Development of an IoT-Based Monitoring System Utilizing Macro- and Micro-Environmental Parameters in Onion Cold Storage

Prince Rhomel V. Pillagara[1], Leo M. Ramos[2], Noel T. Florencondia[3]
[1,2] *College of Engineering and Computer Technology Wesleyan University-Philippines Cabanatuan City, Nueva Ecija.*
[3] *Faculty of Graduate Studies Department, Nueva Ecija University of Science and Technology,Nueva Ecija, Philippines.*

***Abstract*—Onion (*Allium cepa* L.) is a high-value crop in Nueva Ecija, Philippines, yet farmers continue to incur substantial postharvest losses due to inadequate storage monitoring. Conventional cold storage facilities typically measure only macro-environmental conditions, overlooking micro-environmental variations within onion stacks that can accelerate deterioration. This study developed and field-tested an Internet of Things (IoT)-based monitoring system for onion cold storage that simultaneously measures macro- and micro-environmental temperature and relative humidity.**

A quantitative, descriptive–developmental design was employed, using the Rapid Prototyping model of the Systems Development Life Cycle (SDLC). The prototype comprised an ESP32 microcontroller, three DHT22 temperature–humidity sensors, a 5 V power supply, and an enclosure, with data acquisition, transmission, and visualization implemented via the Arduino IoT Cloud platform. Field testing was conducted in an operational cold storage facility in Nueva Ecija over three days, with measurements taken every 30 minutes. System readings were paired with industrial-grade reference instrument readings, and data were analyzed using SPSS, employing independent-samples t-tests at a 0.05 level of significance. Results showed that the system provided stable real-time monitoring for both chamber-level and in-stack conditions. Statistical analysis indicated no significant difference between system and manual measurements for temperature and relative humidity, demonstrating the reliability of the prototype. Additionally, onions stored at temperatures below 0 °C exhibited visible freezing injury, consistent with postharvest literature. The findings suggest that the developed IoT-based system can support more precise environmental control, reduce postharvest losses, and potentially improve the profitability and resilience of onion farmers in Nueva Ecija.

***Index Terms*—Internet of Things, onion cold storage, macro-environment, micro-environment, temperature, relative humidity, postharvest losses**

I. INTRODUCTION

Onion (*Allium cepa* L.) is one of the most economically important vegetable crops in the Philippines, with Nueva Ecija—particularly Cabanatuan City and surrounding municipalities—recognized as a major production area. Despite its economic value, onion farmers and traders face considerable postharvest losses due to weight reduction, sprouting, and decay during storage. The Food and Agriculture Organization (FAO, 2019) reports that postharvest losses in onions in developing countries can reach up to 40%, largely due to improper handling and inadequate storage systems. In Nueva Ecija, supply surpluses combined with limited and sometimes suboptimal cold storage facilities directly affect farmer income and market stability.

Cold storage is widely used to extend onion shelf life; however, many existing systems monitor only macro-environmental parameters, such as overall chamber temperature and relative humidity. Studies on onion storage have shown that environmental conditions strongly influence shrinkage, sprouting, and microbial decay (Pathak et al., 2018; Ramos et al., 2021). More recent work has emphasized that macro-level readings do not fully capture micro-environmental variations within crates, sacks, or piles, where restricted airflow and localized moisture accumulation can accelerate deterioration (Sharma et al., 2020). This highlights the need for monitoring systems capable of capturing both macro- and micro-environmental parameters for more reliable postharvest management.

Parallel to these challenges, the Internet of Things (IoT) has emerged as a key enabling technology for smart agriculture and postharvest systems. IoT-based solutions integrate sensors, microcontrollers, wireless communication, and cloud platforms to collect, transmit, visualize, and analyze real-time data for decision-making (Verdouw et al., 2016; Raut et al., 2019; Elansari & Alhindi, 2020). Such systems have been successfully applied to potatoes, fruits, and other perishable commodities but have seen limited implementation for onions in the Philippine context.

This study addresses that gap by developing and field-testing an IoT-based monitoring system for onion cold storage in Nueva Ecija that utilizes both macro- and micro-environmental measurements. Specifically, the study aimed to:

1. Design and develop a prototype IoT-based monitoring system using an ESP32 microcontroller, multiple DHT22 sensors, and the Arduino IoT Cloud platform.
2. Describe the system in terms of its hardware components, software components, and functional features.
3. Compare system sensor readings with cold storage facility instrument readings for temperature and relative humidity.
4. Identify the practical implications of the developed system for onion storage and farmer profitability.

The study was guided by the null hypothesis that there is no significant difference between the developed system sensor readings and the cold storage facility's manual instrument readings for temperature and relative humidity.

II. MATERIALS AND METHODS

2.1 Research Design and Setting

A quantitative, descriptive–developmental design was used to guide the design, construction, and evaluation of the monitoring system. The Systems Development Life Cycle (SDLC) Rapid Prototyping model served as the main development framework. The prototype was deployed and tested in Kasamne Cold Storage in Palayan City, Nueva Ecija, an operational facility used for commercial onion storage.

2.2 System Development

2.2.1 Hardware Components

The prototype hardware consisted of:

- Main controller: ESP32 Dev Module, which served as the primary processing and communication unit. It integrates Wi-Fi (802.11 b/g/n) and provides multiple General-Purpose Input/Output (GPIO) pins for sensor interfacing and cloud connectivity.
- Sensors: Three DHT22 temperature and relative humidity sensors. One sensor was positioned to capture macro-environmental conditions (chamber-level), while the remaining two were placed within onion stacks to capture micro-environmental conditions. Each DHT22 measures temperature from −40 °C to 80 °C (±2 °C accuracy) and relative humidity from 0–100% RH (±5% accuracy).
- Power supply: A 5 V DC supply powered the ESP32 and sensors, with provision for battery storage to support continuous monitoring.
- Enclosure: A protective system enclosure housed the circuitry and provided basic environmental protection while allowing proper airflow and sensor exposure.

Circuit simulation as shown in Figure 1 using appropriate design tools was first performed to validate the interconnections between the ESP32 and the DHT22 sensors. The ESP32 was powered through the 5 V and ground terminals of the expansion board. The + terminals of the DHT22 sensors were connected to the 3.3 V output, while their − terminals were connected to ground. Data lines from the three sensors were connected to GPIO 21, GPIO 19, and GPIO 18, respectively. The validated circuit served as the basis for assembling the physical prototype.

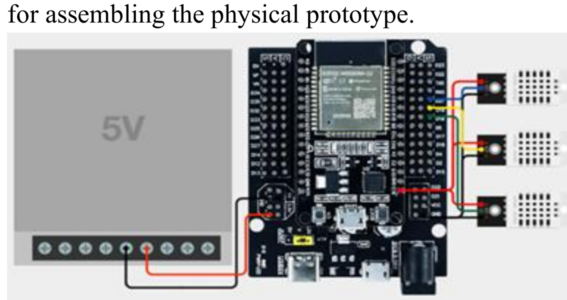

Figure 1: Circuit Simulation

2.2.2 Software Components

The system software was developed using the Arduino IoT Cloud platform. The firmware running on the

ESP32 was written in Arduino-compatible C/C++, using libraries for Wi-Fi connectivity, DHT22 sensor interfacing, and Arduino Cloud communication.

The system flow, implemented as shown in Figure 2, followed these steps:

1. System initialization: ESP32 startup, library loading, and sensor configuration.
2. Network setup: automatic connection to the configured Wi-Fi network, with repeated attempts until a stable connection was established.
3. Data acquisition: periodic sampling of temperature and relative humidity from each DHT22 sensor.
4. Data upload: transmission of measured values to the Arduino IoT Cloud variables.
5. Threshold evaluation: comparison of readings with predefined safety limits for onion storage.
6. Notification: generation of events to trigger push notifications through the Arduino IoT interface when thresholds were exceeded.
7. Looping: return to the initial state to perform continuous monitoring.

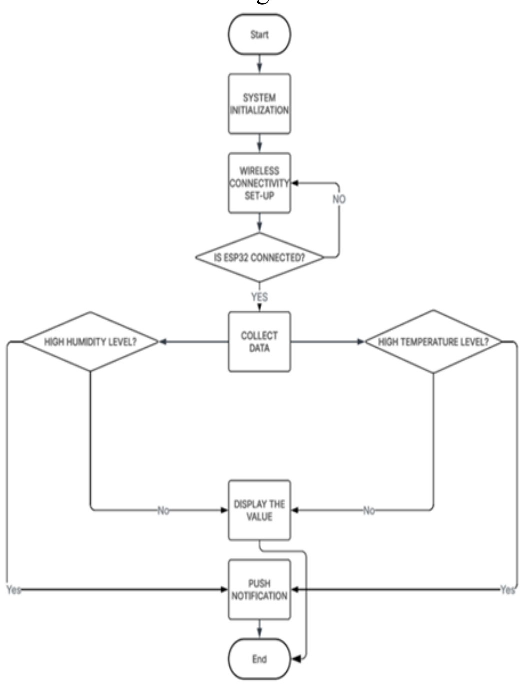

Figure 2: System Flowchart

A cloud dashboard was created using the Arduino IoT interface to display real-time temperature and relative humidity for each sensor, enabling remote monitoring via web browser or mobile application.

2.3 Data Collection Procedures

Data collection was conducted through systematic field testing of the prototype under actual operating conditions in the cold storage facility. The prototype was installed within the onion storage area alongside the facility's existing reference instruments.

Data gathering spanned three consecutive days. On each day, 30 measurement trials were performed at 30-minute intervals between 7:00 a.m. and 10:00 p.m. For each interval, temperature and relative humidity readings from the IoT-based system were recorded with corresponding readings from industrial-grade meters used by the facility.

In addition to environmental measurements, onion bulbs within the storage facility were periodically inspected for visible signs of damage, particularly when temperatures approached or fell below 0 °C. Observations focused on the presence of softening, water-soaked tissues, and other indicators of freezing injury.

2.4 Data Analysis

Recorded data were organized, averaged where appropriate, and processed using SPSS statistical software. Independent-samples t-tests were employed to compare the mean temperature and relative humidity values obtained from the system sensors and the facility's manual instruments at a 0.05 level of significance. This analysis provided an objective assessment of whether the prototype's measurements were statistically comparable to those of standard reference devices.

III. RESULTS AND DISCUSSION

3.1 Prototype Implementation and Dashboard

The developed prototype was successfully assembled and deployed in the onion cold storage facility. The hardware configuration, comprising the ESP32 controller, three DHT22 sensors, power supply, and enclosure, enabled stable operation under cold storage conditions. Field-testing documentation showed that the device could be securely positioned among onion sacks while maintaining proper sensor exposure as shown in Figure 3.

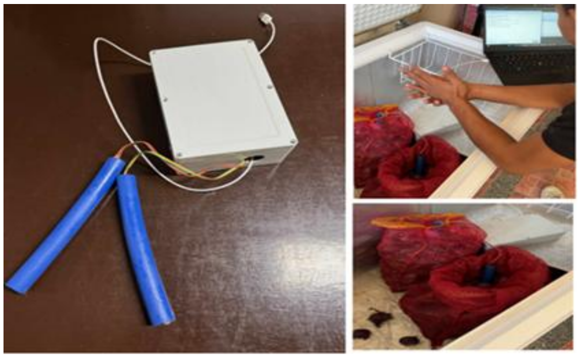

Figure 3: Prototype and Field Testing

The Arduino IoT Cloud dashboard as shown in Figure 4 provided real-time visualization of temperature and relative humidity from each sensor. Continuous updates allowed users to monitor environmental conditions at a glance and to distinguish between macro-level chamber conditions and micro-level conditions within onion piles. Deviations from desired set points could be quickly identified.

Figure 4: System Dashboard display

3.2 Temperature Measurements

Figure 5 presents the three-day trial period, system-generated temperature readings ranged from approximately −21.0 °C to −12.1 °C, with a mean of −17.56 °C. In comparison, manual measurements recorded by the facility's instruments ranged from −9.8 °C to −1.2 °C, with a mean of −5.45 °C. While the absolute values differed, both measurement sets captured similar temporal trends and patterns in cooling behavior.

The discrepancy in absolute values may be attributed to several factors, including differences in sensor placement, sensor calibration, and response time. System sensors located closer to specific onion stacks may have been more exposed to localized cold spots, particularly in areas with higher airflow. Despite these differences, statistical analysis using an independent-samples t-test indicated that the system's temperature readings were not significantly different from those of the manual instruments at the chosen level of significance. This suggests that the prototype's temperature sensing capability is sufficiently comparable for monitoring purposes in the cold storage context.

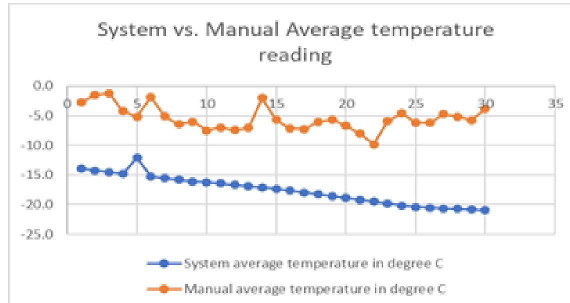

Figure 5: Average Temperature Readings

3.3 Relative Humidity Measurements

Figure 6 shows the relative humidity, system readings ranged from 48.5% to 56.6%, with a mean of 52.91%. Manual measurements exhibited a wider range, from 43.2% to 80.8%, and a higher mean of 59.13%. The narrower range observed in the system readings may reflect the placement of sensors in relatively stable micro-environments or differences in the sensitivity and calibration of the instruments used.

As with temperature, independent-samples t-test results indicated no statistically significant difference between the system and manual humidity measurements. This finding implies that the prototype's humidity sensor configuration is capable of providing reliable and consistent readings, comparable to those obtained using conventional reference devices.

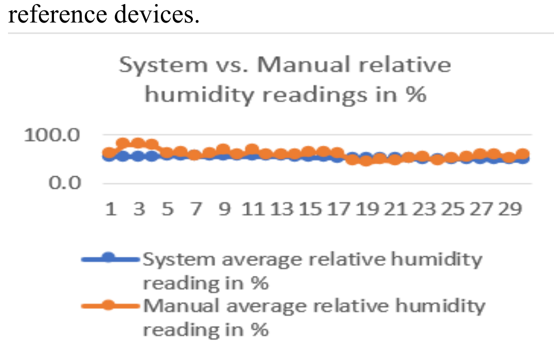

Figure 6: Average Relative Humidity Readings

3.4 Onion Response to Sub-zero Temperatures

During the field trial, onions stored at temperatures below 0 °C developed visible signs of damage. Bulbs exposed to sub-zero conditions exhibited soft, water-soaked tissues and progressive deterioration. These observations are consistent with postharvest literature, which notes that onion bulbs experience freezing injury when stored below their freezing point (approximately −1 to −2 °C), leading to translucent, water-soaked scales and increased decay during storage (Brewster, 2008; UC Davis Postharvest Technology Center, n.d.; Saskatchewan Ministry of Agriculture, n.d.).

The integration of continuous temperature data with visual quality assessments underscores the importance of precise control and monitoring of storage conditions. The IoT-based system can support such control by providing timely alerts when temperatures approach or fall below critical thresholds, thereby allowing operators to prevent or mitigate freezing injury.

IV. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study successfully designed, developed, and field-tested an IoT-based monitoring system for onion cold storage that integrates macro- and micro-environmental sensing using an ESP32 microcontroller, multiple DHT22 sensors, and the Arduino IoT Cloud platform. Guided by the Rapid Prototyping model of the SDLC, the system was implemented as a functional prototype capable of real-time monitoring, remote visualization, and automated notifications.

Experimental results showed that the system's temperature and relative humidity readings were statistically comparable to those of industrial-grade reference instruments, indicating that the prototype can serve as a reliable monitoring tool in commercial storage environments. Additionally, the observed freezing damage in onions stored below 0 °C corroborated postharvest literature, emphasizing the need to avoid sub-zero storage conditions. Overall, the system demonstrates the potential of IoT technologies to enhance postharvest management and economic resilience among onion farmers in Nueva Ecija.

4.2 Recommendations

Based on the findings, the following recommendations are proposed:

1. Calibration and Maintenance: System sensors for temperature and relative humidity should be regularly calibrated and periodically verified against reliable reference instruments to maintain measurement accuracy and long-term reliability.
2. Storage Temperature Management: Onion cold storage should be maintained at approximately 0–2 °C, avoiding temperatures below the freezing point of the bulbs. Postharvest guidelines indicate that dry onions are commonly stored at 0–2 °C for long-term storage to minimize sprouting and decay while preventing freezing injury, which typically occurs near −1 to −2 °C (Brewster, 2008; UC Davis Postharvest Technology Center, n.d.; FAO recommendations).
3. System Expansion and Predictive Analytics: Future work may incorporate additional sensors (e.g., for airflow, gas concentration, or CO_2) and apply predictive modeling techniques to forecast weight loss and quality deterioration. Integration with data analytics platforms could further enhance decision support for storage operators.
4. User Evaluation and Scaling: Subsequent studies may include user evaluation of the system's interface and functionalities, as well as pilot deployments in multiple cold storage facilities to assess scalability, robustness, and economic impact across different operational contexts.

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