Design and Development of an IoT-based Smart Monitoring Bin for Pineapples (Ananas comosus) Quality and Shelf Life

Christian T. Mapayo
Department of Agricultural and Biosystems Engineering, Caraga State University

Endrea Jane O. Piculados
Department of Agricultural and Biosystems Engineering, Caraga State University

Juven G. Luzorata
Department of Agricultural and Biosystems Engineering, Caraga State University

https://doi.org/10.5109/7395679

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 11, pp.1302-1309, 2025-10-30. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

Design and Development of an IoT-based Smart Monitoring Bin for Pineapples (*Ananas comosus*) Quality and Shelf Life

Christian T. Mapayo[1,3], Endrea Jane O. Piculados[1,3], Juven G. Luzorata[1,2,3]
[1]Department of Agricultural and Biosystems Engineering, [2]Center for Resource Assessment, Analytics, and Emerging Technologies (CReATe), [3]Caraga State University
Corresponding author email: jgluzorata@carsu.edu.ph

Abstract: *This study aimed to design and develop an IoT-based smart monitoring bin to extend the shelf life and maintain the postharvest quality of pineapples. The system featured temperature, humidity, oxygen, and carbon dioxide sensors, with a thermoelectric cooling setup maintained at 14°C. Its performance was evaluated based on cooling time, efficiency, and energy consumption. Pineapples were stored under smart bin and ambient conditions was assessed on days 7, 11, and 15 for visual quality, internal browning, firmness, total soluble solids, pH, and weight loss. Results showed that the smart bin has potential to preserved quality for up to 11 days, with slower CO_2 buildup and 6.92 kWh/day energy use. The system shows promising for small-scale postharvest use. Future improvements may include integrating renewable energy and automated gas exhaust systems to enhance sustainability.*

Keywords: IoT-based, Smart Monitoring, pineapple, post-harvest, shelf life

1. INTRODUCTION

Pineapple (*Ananas comosus*) is a globally significant tropical fruit, valued for its sweet flavor and rich nutritional profile, including essential vitamins and antioxidants [1], [2]. Major producers like Costa Rica, the Philippines, and Thailand contribute significantly to the global supply, with the Philippines yielding about 2.7 million metric tons annually [3], [4]. In the Philippines, regions such as Bukidnon and South Cotabato serve as key production centers [5]. Despite its economic impact, pineapple production faces substantial post-harvest losses up to 30%, mainly due to inadequate storage and handling methods [6].

With growing demand for improved food preservation, modern solutions like coatings, modified atmosphere packaging (MAP), and cold storage are being explored. However, limitations remain, such as reduced visual appeal and changes in texture or color [7], [8], [9]. In response, this study aims to design and develop an IoT-based smart monitoring bin tailored for pineapples, enabling real-time tracking of storage parameters like temperature, humidity, and gas composition (oxygen and carbon dioxide). This innovation seeks to address gaps in existing post-harvest methods, especially those not adapted to local Philippine conditions or pineapple-specific needs [10]. While IoT systems exist for crops like mangoes and tomatoes [11], [12], few are dedicated to pineapples. By integrating context-specific features, this study contributes a solution for extending shelf life and maintaining fruit quality.

2. MATERIALS AND METHODS

2.1 Sample Preparation

For the sample preparation, twenty (20) uniform pineapples of the same size, weight, and variety were selected to ensure consistency in the experiment. These pineapples were divided into four groups (T0 to T3), with each group containing five (5) pineapples per chamber in smart bin and to the ambient. The storage and monitoring phase involved two experimental groups, the Smart Bin Group (T1–T3) and the Conventional Storage Group (T0). Pineapples in the Smart Bin Group were stored inside the IoT-based smart bin, where temperature, humidity, and gas levels (oxygen and carbon dioxide) were monitored in real time using IoT sensors. Meanwhile, the Conventional Storage Group was kept under ambient room conditions with no external control over environmental factors. Regarding smart bin storage duration, pineapples were removed in stages to evaluate the effect of storage time on quality and shelf life. Chamber one (1) was removed after 7 days, chamber two (2) after 11 days, and chamber three (3) after 15 days.

2.2 Design considerations for the development of the Smart Monitoring Bin

The subsequent factors were considered during the creation of the Smart Monitoring Bin:

1. Capable of storing pineapple (*Ananas comosus*);
2. Cylindrical shape for better airflow;
3. Compact and attractive device size;
4. Uniform cooling effect throughout the chamber;
5. Operable by a single-phase (220 V) power source; and
6. Ability to store products for a few days and weeks.

2.3 Calculations for Smart Bin

2.3.1 Calculation of cooling capacity

The capacity of the cooling chamber was calculated using Eq. (1):

$$V = \pi \times r2 \times H$$

where, π = 3.14, r = radius (m), and H = height (m).

The following formula expresses the total product holding capacity of the device:

$$Total\ product\ holding\ capacity = \rho \times V$$

where, V = chamber volume (m^3), ρ = product bulk density (kg/m^3).

2.3.2 Heat transmitted by the Smart Bin

Equation (3) was used according to Arora [13] for the calculation of transmitted heat:

$$q_t = (A)(U)(T_{out} - T_{in})$$

where q_t represents the rate at which heat is transmitted (W), A is the total surface area for heat transfer (m^2), U denotes the overall heat transfer coefficient (W/m^2-K),

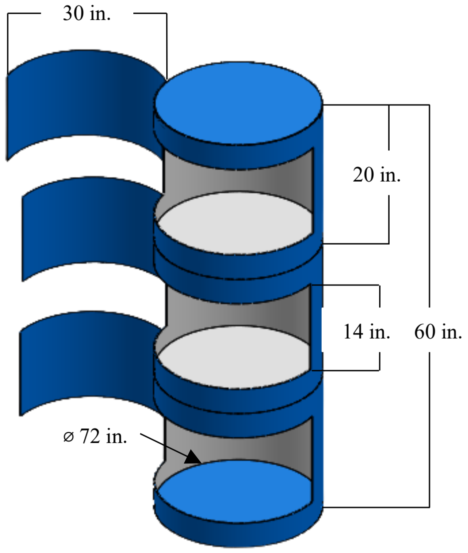

Fig. 1. Design of the IoT-based Smart Bin.

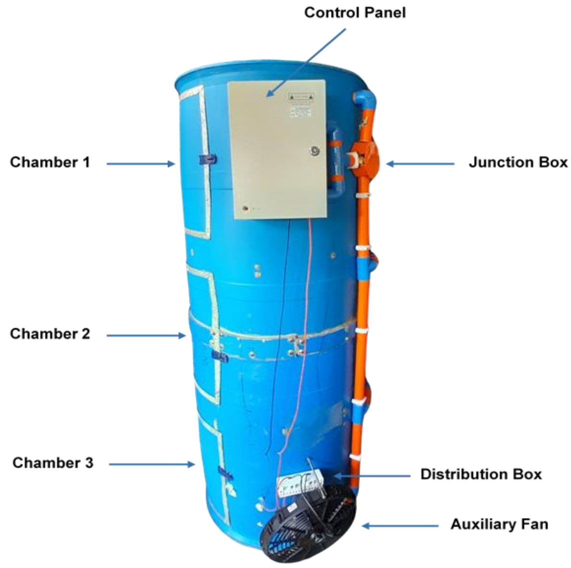

Fig. 2. IoT-based Smart Monitoring Bin.

and T_{out} and T_{in} are the temperatures outside and inside the storage chamber, respectively.

2.3.3 Product load

The amount of heat needed to keep the product above its freezing point was
calculated according to Arora [13] using the following Eq. (4).

$$q_{pa} = (m)(c)(\Delta T)$$

where qpa is the amount of heat above the freezing point (kJ), m is the mass of the product (kg), c is the specific heat capacity at the given state (kJ/kg-K), and ΔT is the temperature change of the product (k). Similarly, the heat released by the product when it cools from its normal temperature to the final device temperature is determined by using Eq. (5).

$$q_{pb} = (m)(c)(\Delta T)$$

where q_{pb} is the heat quantity released (kJ).

2.3.4 Total cooling load

The overall cooling load is the sum of all individual loads, Eq. (6):

$$q_{TCL} = q_t + q_{pa} + q_{pb}$$

where q_{TCL} represents the total cooling load (kJ). The total cooling load (Q_{TCL}) in watts was determined using Eq. (7):

$$Q_{TCL} = \frac{q_{TCL}\ (kJ)}{Time\ taken\ (s)}$$

2.3.5 Factors of safety

A 10% safety factor was incorporated into the design of the smart bin. This factor was incorporated into the overall cooling load as shown in Eq. 8.

$$Safety\ factor = 10\%\ of Q_{TCL}$$

2.4 Development of the Smart Monitoring Bin

The size of the smart monitoring bin and each chamber was planned and finalized based on the number and size of pineapples to be stored. These measurements were made to make sure the space inside each chamber could hold the expected number of pineapples. After this, a detailed engineering drawing (DED) was created to guide the building process (Figure 1). Two plastic drums, each with a volume of 0.3084 cubic meters (m^3), were bought and used as the main body of the bin, the researchers used the plastic drum as the medium of the smart bin because the storage plastic drums do not contaminate the content and can safeguard food products [14]. The top parts of both drums were cut off, and these cut parts were used to help join the drums together. Bolts were used to connect and hold the drums in place tightly. Each chamber was separated using marine wood that was 1-inch-thick and had a round edge (circumference) of 72 inches. These wooden dividers were attached to the inside wall of the bin using wooden screws and rivets. To make the dividers stronger and more stable, L-shaped metal brackets were placed underneath. Small doors were also made for each chamber, each measuring 14 inches long and 30 inches wide. Insulation foam was added inside the bin to help keep the temperature steady and protect the pineapples better. After that, wires were cut to the right length so that the sensors, power supply, and control box could be connected properly. Sensors were placed in each chamber to measure the conditions inside. The cooling parts were then assembled by attaching the Peltier modules to the water blocks and heat sinks using thermal paste. This cooling setup was then placed inside the bin. A coiled copper tube and a straight copper tube were also made and placed inside the chamber to help control the temperature. With all these parts combined shown in Figure 2, the smart bin could keep the conditions for storing pineapples.

2.5 Operating Procedure of the Smart Monitoring Bin

The smart bin system operated through a continuous cycle of data acquisition, transmission, and real-time monitoring, as illustrated in Figure 3. The process began with the initialization of the ESP32 microcontroller. Upon startup, the ESP32 connected to a designated Wi-Fi network and then established a link to the ThingSpeak platform. This connection enabled the wireless transmission of data and remote access. Once connected, the system started collecting data from the sensors placed inside the chamber. These sensors measured important parameters such as temperature, humidity, and gas levels (carbon dioxide and oxygen). The collected data was then transmitted to the ThingSpeak platform, which served as the main hub for data monitoring and visualisation. This setup allowed users to remotely observe the internal environment of the smart bin at any time. The actual wiring and configuration of the electronic components used in the system are shown in Figure 4.

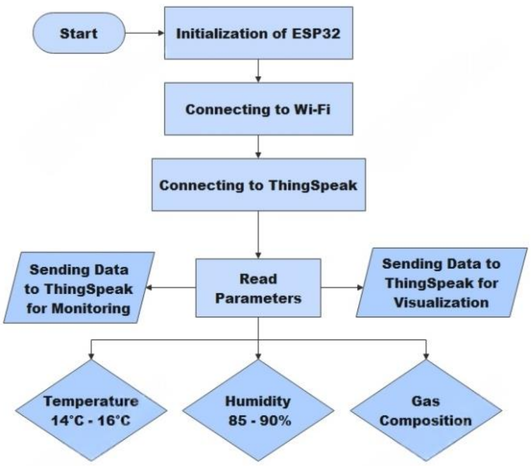

Fig. 3. Algorithm Flowchart of the System.

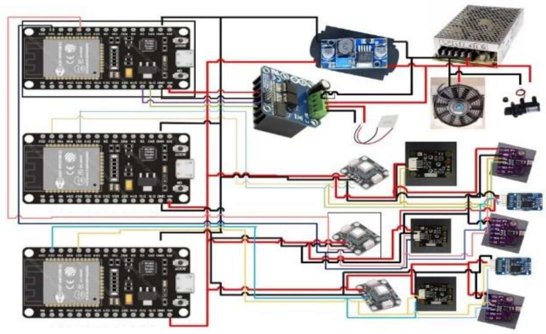

Fig. 4. Circuit Connection Diagram of the Smart Monitoring Bin

2.6 Quality Parameters and Shelf Life

2.6.1 Percent Weight Loss (PWL)

Weight loss is a critical parameter for assessing postharvest quality of fruits like pineapple. Excessive weight loss leads to shriveling, reduced juiciness, and a decrease in overall consumer acceptability. Studies have shown that monitoring weight loss helps in determining optimal storage conditions to extend shelf life. Pineapples in the smart bin were calculated to determine the effect of smart bin storage parameters on the commodity. The calculation for percent weight loss was determined using the approach described by Coelho et al. (2021). Weight loss was measured by determining the weight of each sample before and after storage days. Then, using Equation 9, the percent weight loss is calculated.

$$PWL\ (\%) = \frac{(W_{initial} - W_{final})}{W_{initial}}\ x\ 100$$

2.6.2 Visual Quality Rating (VQR)

The VQR was assessed to gauge the fruit's visual appeal during storage. The visual quality of each fruit was scored using a 9-point hedonic scale developed by Acedo's method, where 9 represents excellent visual condition and 1 indicates severe deterioration [15].

Table 1. A rating standard developed for visual quality rating.

VQR	Description
9	Excellent, field fresh, or no defect
7	Good, defects minor
5	Fair, defects minor, the limit of marketability
3	Poor, defects are serious, the limit of edibility
1	Non-edible under usual conditions

2.6.3 Internal Browning Index (IBI)

The IBI was used as an indicator to assess the pineapple quality in the smart bin when it is stored for longer days under a lower temperature. IBI provides a standardized way to quantify the extent of internal browning, which can be important for quality control, research studies on storage conditions, and comparisons [16].

Table 2. A basic Internal Browning Index table

Browning Level	Description	Index Value
0	No visible browning	0
1	Trace browning, only a few small spots	1-2
2	Mild browning, scattered small areas	3-5
3	Moderate browning, noticeable browning throughout the flesh	6-8
4	Severe browning, large areas of brown discoloration	9-10

2.6.4 Total Soluble Solids (TSS)

TSS, primarily composed of sugars, is a key determinant of pineapple sweetness and overall taste quality. Monitoring TSS levels after storage is important as it indicates the fruit's maturity and sweetness [17]. Changes in TSS can also reflect the conversion of starches to sugars during ripening. Research by Ali highlights the importance of TSS as a quality parameter in pineapple [18]. Pineapple fruits from the smart bin storage conditions were sliced into small pieces. The TSS content was determined using a Digital Brix and Sucrose Refractometer (Biobase Digital Refractometer, China). The measurement was obtained by placing one droplet of juice onto the prism of the instrument. The values were recorded as °Brix throughout the storage period.

2.6.5 pH

The pH level is an important indicator of fruit acidity, which contributes to the overall flavor profile of pineapple. It also plays a role in influencing microbial stability and enzymatic activity during storage. Maintaining optimal pH levels helps preserve fruit quality and prevent spoilage. Pineapple fruits from each treatment were sliced into small pieces. The sliced samples were then squeezed, and the juice was placed in a beaker with a 10 ml volume. The pH level of the sample juice was determined using a pH pen, with the instrument calibrated using distilled water each time a different treatment was analyzed [19].

2.6.6 Firmness

Firmness is a textural attribute that affects the eating quality and consumer acceptance of pineapple. It reflects the structural integrity of the fruit tissue and changes during ripening and storage due to cell wall degradation [20], [21]. Measuring firmness helps in assessing the phase of ripeness and predicting shelf life. The firmness of pineapple samples from both the conventional storage and smart bin treatments was measured using a digital fruit penetrometer, specifically the Lutron Precision Fruit Sclerometer, Model FR-5120. The force required for penetration was systematically measured by placing the probe at two opposing points on the equatorial zone of each fruit. The recorded measurements for each sample were documented and expressed in Newton (N). This method allowed for a precise assessment of pineapple firmness, enabling a comparative evaluation of samples stored under conventional storage and smart bin conditions.

2.6.7 Respiration Rate

Respiration rate is a measure of the metabolic activity of the fruit, indicating the rate at which it consumes oxygen and produces carbon dioxide. It is a critical parameter for determining storage requirements, as higher respiration rates lead to faster deterioration and shorter shelf life [22], [23]. To evaluate the respiration activity of pineapples, researchers assessed the respiration rate of pineapples stored in an IoT-based Smart Bin over different storage durations (7, 11, and 15 days). The oxygen and CO_2 levels inside the storage chamber were monitored using scd41 CO_2 sensor and i2 oxygen sensor. Respiration rates were quantified by measuring the change in CO_2 concentration inside the storage chamber. The calculation was based on the ideal gas conversion and expressed in mg CO_2/kg·h using the following Equation 10:

$$RR = \frac{\Delta CO2 \times 1.96 \times V}{M \times \Delta t} \; x\, 60$$

where $\Delta CO2$ is the increase in CO_2 concentration (ppm), V is the chamber volume in m^3, M is the total fruit mass, and Δt is the time interval.

2.7 Performance Evaluation of the Smart Bin

2.7.1 Cooling Profile

The cooling time of the smart bin device was determined by recording the duration required for the internal temperature of the smart bin to decrease from the dry bulb temperature of the cooling chamber to the target storage temperature of 14°C.

2.7.2 Cooling Efficiency

The cooling efficiency of the smart bin was calculated according to Harris as given in Eq. (11) [24]. This efficiency helped determine the effectiveness of the thermoelectric cooling system in maintaining optimal conditions for pineapple storage.

$$E = \frac{T_1(db) - T_2(db)}{T_1(db) - T_2(wb)}$$

Where $T_1(db)$ is the dry bulb in outdoor (ambient) temperature (°C), $T_2(db)$ is the dry bulb temperature of the cooling chamber (°C), and $T_2(wb)$ is the wet-bulb temperature of the cooling chamber (°C).

2.7.3 Assessment of Energy Consumption

To assess the energy consumption of the smart bin, a calculation procedure was followed. Each electrical component, including the microcontrollers (ESP32), temperature and humidity sensors (BME680), I2C oxygen sensors (DFRobot), CO2 sensors (MQ135), real-time clock modules, and the thermoelectric cooling system (TEC1-12706 Peltier modules) was evaluated based on its voltage and current requirements based on their specifications. The TEC1-12706 Peltier modules, with an average power consumption of 36 W per unit, were the primary contributors to energy usage, operating alongside a 12V DC auxiliary fan (Starking brand) and a 60W micro diaphragm pump. Energy drawn from each component was calculated using the Equation 12,

$$E = \frac{V \times I \times pf \times t}{1000}$$

where V is the supply voltage, I is the current, pf is the power factor (1), and t is the operating time in hours. Cumulative energy consumption was then computed by summing the power used by all active components across the storage duration.

2.8 Statistical Analysis

The quality parameters of pineapple were analyzed using the Statistical Tool for Agricultural Research (STAR) computer software, employing analysis of variance (ANOVA). This allowed for the identification of sources of variation, which included storage days. To distinguish treatment means at $p \leq 0.05$, LSD was applied, and the coefficient of variation was derived from the ratio of standard deviation to mean. The STAR software is provided by the International Rice Research Institute for free, which supported these analyses, and Microsoft Excel was used for the correlation analysis.

3. RESULTS AND DISCUSSION

3.1 Development of an IoT-based smart monitoring bin

The smart monitoring bin obtained temperature of 14°C using four thermoelectric (Peltier) modules paired with water-cooling blocks, heat sinks, and coiled copper tubing. A micro diaphragm pump circulated coolant in a closed-loop system. Despite brief fluctuations during chamber access, the temperature quickly stabilized to 14 ± 0.5 °C. Sensor accuracy was validated against a digital thermal gun (±1–2 °C), confirming reliable and consistent readings. The IoT-based system enabled real-time monitoring of temperature, humidity, and gas levels (O_2 and CO_2). In no-load tests, gas levels remained stable, while load tests with pineapples showed expected respiration patterns decreasing oxygen and increasing carbon dioxide validating sensor responsiveness. All sensors were factory-calibrated before use. Data were collected and visualized via the ThingSpeak dashboard, enabling continuous remote monitoring. Minor disruptions occurred due to brief power outages and temporary ThingSpeak downtime, slightly affecting data logging.

3.2 Quality Parameters

3.2.1 Percent Weight Loss

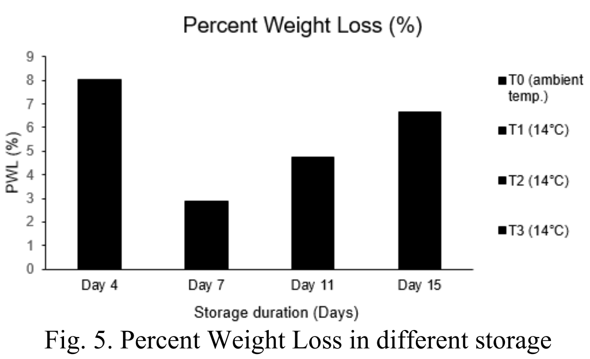

Fig. 5. Percent Weight Loss in different storage durations.

Weight loss increased with temperature and storage duration, reflecting metabolic activity driven by respiration and transpiration. Pineapples at ambient temperature (T0) showed the highest weight loss (8.04%) due to elevated moisture loss [25]. Cold storage at 14°C minimized weight loss, with T1 (7 days) recording the lowest (2.86%), aligning with [26], who noted that low temperatures suppress enzymatic and respiratory activity. As storage duration extended (Figure 5), weight loss rose to 4.76% at T2 (11 days) and 6.68% at T3 (15 days), consistent with [27], who reported that cold storage slows but does not stop deterioration. This confirms that lower temperatures and shorter storage durations are key to reducing postharvest losses in pineapples.

3.2.2 Visual Quality Rating

In (Figure 6) VQR was significantly influenced by storage temperature and duration (P > 0.005). Pineapples stored at 14°C for 7 days (T1) had the highest VQR of 8.20 ("excellent") with minimal defects, supporting [18] who showed that cold storage preserves visual quality by slowing color and texture changes. At 11 days (T2), VQR decreased slightly to 7.80 ("good"), reflecting minor discoloration as noted by [28], who reported that spoilage delays weaken over time due to respiration and microbes. After 15 days (T3), VQR dropped to 5.00 ("fair"), showing visible softening and surface damage, consistent with [29] who found extended cold storage can cause chilling injury and reduce appearance. The ambient control (T0) scored lowest at 3.80 ("poor") due to accelerated enzymatic degradation and moisture loss at higher temperatures, as described by [30]. Visual evidence (Figure 7) confirms T1's vibrant, defect-free appearance versus T0's browning and shriveling.

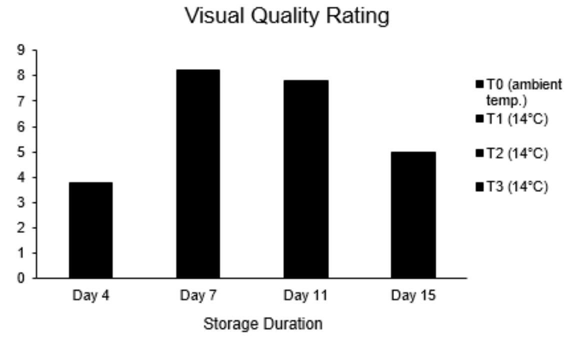

Fig. 6. VQR in different storage durations.

Fig. 7. Visual comparison of pineapple samples under different storage treatments: T0 (ambient), both Day 0 and Day 4; T1 (14°C for 7 days); T2 (14°C for 11 days); T3 (14°C for 15 days), respectively.

3.2.3 Internal Browning Index

Figure 8 shows that the internal browning index (IBI) increased significantly with storage duration at 14°C, from 1.80 at 7 days (T1) to 3.40 at 11 days (T2) and 6.80 at 15 days (T3), indicating worsening internal browning over time. Visual evidence (Figure 9) supports this, with T1 displaying uniform flesh and T3 showing severe discoloration. These results align with [31], who found that prolonged cold storage induces chilling injury in pineapples, while [32] emphasized that such symptoms intensify despite controlled temperatures. Although the IoT-based smart bin maintained a stable 14°C environment, it could not fully prevent internal degradation during extended storage, consistent with [33] and [34], who linked chilling injury to membrane disruption and enzymatic browning.

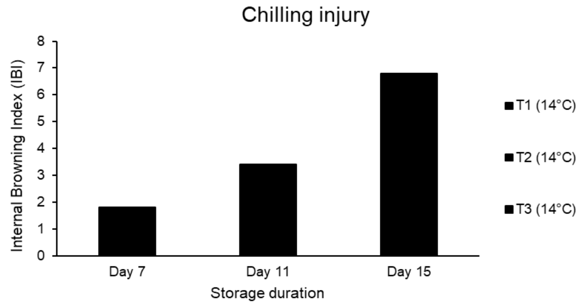

Fig. 8. Chilling injury in different storage durations.

Thus, while storage up to 11 days' preserves quality, longer storage increases browning risk and reduces marketability, highlighting the need to optimize temperature and storage time to maintain fruit quality.

Fig. 9. Internal appearance of pineapple samples under different storage durations at 14°C: increasing browning is evident from T1 (7 days) to T3 (15 days), supporting the IBI measurements.

3.2.4 TSS

Total Soluble Solids (TSS), indicating fruit sweetness, were significantly influenced by storage temperature and duration (Figure 10). The ambient control (T0) had the lowest TSS at 13.30°Brix due to higher respiration reducing sugars, while cold storage at 14°C increased TSS to 15.64°Brix (7 days, T1) and peaked at 16.24°Brix (11 days, T2), reflecting improved sugar retention consistent with [35] and [36]. However, TSS declined to 14.40°Brix at 15 days (T3), suggesting that extended cold storage induces metabolic stress and sugar degradation, as reported by [29] and [37]. This decline likely results from chilling injury impairing carbohydrate metabolism and cell integrity [38]. These findings underscore that cold storage up to 11 days effectively preserves pineapple sweetness, but prolonged storage risks quality deterioration.

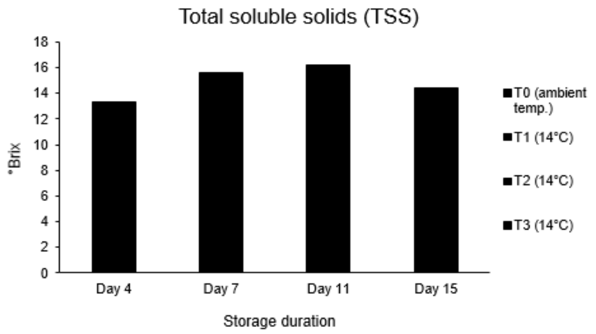

Fig. 10. TSS in different storage durations.

3.2.5 pH

Pineapple pH increased significantly across treatments ($P > 0.005$), from 2.83 at ambient temperature (T0) to 3.83 after 15 days at 14°C (T3), indicating a decline in acidity due to metabolic consumption of organic acids during storage [39], [40]. This aligns with the natural ripening process, where acids are metabolized into sugars or other compounds [38]. While moderate pH elevation improves flavor by reducing sourness, excessive increase, as seen in T3, can suggest overripening and possible quality deterioration [41].

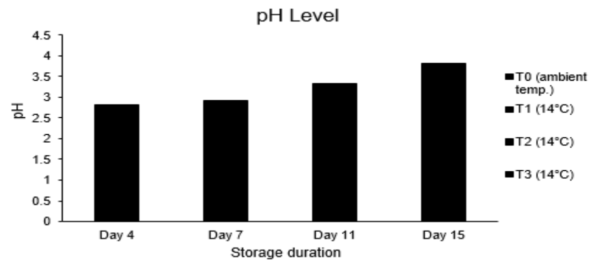

Fig. 11. pH Level in different storage durations.

3.2.6 Firmness

Fruit firmness was significantly affected by storage temperature and time ($P > 0.005$). The lowest firmness (1.54 N) was observed at ambient temperature (T0), attributed to accelerated enzymatic breakdown at higher temperatures [42]. Cold storage at 14°C preserved texture best at 7 days (T1: 8.28 N) but declined over time to 6.98 N (T2) and 4.96 N (T3), reflecting ongoing softening due to enzymatic activity [43], [44]. This confirms that while cold storage delays softening, it cannot prevent senescence beyond a certain period [1].

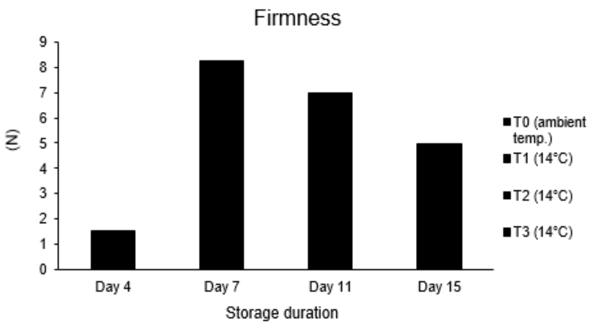

Fig. 12. Firmness in different storage durations.

3.2.7 Respiration Rate

Respiration rates, derived from CO_2 changes, increased over time, from negligible levels at Day 7 (0 mg CO_2/kg·h) to 3.00 mg CO_2/kg·h at Day 11 and 7.81 mg CO_2/kg·h at Day 15, confirming ongoing metabolic activity. CO_2 buildup and O_2 depletion inside the bin reflected active respiration, though cold storage effectively slowed the process [27], [45]. These results emphasize the importance of temperature control in reducing respiration intensity and delaying senescence [23], with the smart bin maintaining favorable gas conditions throughout.

3.2.8 Shelf Life

Pineapples stored at 14°C showed optimal shelf life up to 11 days, with the acceptable overall quality observed. VQR remained high through Day 11 (7.8) but dropped by Day 15 (5.0), while IBI increased from 1.8 to 6.8, indicating onset of chilling injury [37]. Firmness and TSS peaked at Day 7, with reduced weight loss (2.86%) compared to ambient (8.04%), confirming the cold environment preserved moisture and sweetness [38]. The data suggest 11 days is the practical limit for maintaining market quality under these conditions.

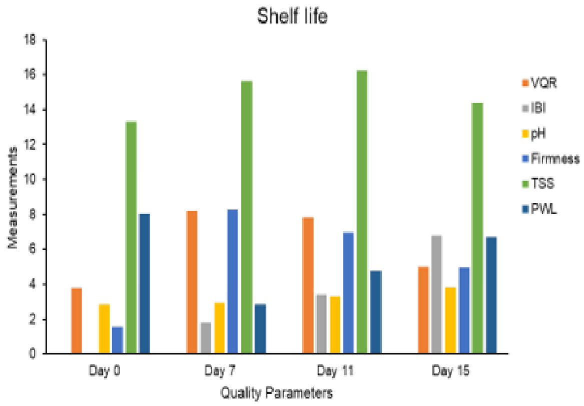

Fig. 13. Pineapple Quality Measurements at Different Storage Intervals.

3.3 Performance Evaluation of the Smart Monitoring Bin

3.3.1 Cooling profile of the smart monitoring bin

The smart bin cooled from ambient (26°C) to the target 14°C within 25 minutes when empty and in 45 minutes when loaded with pineapples. The slower cooling in loaded conditions was due to the high thermal mass and specific heat of pineapples (3.68 kJ/kg°C), which absorbed and retained more heat [46]. The Peltier-based system stabilized at 14°C, consistent with its ΔT limitations, confirming its suitability for postharvest storage of pineapple. Quick temperature reduction helped suppress enzymatic and microbial activity [47].

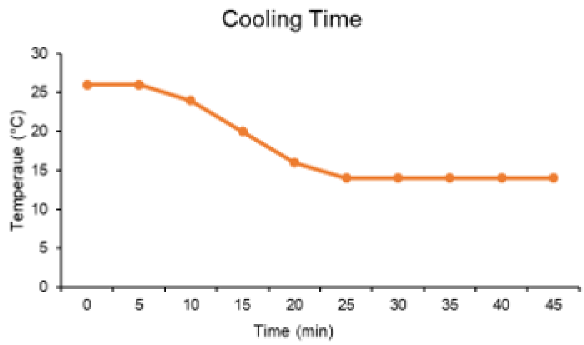

Fig. 14. Cooling time.

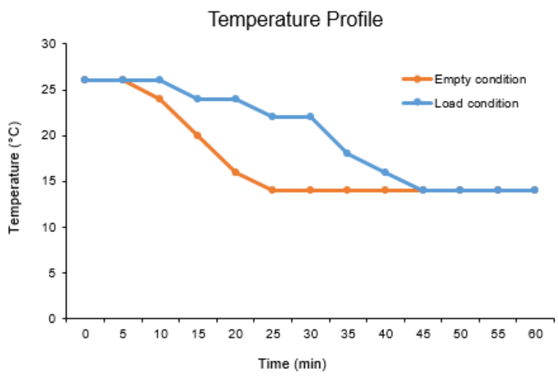

Fig. 15. Temperature profile.

3.3.2 Cooling efficiency (CE) of the bin

During no-load tests, the chamber reached 14°C in 25 minutes and 80% RH in 50 minutes, while under load, it achieved the same temperature in 45 minutes and RH in 60 minutes. The delay under load conditions is attributed to increased thermal load and slower convective heat transfer, validating the influence of fruit mass and surface area on cooling efficiency (Fourier's Law, Newton's Law). These results confirm the bin's capacity to establish and maintain an optimal low-temperature, high-humidity environment for pineapple storage.

3.3.3 Assessment of Energy Consumption

The smart bin's energy demand was dominated by the thermoelectric cooling system, consuming about 284.04 W per hour. The monitoring components consumed only 4.125 W, confirming minimal impact from the sensors. Total energy usage reached 48.41 kWh for 7 days, 76.07 kWh for 11 days, and 103.73 kWh for 15 days. Despite the relatively high energy cost of thermoelectric systems, the smart bin maintained storage parameters, supporting its potential in extending pineapple shelf life.

4. CONCLUSION

This study demonstrated that the IoT-based smart bin has a potential to extended the shelf life and preserved the quality of pineapples in 14°C temperature using a thermoelectric cooling system. It slowed physiological processes, reducing weight loss and maintaining firmness and appearance for up to 11 days. Real-time monitoring of temperature, humidity, oxygen, and CO_2 confirmed optimal storage conditions. While cooling components consumed most of the energy (up to 284W/hr), the monitoring system required minimal power, proving IoT integration is feasible without significant energy cost. However, quality declined in 15 days, making further storage less beneficial. Overall, the smart bin is an energy-efficient postharvest solution for 11 days' pineapple storage.

5. ACKNOWLEDGEMENTS

The authors are thankful to the Department of Agricultural and Biosystems Engineering (DABE), College of Agriculture and Agri-Industries and the Center for Resources Assessment, Analytics, and Emerging Technologies (CReATe) for their invaluable provision of equipment, facilities, and services, which greatly facilitated the execution of this study.

6. REFERENCES

[1] L. M. Cardona, M. Cortés-Rodríguez, F. J. C. Galeano, and J. C. Arango, "Physicochemical stability of pineapple suspensions: the integrated effects of enzymatic processes and homogenization by shear," *J Food Sci Technol*, vol. 59, no. 4, pp. 1610–1618, Apr. 2022, doi: 10.1007/s13197-021-05172-8.

[2] K. LaRue, "What Are the Health Benefits of Pineapple?," EatingWell.

[3] M. Shahbandeh, "Global pineapple production by leading countries 2022," Statista.

[4] Statista, "Philippines: pineapple production volume 2022," Statista.

[5] J. B. Lagare, " PH pineapple exports up 5% in 2023," Inquirer Business.

[6] FAO, "Resilience gaps and opportunities for the pineapple industry," in *Resilience assessment of avocado and pineapple value chains*, FAO, 2023. doi: 10.4060/cc5967en.

[7] C. Garreau *et al.*, "Preparation of highly stable and ultrasmooth chemically grafted thin films of chitosan," *Soft Matter*, vol. 19, no. 8, pp. 1606–1616, 2023, doi: 10.1039/D3SM00003F.

[8] X. Liao, Y. Xing, X. Fan, Y. Qiu, Q. Xu, and X. Liu, "Effect of Composite Edible Coatings Combined with Modified Atmosphere Packaging on the Storage Quality and Microbiological Properties of Fresh-Cut Pineapple," *Foods*, vol. 12, no. 6, p. 1344, Mar. 2023, doi: 10.3390/foods12061344.

[9] W. Arthur, P. T. Akonor, C. Oduro-Yeboah, L. C. B. Gyasi, E. M. Essel, and J. Dowuona, "Assessment of Quality Characteristics of Organic and Conventional Sugarloaf Pineapples (Ananas comosus, ananas) Under Cold Storage," *Agricultural and Food Science Journal of Ghana*, vol. 15, no. 1, pp. 1618–1630, Mar. 2023, doi: 10.4314/afsjg.v15i1.9.

[10] P. Rajak, A. Ganguly, S. Adhikary, and S. Bhattacharya, "Internet of Things and smart sensors in agriculture: Scopes and challenges," *J Agric Food Res*, vol. 14, p. 100776, Dec. 2023, doi: 10.1016/j.jafr.2023.100776.

[11] A. Lamberty and J. Kreyenschmidt, "Ambient Parameter Monitoring in Fresh Fruit and Vegetable Supply Chains Using Internet of Things-Enabled Sensor and Communication Technology," *Foods*, vol. 11, no. 12, p. 1777, Jun. 2022, doi: 10.3390/foods11121777.

[12] H. M. Rai, K. K. Shukla, Y. Goya, S. Amanzholova, and A. Nessibely, "IoT-based real-time monitoring and control system for tomato cultivation," *Procedia Comput Sci*, vol. 241, pp. 433–438, 2024, doi: 10.1016/j.procs.2024.08.060.

[13] R. C. Arora, *Refrigeration and Air Conditioning* . New Delhi: PHI Learning Private Limited, 2010.

[14] Basco Container, "Food Grade Poly Drums and the Benefits from Using Them," Basco Container.

[15] A. Acedo, "Postharvest physiology of perishable crops. Laboratory Manual in Horticulture 111," 1999.

[16] S. H. E. J. Gabriëls, P. Mishra, M. G. J. Mensink, P. Spoelstra, and E. J. Woltering, "Non-destructive measurement of internal browning in mangoes using visible and near-infrared spectroscopy supported by artificial neural network analysis," *Postharvest Biol Technol*, vol. 166, p. 111206, Aug. 2020, doi: 10.1016/j.postharvbio.2020.111206.

[17] V. Chi Khang, T. Le Dang, N. Van Muoi, and T. Thanh Truc, "Evaluation of Freezing Temperatures and Ripeness Levels on The Quality Characteristics of Frozen Pineapple Fruits," *Journal of microbiology, biotechnology and food sciences*, vol. 12, no. 3, p. 5439, Oct. 2022, doi: 10.55251/jmbfs.5439.

[18] S. M. Y. Ali *et al.*, "Physical and Chemical Characteristics of Pineapples Grown in Bangladesh," 2015. [Online]. Available: http://www.ijbssr.com/currentissueview/14013112

[19] D. B. Kiin-Kabari, C. O. Ebere, O. M. Akusu, and D. B. Kiin-Kabari, "Quality Characteristics of Orange/Pineapple Fruit Juice Blends," *American Journal of Food Science and Technology*, vol. 4, no. 2, pp. 43–47, 2016, doi: 10.12691/ajfst-4-2-3.

[20] P. Jin, H. Shang, J. Chen, H. Zhu, Y. Zhao, and Y. Zheng, "Effect of 1-Methylcyclopropene on Chilling Injury and Quality of Peach Fruit during Cold Storage," *J Food Sci*, vol. 76, no. 8, Oct. 2011, doi: 10.1111/j.1750-3841.2011.02349.x.

[21] B. A. M. S. Kumara and K. D. T. Hettige, "Ripening Stage Affects the Quality of Fresh and Dehydrated Pineapples (Ananas comosus (L.) Merr.)& cv. Mauritius in Sri Lanka," *Sustainable Food*

Production, vol. 8, pp. 29–37, Oct. 2020, doi: 10.18052/www.scipress.com/SFP.8.29.

[22] F. Guillén, J. Medina-Santamarina, M. E. García-Pastor, N. J. Chen, G. Uruu, and R. E. Paull, “Postharvest melatonin treatment delays senescence and increases chilling tolerance in pineapple,” *LWT*, vol. 169, p. 113989, Nov. 2022, doi: 10.1016/j.lwt.2022.113989.

[23] P. Kandasamy, “Respiration rate of fruits and vegetables for modified atmosphere packaging: a mathematical approach,” *Journal of Postharvest Technology*, vol. 10, no. 1, pp. 88–102, 2022, [Online]. Available: www.jpht.in

[24] N. C. Harris, *Modern air conditioning practice*. New York, N.Y: Gregg Division, McGraw-Hill, 1983.

[25] L. A. Ramallo and R. H. Mascheroni, “Quality evaluation of pineapple fruit during drying process,” *Food and Bioproducts Processing*, vol. 90, no. 2, pp. 275–283, Apr. 2012, doi: 10.1016/j.fbp.2011.06.001.

[26] M. J. Gidado, A. A. N. Gunny, S. C. B. Gopinath, A. Ali, C. Wongs-Aree, and N. H. M. Salleh, “Challenges of postharvest water loss in fruits: Mechanisms, influencing factors, and effective control strategies – A comprehensive review,” *J Agric Food Res*, vol. 17, p. 101249, Sep. 2024, doi: 10.1016/j.jafr.2024.101249.

[27] E. Yahia, *Postharvest biology and technology of tropical and subtropical fruits*, vol. 1. 2011.

[28] A. A. Kader and R. S. Rolle, *The Role of Post-harvest Management in Assuring the Quality and Safety of Horticultural Produce*. Food and Agriculture Organization of the United Nations, 2004.

[29] M. Mohd Ali, N. Hashim, S. Abd Aziz, and O. Lasekan, “Shelf Life Prediction and Kinetics of Quality Changes in Pineapple (Ananas comosus) Varieties at Different Storage Temperatures,” *Horticulturae*, vol. 8, no. 11, Nov. 2022, doi: 10.3390/horticulturae8110992.

[30] R. B. H. Wills and J. Golding, *Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables*, 6th ed. NewSouth Publishing, 2016.

[31] N. H. Dolhaji, I. D. Muhammad, H. Yaakob, and A. Mohd Marsin, “Chilling injury in pineapple fruits: physical quality attributes and antioxidant enzyme activity,” *Food Res*, vol. 4, no. S5, pp. 86–95, Dec. 2020, doi: 10.26656/fr.2017.4(S5).004.

[32] N. H. Dolhaji, I. I. Muhamad, H. Ya’akub, and A. Abd Aziz, “Evaluation of chilling injury and internal browning condition on quality attributes, phenolic content, and antioxidant capacity during sub-optimal cold storage of malaysian cultivar pineapples,” *Malaysian Journal of Fundamental and Applied Sciences*, vol. 14, no. 4, pp. 456–461, Jan. 2019, doi: 10.11113/mjfas.v14n4.1072.

[33] L. L. Morris, “Chilling Injury of Horticultural Crops: an Overview,” *HortScience*, vol. 17, no. 2, pp. 161–162, Apr. 1982, doi: 10.21273/HORTSCI.17.2.161.

[34] O. Nukuntornprakit, K. Chanjirakul, W. G. van Doorn, and J. Siriphanich, “Chilling injury in pineapple fruit: Fatty acid composition and antioxidant metabolism,” *Postharvest Biol Technol*, vol. 99, pp. 20–26, Jan. 2015, doi: 10.1016/j.postharvbio.2014.07.010.

[35] M. G. Lobo and R. E. Paull, *Handbook of Pineapple Technology: Production, Postharvest Science, Processing and Nutrition*. Wiley, 2017.

[36] E. R. Rajan, “Effect of Hot Water Treatment and Storage Temperature on Biochemical Properties of Pineapple cv. Mauritius,” *Environment and Ecology*, vol. 39, no. 1, pp. 134–142, 2021, [Online]. Available: https://cabidigitallibrary.org

[37] A. A. Kader, “Postharvest Technology of Horticultural Crops-An Overview from Farm to Fork,” 2013.

[38] M. E. Saltveit, “A Summary of CA Requirements and Recommendations for Vegetables,” *Acta Hortic*, no. 600, pp. 723–727, Mar. 2003, doi: 10.17660/ActaHortic.2003.600.110.

[39] P. Saradhuldhat and R. E. Paull, “Pineapple organic acid metabolism and accumulation during fruit development,” *Sci Hortic*, vol. 112, no. 3, pp. 297–303, Apr. 2007, doi: 10.1016/j.scienta.2006.12.031.

[40] V. L. Singleton and W. A. Gortner, “Chemical and Physical Development of the Pineapple Fruit II. Carbohydrate and Acid Constituents,” *J Food Sci*, vol. 30, no. 1, pp. 19–23, Jan. 1965, doi: 10.1111/j.1365-2621.1965.tb00255.x.

[41] V. Paul and R. Pandey, “Role of internal atmosphere on fruit ripening and storability—a review,” *J Food Sci Technol*, vol. 51, no. 7, pp. 1223–1250, Jul. 2014, doi: 10.1007/s13197-011-0583-x.

[42] R. V. Patil, V. R. Patil, and C. V. Pujari, “Effect of maturity stages on shelf life of papaya (Carica papaya L.),” *Asian Journal of Dairy and Food Research*, no. of, Dec. 2018, doi: 10.18805/ajdfr.DR-1340.

[43] T. Guo *et al.*, “Low temperature inhibits pectin degradation by PpCBFs to prolong peach storage time,” *J Food Sci*, vol. 88, no. 9, pp. 3725–3736, Sep. 2023, doi: 10.1111/1750-3841.16731.

[44] S. K. Bose, M. H. Rahman, M. F. Mondal, S. K. Bose, and T. Haque, “Physico-chemical changes in papaya fruits during storage,” *J. Bangladesh Soc. Agric ScL Technol*, vol. 4, no. 4, pp. 145–148, 2007, https://www.researchgate.net/publication/335232749

[45] C. L. Moretti, L. M. Mattos, A. G. Calbo, and S. A. Sargent, “Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: A review,” *Food Research International*, vol. 43, no. 7, pp. 1824–1832, Aug. 2010, doi: 10.1016/j.foodres.2009.10.013.

[46] A. U. Anonaba, U. S. Mbamara, and E. C. Mbamala, “Thermal Properties of Pineapple Leaf Composite and its Suitability as a Viable Alternative for Efficient Roofing Material,” *To Physics Journal*, vol. 4, pp. 40–47, 2019.

[47] R. A. Abraham, J. Joshi T, and S. Abdullah, “A comprehensive review of pineapple processing and its by-product valorization in India,” *Food Chemistry Advances*, vol. 3, p. 100416, Dec. 2023, doi: 10.1016/J.FOCHA.2023.100416.