An Internet of Things Framework for Real-Time Fruit Ripeness Monitoring and Analysis for Logistic Enhancement

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ABSTRACT

A significant challenge in the agricultural supply chain sector is the post-harvest loss of fruits and vegetables during transport and storage. This study focuses on mitigating post-harvest losses, especially in bananas. A comprehensive solution is presented through a robust real-time fruit condition monitoring framework that involves the timely analysis of parameters captured using multiple sensors, addressing the existing gap in the current agricultural logistics system. The systematic design and architecture of the system enable the sensors to measure temperature, ethylene, and carbon dioxide, while the Raspberry Pi Pico W handles data processing. The fruit shelf life is extended by incorporating an energy-efficient cooling mechanism using a Peltier device and an algorithmic optimization of battery management. The user-friendly dashboard assists vendors by providing real-time visualization of the ripening status of each fruit box, thereby facilitating logistics. The experimental results using bananas demonstrate the system's impact on improving shelf life, reducing spoilage, and enhancing decision-making during transportation.

Keywords-real-time monitoring; fruit ripening; IoT; logistics; ethylene; cloud storage; post-harvest loss

I. INTRODUCTION

The lack of post-harvest techniques significantly contributes to post-harvest losses of agricultural produce in the entire supply chain from producer to retailer [1]. The greatest portion of the produce gets spoiled during logistics and storage because of uncontrolled environmental conditions. Agricultural produce, particularly fruits, is commonly packed in boxes, and huge quantities are transported in the absence of real-time monitoring and improper logistic decisions. Fruits, such as bananas, mangoes, papayas, and avocados, commonly face great post-harvest loss. An estimate of 30-40% of fruits and vegetables are lost between harvest and consumption [2], largely due to infrastructure limitations, transportation inefficiencies, and the lack of technological support. Therefore, enhanced logistics planning and support of technology driven user friendly solutions are required for achieving sustainable agricultural supply chains in India [3].

Fruits are highly perishable and have shorter shelf lives. Extension of the latter is highly influenced by factors such as light sensitivity, temperature, gaseous exchange, and intra-box placement, including physical compactness [4]. The first and most widely adopted method to slow down fruit spoilage is cold storage. Refrigeration slows spoilage but demands stable electricity, high investment, and technical maintenance. Incorporating Internet of Things (IoT) technologies into cold supply chains enables real-time monitoring and managing temperature-controlled storage and transportation, thereby enhancing efficiency, traceability, and quality assurance [5]. However, the currently available cold storage solutions for shelf-life extension during transportation are often expensive, limiting their adoption, particularly among local fruit vendors.

The ripening of fruits is accelerated by ethylene gas, a natural plant hormone [6]. The packing of fruits within transport containers promotes the accumulation of ethylene gas, thereby speeding up the ripening process, reducing their shelf life, and increasing the spoilage rate [7]. Unregulated variations in temperature and humidity inside the containers further facilitate the fruit ripening process. Integrating IoT services enhances food supply chains by monitoring critical environmental parameters and ensuring traceability [8]. An IoT-based system for predicting fruit expiration dates and estimating fruit lifespan was developed in [0], using low-cost embedded hardware equipped with gas sensors and machine learning estimation for measuring fruit freshness span. An IoT-based solution was proposed for reducing post-harvest onion losses through the monitoring and automatic regulation of environmental parameters [101], achieving a 15–20% reduction in spoilage compared with traditional methods. Detection of rotten fruits is essential as it produces ethylene accelerating ripening. An IoT system for detecting early signs of fruit ripening was developed in [12], using sensor networks and demonstrated increased accuracy over manual inspection methods. An IoT and machine learning-based approach for fruit ripeness detection was presented using temperature, humidity, and gas emission sensors [12]. A hybrid reinforcement learning framework combining Deep Q-Learning that learns from both real IoT sensor inputs and synthetic data was used to improve adaptive decision-making and accuracy in food spoilage prediction [13]. Authors in [14] dynamically monitored ethylene and studied its impact on post-harvest losses. An IoT-based ethylene sensing platform dynamically tracks ethylene concentration, enabling timely decision-making to regulate fruit ripening. The present study focuses only on ethylene-based control, with limited consideration of other parameters affecting fruit ripening.

Existing approaches do not offer a cost-effective packaging solution capable of remotely and accurately communicating fruit ripening status. Furthermore, many approaches emphasize sensing and monitoring of parameters without integrating energy optimization strategies, essential for a sustainable power system in portable or remote fruit boxes. Present approaches lack a centralized, web-based platform that aggregates sensor data from multiple fruit boxes and offers decision-support recommendations, such as prioritizing the dispatch of fruit boxes based on freshness, thereby extending the shelf life of fruits.

A reasonable solution to post-harvest fruit losses is smart packing systems [15], over conventional packaging. The current study addresses the limitations of existing systems through an IoT-driven smart fruit transportation box embedded with multi-sensors that facilitate real-time monitoring of fruit ripening conditions during the entire transportation process. The system comprises ethylene and CO_2 detection sensors, temperature and humidity sensors, a Raspberry Pi Pico W processing unit, and wireless connectivity for cloud-based data visualization. Through a user-friendly web dashboard, the system displays the fruit ripening stages and provides informed decision-making during transit by assisting in prioritizing the dispatch of fruit boxes. The proposed smart fruit box is designed to enhance fruit supply chain efficiency, improve shelf life, and minimize post-harvest loss. Banana tests show that the system is feasible and effective for real-world agricultural logistics.

Enhanced logistics efficiency can assist in minimizing dependencies on intermediaries, thus improving the delivery timelines and enhancing the overall profitability for farmers [17, 17]. This study emphasizes integrating advanced technologies with strategic logistics planning to reduce post-harvest losses in the fruit supply chain. The implementation of embedded sensors is examined, highlighting the potential of IoT networks and remote monitoring to enhance the food industry.

II. SYSTEM ARCHITECTURE AND DESIGN

The proposed IoT-driven smart fruit box system is designed to monitor and control the internal environmental conditions of fruits during transportation and short-term storage. The system continuously measures temperature, humidity, ethylene-related gas concentration, and transmits the data wirelessly for real-time monitoring and logistics optimization. The whole system consists of hardware sensing units, a processing and control unit, a cooling mechanism, a power management system, and a software platform. Figure 1 shows the schematic layout of the proposed system, which illustrates the interactions between the sensors, microcontroller, cloud services, and user interfaces.

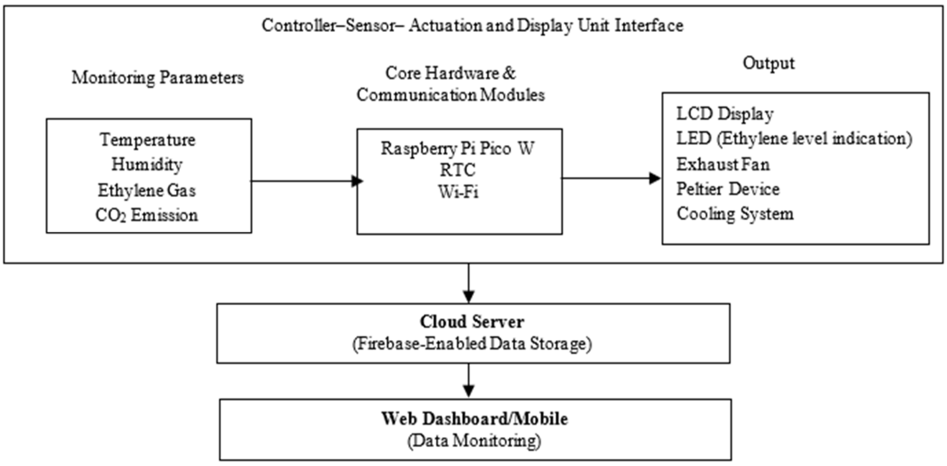

Fig. 1. Schematic layout of the system.

A. The Interface of Controller and Sensors

Each sensor in Figure 1 plays a crucial role in monitoring environmental conditions, systematically tracking fruit ripening stages. The Raspberry Pi Pico W operates as the central processing unit of the sensor node and functions as a microcontroller for data acquisition and control. The Digital Humidity and Temperature (DHT) sensor measures ambient temperature and relative humidity inside the smart fruit box. The MQ-3 sensor was employed as a low-cost indirect indicator of ethylene-induced ripening by sensing the build-up of volatile organic compounds inside the fruit box, indicating ripeness in climacteric fruits like bananas. Changes in the sensor output voltage correspond to variations in ethylene levels, allowing the system to classify fruit ripeness stages accurately. These parameters significantly influence fruit shelf life and ripening speed. Thonny, an open-source Integrated Development Environment (IDE), was used for programming control logic for sensor interfacing on the Raspberry Pi Pico W microcontroller. For experimentation, a plastic container was used to embed the sensors, store the fruits, and monitor the parameters during the ripening process.

B. Firebase-Enabled Cloud Data Storage

The present study explores Firebase for cloud storage, as it offers real-time data synchronization and distributed storage, making it suitable for current IoT-enabled applications that demand low latency [18]. The proposed fruit ripeness monitoring system records temperature, humidity, CO_2 concentration, and ethylene gas levels from each storage box, storing the complete dataset in Google Firebase. The system acquires new sensor readings from multiple sensors, and the microcontroller processes the data to evaluate them using preset threshold values. The system uploads the corresponding ripeness status labels to Firebase in a structured JavaScript Object Notation (JSON) format. This ensures that no data were lost during device restarts, dashboard termination, or temporary network and system outages. The stored dataset can be retrieved at any time to analyze fruit ripening status at different environmental conditions during transportation. Firebase enables time-stamped logging, which helps correlate ethylene gas levels, temperature rise, and humidity variations over the ripening stages of the fruit. The system uses these different status labels corresponding to the records measured at different time instants of experimenting with the ripening stages of the banana fruits: "Fruits are unripe", "Starting to Ripe", "Ripe and Dispatch-Ready", and "Over-Ripe".

III. IMPLEMENTATION METHODOLOGY

The workflow of the system is shown in Figure 2. The system systematically records key indicators of fruit ripeness, such as temperature, humidity, ethylene concentration, and CO_2 levels, using multiple sensors embedded in the fruit boxes. Data from these sensors are processed by Raspberry Pi Pico W. Sensor readings are transmitted via Wi-Fi to the cloud platform, enabling remote monitoring through a web dashboard. The data on the web dashboard offer a user-friendly visualization of each fruit box's parameters, ensuring that the vendors have immediate access to ripeness trends. This real-time transparency supports informed decision-making, enabling vendors to prioritize the dispatch of relevant fruit boxes. Cloud data analysis offers traceability of each fruit box, ensuring that each storage unit can be individually identified, monitored, and managed.

The system measures the status of fruit ripening only at intermediate time instants. This further benefits the former by enabling efficient power distribution to sensors and communication modules. During periods of inactivity, the latter are placed into low-power mode by putting them into sleep states. In the event of elevated gas concentrations in the fruit box, the system actuates the exhaust mechanism. This enables the rapid purging of ethylene and CO_2 through specially designed outlets. The controlled evacuation prevents the accumulation of gaseous agents that accelerate ripening and spoilage.

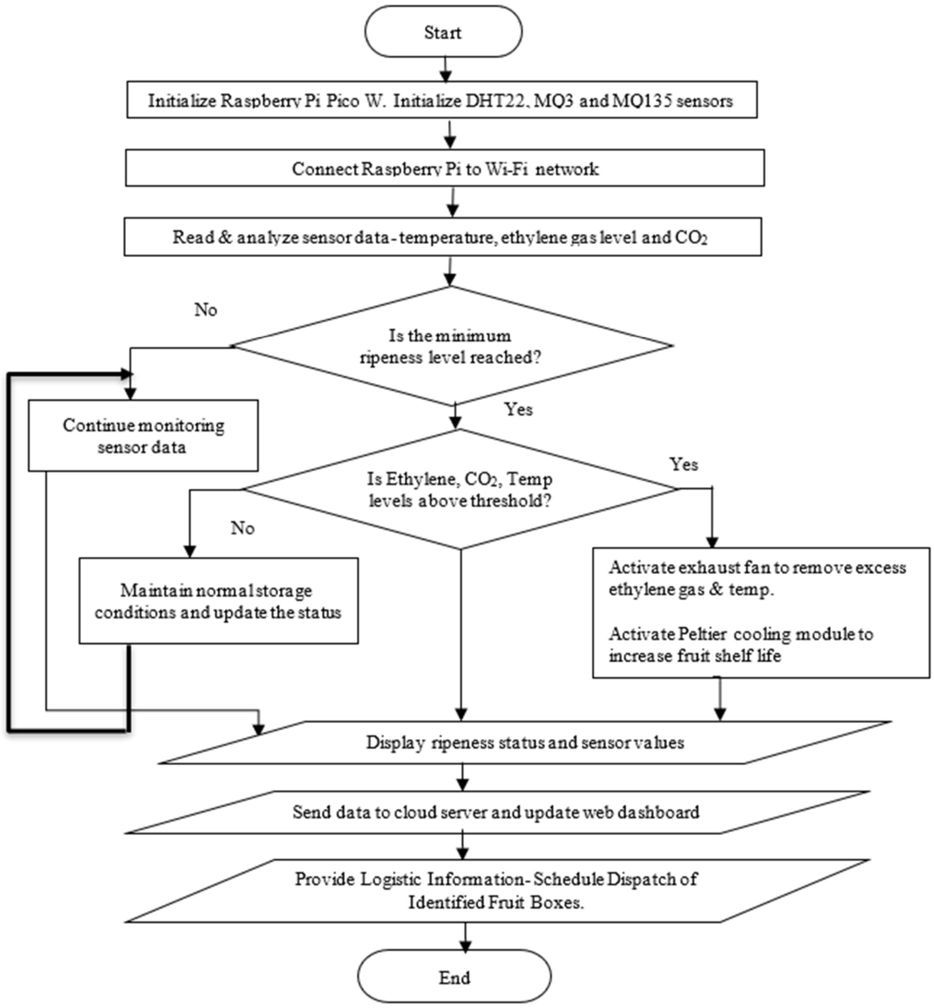

Fig. 2. Entire system workflow.

IV. SYSTEM ALGORITHMS

The Wi-Fi initialization and web server setup implemented on Raspberry Pi Pico W are presented in Algorithm 1. Algorithm 2 describes the process for temperature and humidity sensing, while Algorithms 3 and 4 outline the communication procedures with the MQ3 and MQ135 gas sensors for ethylene-related gas and CO_2 monitoring, respectively. Based on the acquired sensor readings, Algorithms 5, 6, and 7 present the operational logic for ripeness detection, cooling system activation, and web-based dashboard monitoring. All algorithms presented below were implemented in Python.

A. Wi-Fi Initialization and Web Server Setup

- Start
- Import required Python libraries
- network, socket, time, ujson
- Initialize Wi-Fi module in station mode
- Set SSID and Password. Connect Raspberry Pi to Wi-Fi network
- Wait until connection is established
- Display assigned IP address. Create socket object
- Bind socket to port 80. Start listening to client requests
- End;

B. Temperature and Humidity Sensing

- Start
- Import DHT22 and Pin modules
- Read temperature and humidity value from sensor
- If sensor adding fails, retry reading up to 3 times
- Store temperature and humidity values
- Send data to main controller
- End;

C. Ethylene Gas Detection

- Start
- Import ADC and Pin modules
- Initialize MQ3 sensor at ADC pin 26
- Read analog value from MQ3 sensor
- Convert ADC value to voltage
- Calculate ethylene gas concentration (ppm)
- Send ethylene data to controller
- End;

D. CO_2 Gas Detection

- Start
- Initialize MQ135 gas sensor using ADC pin 27
- Acquire analog voltage readings from sensor
- Convert voltage to CO_2 concentration (ppm)
- Transmit the CO_2 data to the controller
- End;

E. Ripeness Detection

- Start
- Read ethylene gas level from MQ3 sensor
- Read CO_2 level from MQ135 sensor
- Read temperature from DHT22
- If ethylene voltage < threshold, set stage = "Fruits are unripe”
- Else if ethylene voltage within medium range, set stage = "Starting to Ripe"
- Else if ethylene voltage is high, set stage = "Ripe and Dispatch-Ready"
- Else CO_2 and temperature exceed limits, set stage = "Overripe"
- Record the ripeness status
- End;

F. Fan and Peltier Automation

- Start
- Initialize relay pins for fan and Peltier
- Continuously monitor ethylene gas value
- If ethylene level > threshold, activate the exhaust fan
- After fixed time delay ,deactivate the exhaust fan
- Activate the Peltier cooling module
- After the specified cooling duration, deactivate the Peltier module
- If the ethylene level remains within normal limits, deactivate all actuators
- End;

G. Web Interface Data Display

- Start
- Wait for client HTTP request
- If request is /sensor, acquire data from all integrated sensors, encode the sensor data into JSON format, send JSON response to client
- Else send HTML dashboard page
- Refresh sensor data periodically
- End;

V. RESULTS AND DISCUSSION

The performance of the proposed system is evaluated using banana fruits. Bananas are mainly transported interstate, contributing to a large consumer market across India and constituting a significant share of the domestic fruit trade. Maharashtra, Tamil Nadu, Andhra Pradesh, Uttar Pradesh, and Gujarat states are production hubs for banana production in India. These target producers rely on road and railway transport for interstate transport of their produce. Small traders usually prefer to use normal transportation systems, such as trucks or vans, and open crates for banana transportation. Factors such as long-distance transportation, poor road conditions, inadequate packaging, and the absence of an efficient cold chain significantly contribute to post-harvest banana losses, which are typically reported in the range of approximately 20-30% across traditional supply chains [10, 19]. The current study addresses these challenges by offering a targeted solution that plays a significant role in minimizing losses during banana transportation. Figure 3 depicts the complete system setup for fruit ripeness detection.

The post-harvest life of mature green bananas stored at ambient temperatures is commonly limited to about 4-10 days before they ripen and become soft and edible. The system is tested by enclosing the bananas in the fruit box embedded with sensors, as portrayed in Figure 3. The sensor readings are captured at specific time intervals for over four days, analyzing the variations and recording the corresponding ripening stages on the cloud.

Fig. 3. Fruit box with embedded sensors.

A. The Sensor Response

Figures 4 and 5 illustrate the variations in the sensor output voltage and the estimated gas concentration in ppm for ethylene (MQ-3) and CO_2 (MQ-135), which were measured during the testing of the fruit ripening process inside the smart storage box.

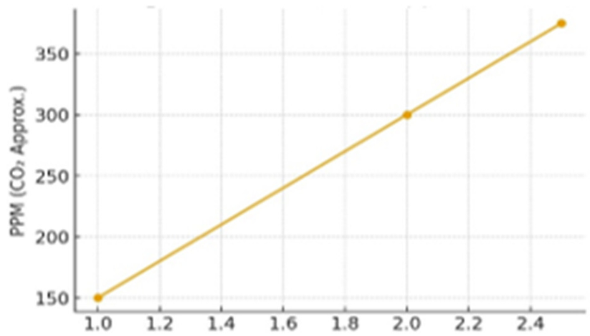

Fig. 4. Measured voltage versus ppm for CO2 concentration levels.

Figure 4 reveals a gradual increase in CO2 concentration from around 150 ppm to 380 ppm, reflecting metabolic respiration activity during ripening. An increase in ethylene concentration was detected from 0 ppm to about 120 ppm. This indicates a strong positive correlation between the measured voltage level from the sensor and ethylene emission, where higher voltage represents higher ethylene emission in alignment with the fruit ripening process. The "Unripe" stage indicates low voltage levels of ethylene emission, the "Starting to Ripe" stage corresponds to intermediate levels of ethylene, while higher voltage and ppm values indicate the "Overripe" stage. CO_2 levels are used as a supporting parameter to validate the intensity of respiration and refine ripeness decisions.

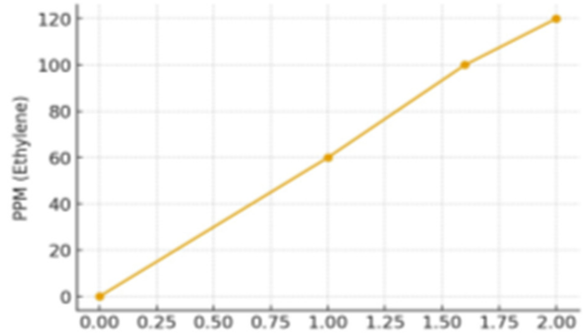

Fig. 5. Measured voltage versus ppm for ethylene concentration levels.

B. Fruit Testing Results

The system was tested for four days, during which the bananas remained inside the box. Sensor readings were recorded at different time points, as shown in Table I. The experimental setup of the system monitors the bananas enclosed within the box at specific time stamps, tracking the ripening progression. As observed in Table I, the initial readings within the fruit box were 25.4 °C for temperature, 1.08 V for ethylene, and 0.43 V for CO2. A substantial change in the measured sensor parameters was observed during the four days of the experimental testing period. The recorded variations correlated with the visible physical changes observed in the banana ripening. The results showed that the system can continuously monitor sensors and accurately track the fruits' real-time status.

TABLE I. SENSOR DATA READINGS AND SYSTEM STATUS FOR BANANA TESTING

Testing day	Time stamp	Measured sensor data			Fruit ripening status
		Temperature (°C)	Ethylene (V)	CO2 (V)	
Day 1	10:04:32 (2025-12-09)	25.4	1.08	0.43	Fruits are unripe
Day 1	18:38:33 (2025-12-09)	26.7	1.16	0.41	Starting to ripe
Day 2	10:51:03 (2025-12-10)	27.3	1.31	0.46	Starting to ripe
Day 2	17:10:18 (2025-12-10)	27.8	1.43	0.46	Starting to ripe
Day 3	11:54:32 (2025-12-11)	28.5	1.74	0.74	Ripe and dispatch-ready
Day 4	08:14:42 (2025-12-12)	29.3	2.7	1.57	Over-ripe

C. Results of the Web Interface

Cloud connectivity is established through wireless communication modules integrated with the Raspberry Pi Pico W microcontroller, enabling the seamless transmission of time-stamped sensor data to a remote server. The web-based dashboard offers a real-time visualization of all sensor parameters, as displayed in Figure 6. This remote interface enables vendors to simultaneously monitor multiple fruit boxes and view their real-time ripeness status, with single-click access to track the progress of each box, knowing that the ripeness of fruits helps vendors organize logistics more efficiently, allowing them to plan and schedule the dispatch of fruit boxes.

D. Economic Feasibility Analysis

An economic feasibility analysis was performed for banana transportation from traders to local vendors by considering the transportation mode, vehicle capacity, and prevailing market price. For a medium to small truck carrying approximately 3 tons of bananas at a selling price of ₹50 per dozen, the total consignment value is estimated at ₹1,25,000. Assuming a 20% post-harvest transportation loss, the financial loss is approximately ₹50,000, representing an economic loss of nearly 40% to the trader. The capital, operating, and maintenance costs of the proposed IoT-driven smart fruit transportation box system, considering 200 boxes in the small truck, amount to ₹8,00,000. Under the assumed logistics operating conditions, the proposed solution yields a payback period of 16 transportation cycles. Depending on the frequency of trips by the trader, this corresponds to a significantly short recovery duration, thereby demonstrating the economic viability of the proposed system for large-scale deployment.

E. Comparative Analysis with Existing Techniques

The proposed system is compared with existing approaches for IoT-based, banana post-harvest systems, considering the key metrics, namely target monitoring unit, sensing parameters, user interface type for vendors, and facility for shelf life extension. The comparative analysis presented in Table II focuses on IoT-based systems monitoring individual fruit boxes rather than the overall logistics container. While several IoT-enabled solutions offer a systematic, vendor-side user interface, they are restricted to condition monitoring and lack provisions for active shelf-life extension. The proposed work addresses this research gap by incorporating an energy-efficient, Peltier-based cooling mechanism, which enables automatic environmental control for prolonging the post-harvest life of bananas [13, 22-24].

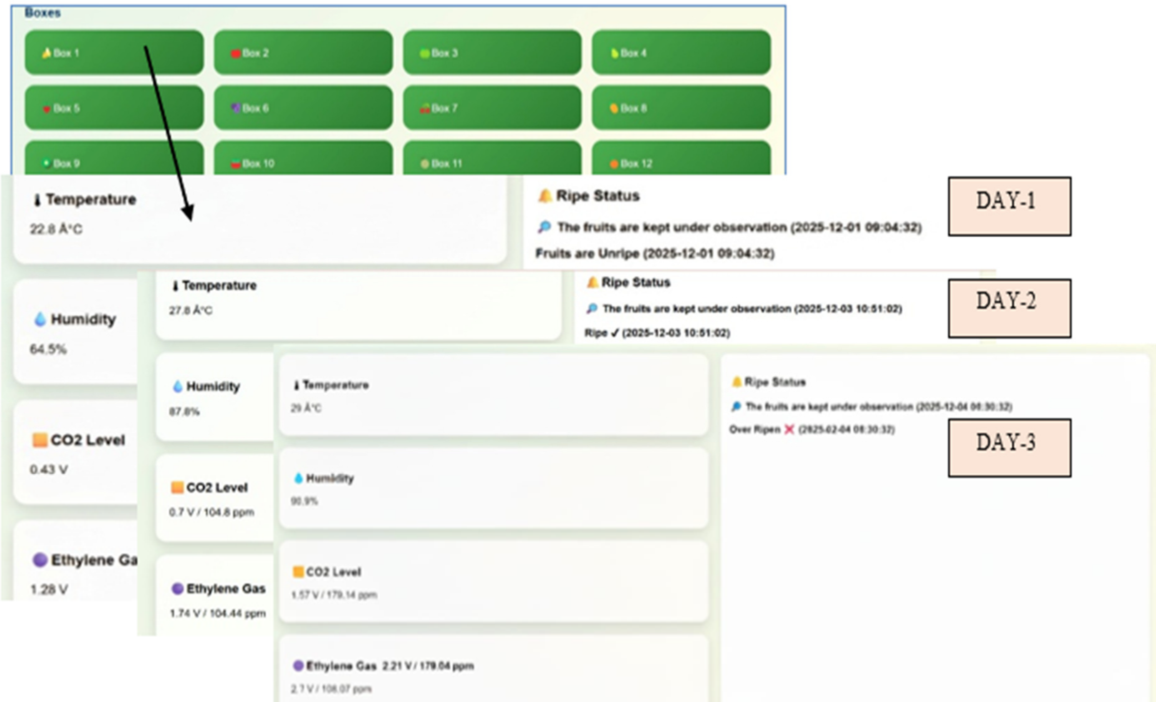

Fig. 6. Dashboard view of fruit boxes and ripeness status.

TABLE II. PROPOSED METHOD VERSUS EXISTING APPROACHES FOR IOT-BASED BANANA POST-HARVEST SYSTEMS

Target monitoring unit	Sensing parameters	User interface for vendor	Shelf-life extension mechanism
Each fruit box in the container	Temperature, relative humidity, gas, image features	Cloud dashboard	No active control (decision support only)
	Gas sensor array for volatile organic compound aroma	Web interface	No control action (monitoring and classification only)
	Color, temperature, relative humidity	Graphical user interface	No actuation
	Camera and environmental sensors	Web app	No actuation
	Ethylene, CO2, temperature, humidity	Cloud dashboard	Full active control of actuation unit

VI. CONCLUSION

The findings of this study contribute to the minimization of post-harvest loss of banana fruits during transportation. The proposed system seamlessly integrates multiparameter sensing of temperature, ethylene, and CO_2, using sensors interfaced with a Raspberry Pi Pico W for data processing embedded in the fruit box. The fruit shelf life was extended by integrating an energy-efficient cooling mechanism using a Peltier device. The user-friendly dashboard supports vendors by providing real-time visualization of the ripening status of each fruit box, thereby aiding logistical decision-making.

This study can be extended to other perishable and widely transported fruits. The smart fruit box capabilities allow farmers, traders, and logistics providers to prioritize the dispatch of relevant fruit boxes, thereby reducing post-harvest losses and building a more sustainable, data-driven fruit distribution ecosystem.

DECLARATION OF COMPETING INTERESTS

The authors declare no conflict of interest.

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DATA AVAILABILITY

This study does not involve the use of any datasets.

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