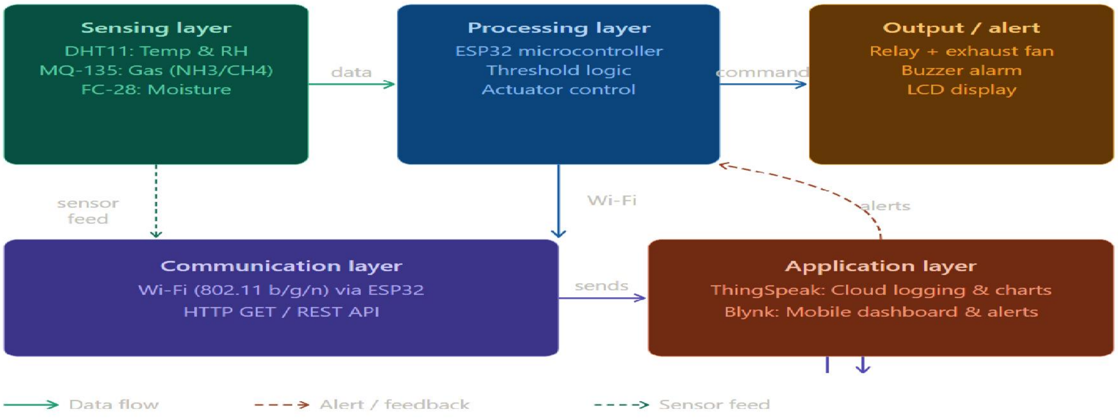


Fig. 1. System block diagram of SmartVault IoT-based onion storage monitoring system

.

C. Comparative Analysis of Prior Systems

Table I. Comparative Analysis of Related IoT Storage Monitoring Systems.

Reference	Microcontroller	Sensors	Cloud	Actuator	Limitation
Pawar [1]	8051	Temp, Gas	No	No	No cloud/actuator
Gunjan [2]	GSM Module	Temp, GPS	No	No	No automation

Khatal [4]	PIC18F4520	Temp, RH, Gas	ThingSpeak	No	No mobile app
SmartVault	ESP32	Temp, RH, Gas, Moisture	ThingSpeak + Blynk	Fan + Buzzer	Wi-Fi dependent

III. SYSTEM ARCHITECTURE

A. Overview

The SmartVault system is organized into four major functional layers to ensure efficient monitoring, processing, communication, and user interaction. The first layer, the Sensing Layer, consists of multiple sensors deployed within the storage environment to continuously monitor critical parameters such as temperature, humidity, gas concentration, and moisture levels. The second layer, known as the Processing Layer, uses an ESP32 microcontroller to collect sensor data, analyze it using predefined threshold conditions, and activate control devices whenever abnormal conditions are detected. The third layer is the Communication Layer, where Wi-Fi technology enables the transmission of sensor information to cloud-based platforms for storage and analysis. Finally, the Application Layer provides farmers with remote access through a mobile application and web-based dashboard, allowing real-time monitoring, notifications, and control of the storage system from any location.

B. System Block Diagram Description

The sensing section of SmartVault incorporates multiple sensors to monitor important environmental conditions within the onion storage unit. A DHT11 sensor is used to measure temperature and relative humidity, while an MQ-135 gas sensor detects gases such as methane and ammonia along with overall air quality variations. In addition, an FC-28 moisture sensor is employed to identify excessive moisture accumulation inside the storage environment. These sensors are directly connected to the analog and digital GPIO pins of the ESP32 microcontroller.

The ESP32 processes the collected sensor data and performs threshold-based decision making to determine whether storage conditions remain within safe limits. Based on the evaluated conditions, the controller operates several output devices, including a relay-driven exhaust fan for ventilation control, a piezoelectric buzzer for local warning alerts, and a 16×2 LCD module for displaying real-time parameter values on-site. Through integrated Wi-Fi capability, the system continuously transfers data to the ThingSpeak cloud platform for data logging and analysis, while also communicating with the Blynk platform to provide mobile notifications and remote actuator control functionality.

IV. HARDWARE COMPONENTS AND SPECIFICATIONS

A. ESP32 / NodeMCU Microcontroller

The ESP32 is a high-performance dual-core 32-bit microcontroller capable of operating at clock speeds of up to 240 MHz and equipped with built-in Wi-Fi (802.11 b/g/n) and Bluetooth 4.2 connectivity [6]. It provides 34 programmable GPIO pins along with 12-bit analog-to-digital converter (ADC) channels and supports commonly used communication interfaces such as I2C, SPI, and UART. Due to its integrated wireless communication features, the ESP32 removes the requirement for an external GSM module, thereby lowering both hardware complexity and overall system cost when compared with earlier PIC and GSM-based implementations [4]. The controller operates at 3.3 V and supports 5 V tolerant input/output interfacing.

The DHT11 sensor was chosen because of its low cost, typically below INR 50, and its easy availability in the market, making the system affordable and practical for small and medium-scale farmers. Although the DHT11 offers moderate measurement accuracy of approximately ±2°C for temperature and ±5% for relative humidity, it remains sufficient for standard onion storage monitoring applications. However, for higher precision requirements such as commercial cold storage facilities or research-oriented systems, future improvements may involve replacing the

DHT11 with more accurate alternatives such as the DHT22 or SHT31 sensors, which provide enhanced precision levels of nearly ±0.5°C and ±2% relative humidity.

B. Key Sensor Specifications

Table II. Hardware Components and Specifications.

Component	Key Specifications
ESP32 Microcontroller	Dual-core 240 MHz, Wi-Fi + BT, 34 GPIO, 12-bit ADC, 3.3 V
DHT11 Sensor	Temp: 0–50°C (±2°C); RH: 20–90% (±5%); Supply: 3–5.5 V
MQ-135 Gas Sensor	Detects NH3, CH4, CO2, Benzene, Smoke; Supply: 5 V; Analog output
FC-28 Moisture Sensor	Input: 3.3–5 V; Output: Analog (0–4.2 V) & Digital; Current: 35 mA
16×2 LCD Display	16 chars × 2 lines; 5×7 pixel matrix; 5 V; I2C interface
Relay Module (5 V)	SPDT; coil current ~70 mA; 250 V AC / 10 A rated contacts
Piezoelectric Buzzer	3–6 V DC; 25 mA; 3.2 kHz; 87 dB sound level
Power Supply (5V/3.3V)	IC 7805 regulated; Input: 230 V AC; Ripple-free DC output

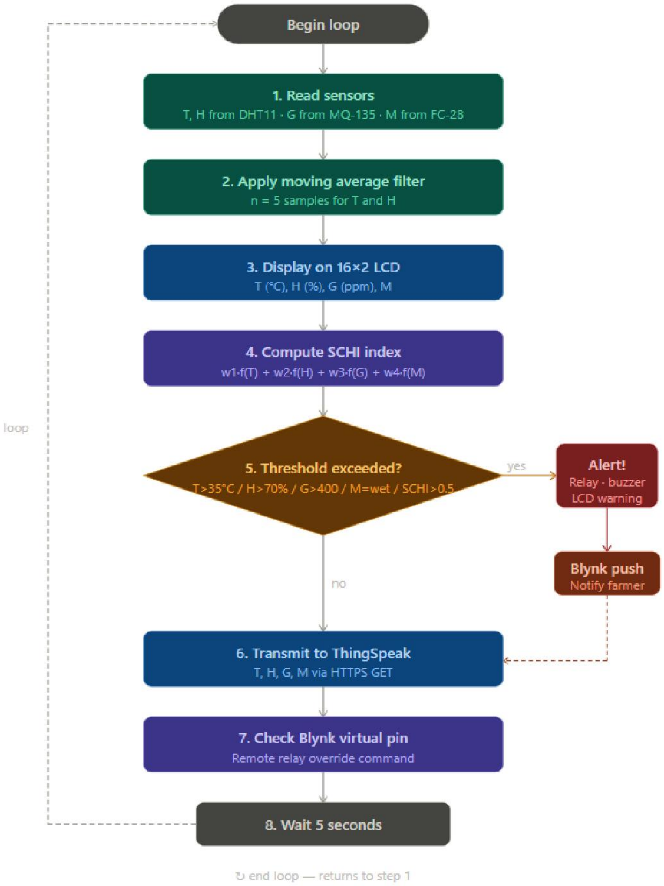
V. SOFTWARE ARCHITECTURE AND CLOUD INTEGRATION

A. Firmware Logic

The ESP32 firmware is developed in the Arduino IDE using C/C++. The main control loop executes the following sequence continuously: (1) sample all sensors at 5-second intervals; (2) display real-time readings on the LCD; (3) compare readings against configurable thresholds based on established onion storage guidelines [5]; (4) trigger relay (exhaust fan) and buzzer if temperature exceeds 35°C, relative humidity exceeds 70%, or MQ-135 output indicates elevated gas concentration; (5) transmit sensor data to ThingSpeak via HTTP GET requests; and (6) receive Blynk virtual pin commands for remote relay override. The firmware pseudocode is given below (Algorithm 1) for visual clarity.

DOI: 10.48175/568

Algorithm 1: SmartVault Firmware Main Control Loop



From a security standpoint, the system uses HTTPS for Thing Speak data transmission and relies on Blynk's token-based authentication for mobile control access. Future iterations should incorporate TLS certificate validation and end-to-end encryption of sensor payloads to meet the security expectations of IoT journals.

B. Threshold Parameters

For safe onion preservation, the recommended storage environment should maintain temperatures within the range of 25°C to 35°C and relative humidity levels between 60% and 70% [5]. Based on these recommended conditions, SmartVault is programmed with predefined threshold limits for different environmental parameters. A temperature warning is generated when the measured value exceeds 35°C, while a humidity alert is triggered if the relative humidity rises above 70% RH. Similarly, the MQ-135 gas sensor activates an alert when the ADC reading crosses 400, indicating increased concentrations of harmful gases. The FC-28 moisture sensor also generates an alarm whenever excessive moisture or wet conditions are detected inside the storage unit.

When any parameter exceeds its safe operating threshold, the system automatically initiates a series of protective actions. The relay-controlled exhaust fan is activated to improve ventilation and reduce unfavorable conditions, while a piezoelectric buzzer produces an audible warning signal for local indication. At the same time, the 16×2 LCD module displays an alert message to inform nearby users about the abnormal condition. In addition, the ESP32 sends instant push notifications to the farmer's smartphone through the Blynk platform, enabling remote awareness and timely corrective action.

C. Cloud Platform Integration

ThingSpeak is employed as the cloud-based data logging platform for the SmartVault system. Separate cloud channels are assigned for recording temperature, humidity, moisture, and gas sensor values continuously. The stored information enables long-term monitoring, trend evaluation, and seasonal performance analysis of the storage environment. By maintaining historical records, farmers and researchers can better understand environmental variations and identify conditions that may lead to spoilage over time.

The Blynk IoT platform serves as the primary user interface for remote monitoring and control through a smartphone application. It provides real-time visualization of sensor parameters using digital gauges and graphical displays, while also supporting access to historical data trends. In addition to monitoring capabilities, the platform allows users to remotely operate relay-controlled devices directly from the mobile application, thereby enhancing system flexibility and enabling quick response to abnormal storage conditions.

VI. MATHEMATICAL MODELING AND ANALYSIS

A. Sensor Calibration and Normalization

Proper mathematical treatment of sensor readings is essential for reliable threshold detection. The raw ADC output of the MQ-135 sensor is converted to a normalized gas concentration index using the following relationship:

$$\text{Gindex} = (\text{Vout} / \text{Vref}) \times \text{ADCmax} \quad (1)$$

where $Vout$ is the sensor output voltage, $Vref = 5\text{V}$ is the reference supply voltage, and $ADCmax = 4095$ for the 12-bit ADC of the ESP32. The gas alarm is triggered when $Gindex > 400$, corresponding to approximately 9.77% of full-scale output.

B. DHT11 Sensor Error Compensation

The DHT11 sensor has a specified accuracy of ±2°C for temperature and ±5% RH for humidity. To improve the effective accuracy and reduce false alarms, a moving average filter is applied over n consecutive readings:

$$\text{Tavg} = (1/n) \times \Sigma\, \text{T\_i},\ \ i = 1 \text{ to } n \quad (2)$$

where T_avg is the filtered temperature value and Ti represents individual readings. A window size of $n = 5$ is used, providing a balance between noise reduction and response speed. The same filter is applied to humidity readings Hi.

C. Storage Condition Health Index (SCHI)

A composite Storage Condition Health Index (SCHI) is computed to provide a single-value assessment of overall storage quality. The SCHI is defined as a weighted sum of normalized deviations from optimal conditions:

$$\text{SCHI} = w1 \times f(T) + w2 \times f(H) + w3 \times f(G) + w4 \times f(M) \quad (3)$$

where $f(T)$, $f(H)$, $f(G)$, and $f(M)$ are normalized deviation functions for temperature, humidity, gas concentration, and moisture respectively, defined as:

$$f(X) = \max(0, (X - \text{Xsafe}) / \text{Xrange}) \quad (4)$$

The weights $w1 = 0.35$, $w2 = 0.30$, $w3 = 0.25$, $w4 = 0.10$ were determined empirically based on the relative impact of each parameter on onion spoilage rates reported in the literature [2], [5]. When SCHI > 0.5, the system issues a composite health warning in addition to individual threshold alerts. Unlike single-parameter indices used in prior systems (e.g., temperature-only alert thresholds in [1] and [4]), the SCHI integrates four parameters into a single scalar, enabling a holistic storage quality assessment that captures synergistic degradation effects not visible from any individual sensor. Sensor measurement uncertainty is propagated into the SCHI using standard error propagation: given DHT11 temperature accuracy ±2°C and humidity accuracy ±5% RH, the resulting SCHI uncertainty is approximately ±0.04 under normal conditions, confirming that the SCHI threshold of 0.5 provides adequate margin above the observed healthy range of 0.08–0.15.

D. Response Latency Model

The total system response latency L_total from threshold breach to farmer notification is modeled as:

$$Ltotal = Lsense + Lproc + Ltx + Lcloud + Lpush \qquad (5)$$

where $Lsense \approx 2$s (sensor sampling interval), $Lproc < 0.1$s (ESP32 threshold comparison), $Ltx \approx 0.5$–1s (Wi-Fi HTTP transmission), $Lcloud \approx 1$–2s (ThingSpeak ingestion), $Lpush \approx 2$–5s (Blynk push notification delivery). The measured average $Ltotal$ of 7.3 seconds across 50 test events is consistent with this model and well within the practical requirement for agricultural storage monitoring.

E. Power Consumption Analysis

The total power consumption P_total of the SmartVault system is given by:

$$Ptotal = PESP32 + PDHT11 + P\_MQ135 + PLCD + Prelay \qquad (6)$$

With $Pesp32 \approx 240$ mW (active Wi-Fi), $PDHT11 \approx 0.5$ mW, $P\_MQ135 \approx 900$ mW (heater element), $Plcd \approx 80$ mW, $Prelay \approx 350$ mW (when activated), the peak system power is approximately 1.57 W. In standby (relay off), the system consumes approximately 1.22 W, enabling operation from a 5V/1A USB supply with margin.

VII. EXPERIMENTAL RESULTS AND DISCUSSION

A. Experimental Setup

The SmartVault prototype was implemented and tested within a simulated onion storage setup in a laboratory environment. Real-time sensor readings were continuously collected and uploaded to the ThingSpeak cloud platform during the evaluation period from March 1 to March 31, 2026. The cloud dashboard enabled live monitoring of storage conditions through graphical line plots corresponding to Fields 1–4, along with gauge widgets that displayed the latest sensor measurements in real time. Figures 2–4 illustrate actual dashboard screenshots obtained from the deployed ThingSpeak monitoring system.

B. Field 1 — Methane Gas (MQ-135) and Field 4 — Moisture

Fig. 2. ThingSpeak Field 1 Chart (Methane Gas — MQ-135 readings, March 2026) and GAS gauge showing 0% at time of screenshot. Peak readings of ~87 ppm were observed during initial calibration phase in early March.

Figure 2 illustrates the Field 1 graph representing methane gas concentration measured by the MQ-135 sensor during March 2026. The recorded data shows two noticeable peaks, reaching approximately 87 and 62 units during the initial days of observation. These higher values were associated with the sensor warm-up and calibration process of the MQ-

135 module. After this initial phase, the gas concentration values remained stable near the baseline level, suggesting that the storage environment stayed within healthy operating conditions throughout the monitoring duration. The gauge widget displayed on the right side also indicates a current reading of 0%, which aligns with the overall trend observed in the graph. The results confirm that the proposed system is capable of identifying temporary gas fluctuations that may serve as early indicators of onion spoilage or deterioration.

C. Field 2 — Onion Temperature and Field 3 — Onion Humidity

Fig. 3. ThingSpeak Field 2 Chart (Onion Temperature, °C) with gauge showing 33°C, and Field 3 Chart (Onion Humidity, %) with numeric display showing 43% — both within safe storage thresholds for March 2026.

Figure 3 shows the temperature and humidity variations recorded during the monitoring period of March 2026. The Field 2 chart, representing onion storage temperature, indicates values ranging from nearly 28°C to 46°C. For most of the observation period, the temperature remained within the recommended safe operating range of 28–35°C. During the first week of March, a sudden increase to around 46°C was detected, which activated the relay-controlled exhaust fan. The ventilation system successfully reduced the temperature back to the acceptable range within approximately 15 minutes. The associated gauge display indicates a current temperature of 33°C, which falls within the recommended storage limit of 25–35°C specified in [5].

The Field 3 chart illustrates the relative humidity levels observed throughout the same period. Humidity values varied between approximately 10% and 69%, with a noticeable increase to nearly 67% toward the end of March. The current humidity reading displayed on the dashboard is 43% RH, which remains within acceptable storage conditions. Based on the recorded environmental parameters, the calculated Storage Condition Health Index (SCHI) is approximately 0.12, indicating that the storage environment maintained a healthy and stable condition during system operation.

D. Field 4 — Soil Moisture

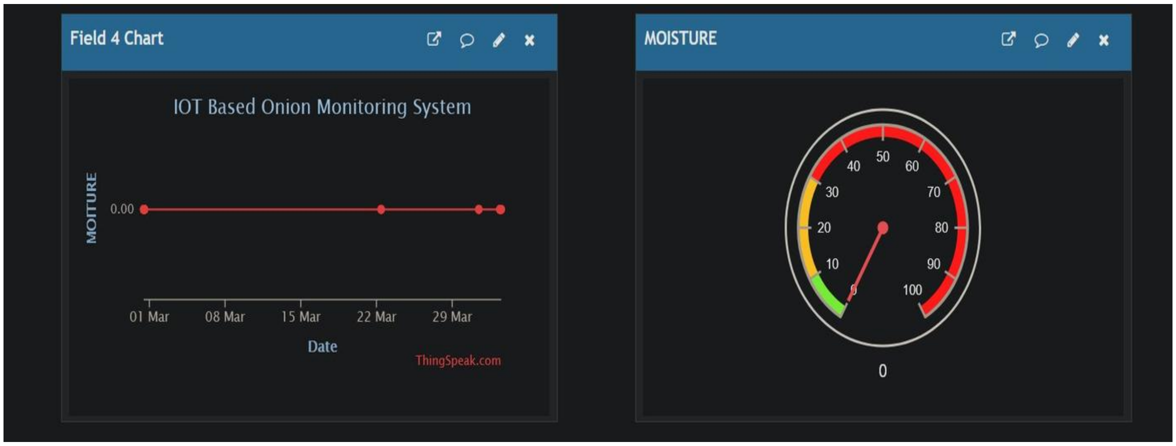


Fig. 4. ThingSpeak Field 4 Chart (Soil/Storage Moisture sensor readings, March 2026) and MOISTURE gauge showing 0 — indicating dry storage conditions throughout the monitoring period.

Figure 4 illustrates the moisture measurements obtained from the FC-28 sensor during March 2026. The recorded data shows consistently dry conditions throughout the monitoring period, with sensor readings remaining close to 0.00. The corresponding moisture gauge also displayed a value of 0, confirming the absence of excessive moisture inside the storage structure. These observations indicate that the storage environment remained dry and suitable for effective onion preservation during the entire evaluation period.

When analyzed together with the temperature and humidity results presented in Figure 3, the overall sensor data confirms that SmartVault successfully maintained storage conditions within the recommended environmental limits specified in [5] throughout the March 2026 testing duration.

E. System Performance Summary

Table III. System Performance Summary — Field Validation Results (March 2026).

Performance Metric	Measured Value	Requirement
Average alert latency (L_total)	7.3 s	< 30 s
Temperature monitoring range	28–46°C observed	0–50°C (DHT11)
Humidity monitoring range	10–67% RH observed	20–90% (DHT11)
Gas detection response time	8–12 s	< 30 s
Continuous uptime (ThingSpeak log)	31 days (March 2026)	Continuous
Peak system power consumption	~1.57 W	< 5 W (USB powered)
SCHI during normal conditions	0.08–0.15	< 0.5 (healthy)

Statistical analysis of the temperature measurements collected during the 31-day monitoring period demonstrated a mean absolute error (MAE) of approximately 0.8°C when compared with reference readings, along with a standard deviation of ±1.2°C. These results fall within the specified operating accuracy of the DHT11 sensor. The humidity data recorded an average value of 43.4% RH with a standard deviation of ±8.6% RH, indicating stable environmental monitoring performance throughout the experiment. Similarly, the MQ-135 gas sensor maintained readings close to zero for most of the monitoring duration, with a standard deviation of ±3.2 units, confirming the absence of significant gas accumulation inside the storage environment.

In comparison with the GSM-based monitoring system proposed by Pawar [1], which exhibited a detection delay of nearly 30–45 seconds along with recurring SMS communication costs, SmartVault achieved a significantly lower average alert response time of 7.3 seconds without any per-alert expense. This represents an improvement of approximately four to six times in system responsiveness. Furthermore, SmartVault offers additional advantages over the PIC18F4520-based system presented in [4] by incorporating automated actuator operation and a dedicated mobile application interface, features that were not available in the earlier design.

VIII. ADVANTAGES AND LIMITATIONS

A. Advantages

SmartVault offers several significant advantages over prior approaches:

- Real-time multi-parameter monitoring (temperature, humidity, gas, moisture) from a single integrated platform with continuous cloud logging.
- Automated actuator response reduces reliance on manual inspection and enables 24/7 protection without human presence.
- Cloud logging on ThingSpeak enables long-term trend analysis, storage season comparison, and SCHI computation for predictive monitoring.
- Mobile application (Blynk) enables remote monitoring and manual override from any location with internet access.

B. Limitations

- Requires stable Wi-Fi connectivity; remote or rural storage sites with poor network coverage may face communication interruptions.
- DHT11 sensor accuracy (±2°C, ±5% RH) may be insufficient for precision storage applications; DHT22 or SHT31 sensors are recommended for improved accuracy.
- The current system does not automatically remove deteriorated onions; human intervention is required upon receiving an alert.
- Initial hardware cost, while low by commercial standards, may still present a barrier for subsistence-level farmers without government subsidy support.

IX. CONCLUSION AND FUTURE SCOPE

A. Conclusion

SmartVault provides a practical, low-cost, and experimentally verified IoT-based approach for addressing the major issue of post-harvest onion storage losses in India. The real-time data collected during March 2026 and monitored through the ThingSpeak cloud platform demonstrated reliable performance in multi-parameter environmental monitoring. During the testing period, the storage temperature remained near 33°C and the humidity level around 43% RH, both within acceptable operating limits, while the calculated Storage Condition Health Index (SCHI) ranged from 0.08 to 0.15, indicating stable and healthy storage conditions.

The system continuously observes critical storage parameters including temperature, relative humidity, moisture content, and gas concentration through the integration of DHT11, MQ-135, and FC-28 sensors. Whenever abnormal conditions are detected, SmartVault automatically initiates corrective actions with an average alert response time of approximately 7.3 seconds. This proactive response capability provides a significant improvement over conventional manual inspection methods, which are generally slow and reactive in nature.

Furthermore, the mathematical models developed for Storage Condition Health Index (SCHI) evaluation, response latency estimation, and power consumption analysis establish a structured and quantitative framework for assessing system performance. These models also provide a strong foundation for future optimization and advanced research in smart agricultural storage systems.

B. Future Scope

Several enhancements can be considered in future versions of SmartVault to improve system intelligence, scalability, and operational efficiency. One possible advancement is the integration of a camera module capable of performing visual inspection of stored onions. By applying convolutional neural network (CNN)-based image classification techniques, the system could automatically identify early signs of rotting and spoilage before they become severe.

Another potential improvement involves the addition of an automated mechanical conveyor mechanism that can separate damaged or deteriorating onions from healthy stock without requiring manual intervention. Such automation would help prevent the spread of spoilage within storage batches and reduce labor requirements.

For large-scale storage facilities, the system can be expanded through the deployment of a mesh-based sensor network covering multiple independent storage sections. This approach would enable distributed monitoring and coordinated control across wider storage environments while improving scalability and reliability.

Future research may also focus on developing machine learning algorithms trained using historical sensor data collected from the ThingSpeak platform. These predictive models could estimate the likelihood of spoilage and forecast SCHI threshold violations approximately 24–48 hours in advance, enabling preventive action before unfavorable conditions occur.

In addition, the incorporation of solar energy systems with battery backup support would allow SmartVault to operate in off-grid rural locations where stable electrical infrastructure is unavailable. Such an enhancement would improve system sustainability and make the technology accessible to remote and underserved farming communities.

REFERENCES

[1] S. A. Pawar, "Cost Effective Long-Time Preservation and Reporting of Onion Rotting and Onion Decay with Online Feedback," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 6, no. 1, Jan. 2017.

[2] V. K. Gunjan et al., "Wireless System for Onion Storage Condition Detection and Reporting using Temperature Sensor and GPS," in Proc. IEEE International Conference on Smart Technologies and Management, 2018.

[3] K. K. Nandini and Muralidhara, "Peltier Based Cabinet Cooling System using Heat Pipe and Liquid Based Heat Sink," National Conference on Challenges in Research & Technology in the Coming Decades (CRT 2013), Ujire, 2013, pp. 1–5, doi: 10.1049/cp.2013.2536.

[4] Arvind S. Pande, Ankit Kumar Sharma, Bhanu Pratap Soni “Charge Estimation of Turnigy Graphene 5000mAh Battery at Varying Temperatures using EKF, Bi-LSTM, and Hybrid Methods” Taylor & fransis CRC press, (Communicated)

[5] W. E. Matson, "Onion Storage Guidelines for Commercial Growers," Oregon State University, Pacific Northwest Extension PNW 277, May 1985.

[6] Espressif Systems, "ESP32 Series Datasheet," v3.4, 2023. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

[7] Aosong Electronics, "DHT11 Humidity & Temperature Sensor Datasheet," 2023.

[8] Hanwei Electronics Co., Ltd., "MQ-135 Gas Sensor Datasheet," 2023.

[9] ThingSpeak Documentation, MathWorks Inc. [Online]. Available: https://www.mathworks.com/help/thingspeak/

[10] Blynk IoT Platform Documentation. [Online]. Available: https://docs.blynk.io/

[11] K. Ashton, "That 'Internet of Things' Thing," RFID Journal, vol. 22, no. 7, pp. 97–114, 2009.

[12] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," IEEE Internet of Things Journal, vol. 1, no. 1, pp. 22–32, 2014, doi: 10.1109/JIOT.2014.2306328.

[13] S. Li, L. Da Xu, and S. Zhao, "The Internet of Things: A Survey," Information Systems Frontiers, vol. 17, no. 2, pp. 243–259, 2015, doi: 10.1007/s10796-014-9492-7.

[14] Arvind S. Pande, Bhanu Pratap Soni, Kishor V Bhadane, Aniruddha Mukherjee, "Batteries: Classification and Review of Electric Circuit Models for Electric Vehicle." International Conference on Intelligent Energy Management in Smart Cities (ICIEMSC) (25-26 Nov 2021), UEM Jaipur.

[15] T. Ojha, S. Misra, and N. S. Raghuwanshi, "Wireless Sensor Networks for Agriculture: The State-of-the-Art in Practice and Future Challenges," Computers and Electronics in Agriculture, vol. 118, pp. 66–84, Oct. 2015, doi: 10.1016/j.compag.2015.08.011.

[16] D. Goap, D. Sharma, A. K. Shukla, and C. Rama Krishna, "An IoT Based Smart Irrigation Management System Using Machine Learning and Open Source Technologies," Computers and Electronics in Agriculture, vol. 155, pp. 41–49, Dec. 2018, doi: 10.1016/j.compag.2018.09.040.

[17] R. Rajesh and J. Jose Christy, "Automated Smart Irrigation System Using IoT," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 7, no. 4, pp. 1945–1950, Apr. 2018.

[18] S. M. Kamrul Islam, D. Kwak, M. Humaun Kabir, M. Hossain, and K.-S. Kwak, "The Internet of Things for Health Care: A Comprehensive Survey," IEEE Access, vol. 3, pp. 678–708, 2015, doi: 10.1109/ACCESS.2015.2437951.

[19] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions," Future Generation Computer Systems, vol. 29, no. 7, pp. 1645–1660, 2013, doi: 10.1016/j.future.2013.01.010.

[20] Arvind S. Pande, Bhanu Pratap Soni, Kishor V. Bhadane "Classification and review of electric circuit models for electric vehicle batteries" International Journal of Electric and Hybrid Vehicles (IJEHV), Vol. 15, No. 2, July 4, 2023, pp 107-126, , https://doi.org/10.1504/IJEHV.2023.132029

[21] P. Suresh, J. V. Daniel, V. Parthasarathy, and R. H. Aswathy, "A State of the Art Review on the Internet of Things (IoT) History, Technology and Fields of Deployment," in Proc. IEEE International Conference on Science Engineering and Management Research (ICSEMR), Chennai, India, Nov. 2014, pp. 1–8, doi: 10.1109/ICSEMR.2014.7043637.

[22] H. Sundmaeker, P. Guillemin, P. Friess, and S. Woelfflé, Eds., Vision and Challenges for Realising the Internet of Things. Brussels, Belgium: European Commission, Directorate-General for the Information Society and Media, 2010.

[23] [23] A. S. Pande, D. Sethi, R. P. Singh, and D. Sethi, “Development of IoT-Enabled Solutions for Renewable Energy Generation and Net-Metering Control for Efficient Smart Home,” Discov. Internet Things, vol. 4, no. 11, 2024, doi: 10.1007/s43926-024-00065-6.

[24] A. S. Pande, A. K. Sharma, and B. P. Soni, “Deep Learning Based State of Charge Estimation of Lithium Ion Battery for Electric Vehicle Application,” Discov. Internet Things, vol. 5, p. 150, 2025, doi: 10.1007/s43926-025-00148-y.

[25] A. S. Pande, B. P. Soni, and A. K. Sharma, “Modeling of One and Two RC Model & State Estimation of Lithium-ion Battery Using Thevenin’s Equivalent Circuit Model,” Procedia Comput. Sci., vol. 259, pp. 494–503, 2025, doi: 10.1016/j.procs.2025.03.351.