AI-Biosentry: A Decentralized Iot-Based Multi-Modal System For Real-Time Ripeness Monitoring

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Abstract- *Agricultural sustainability is challenged by nearly 40% post-harvest losses due to inefficient manual and destructive ripeness testing. Bio-Sentry is an advanced, non-destructive automated system designed to bridge this gap through a Multi-dimensional Sensing approach. The core system is built on the ESP32 microcontroller, which orchestrates a sophisticated Multi-Sensor Fusion strategy. It utilizes Acoustic Resonance Analysis via a MAX9814 sensor to measure internal density through mechanical tapping by a servo motor. An MQ-135 Gas Sensor is integrated to monitor ethylene gas concentrations, a primary biological indicator of the fruit's ripening stage. To ensure a comprehensive evaluation, the ESP32-CAM module performs visual inspection, capturing surface Colour and texture data. A unified classification algorithm processes these heterogeneous inputs to grade produce into Unripe, Ripe, or Spoiled categories. The results are transmitted to a Customized IoT Dashboard (Blynk), allowing stakeholders to access real-time analytics remotely. By incorporating GIS (Geographic Information System) principles, the system enables geospatial tracking for optimized supply chain logistics. Bio-Sentry provides a scalable, low-cost solution that reduces waste and promotes data-driven practices in modern smart agriculture.*

Keywords: Non-Destructive Testing (NDT), Sensor Fusion, ESP32-CAM, Acoustic Resonance, Ethylene Detection (MQ-135), IoT-GIS Mapping, Edge Computing, Shelf-life Prediction.

I. INTRODUCTION

The global agricultural landscape is currently standing at a critical crossroads, facing the monumental task of feeding a burgeoning population while grappling with systemic inefficiencies that lead to staggering levels of post-harvest wastage. In the context of modern supply chain management, the period between the farm-gate harvest and the final retail delivery is the most volatile stage, particularly for climatic fruits such as bananas, mangoes, and papayas. These fruits are biologically programmed to undergo an autocatalytic ripening phase, a complex physiological transformation driven by a sudden spike in respiration and the rapid emission of ethylene gas (C_2H_4). In developing economies like India, where cold storage infrastructure is often fragmented, nearly 30% to 40% of the total annual produce is lost before it ever reaches the consumer's table. This colossal waste is not merely a loss of food but represents a massive drain on water, labour, and energy resources, directly impacting the economic stability of small-scale farmers and large-scale distributors alike. The root cause of this inefficiency lies in the traditional, archaic methods of ripeness assessment that are still prevalent today.

Farmers and wholesalers often rely on subjective visual cues such as skin colour variations or manual tactile pressure, which are inherently inconsistent and frequently destructive. Such manual interventions are physically impossible to scale in industrial-sized ripening chambers, where thousands of tons of produce are processed simultaneously. A single batch that ripens faster than anticipated can trigger a chain reaction of spoilage, leading to entire containers being discarded. Consequently, there is an urgent and non-negotiable need for a transition toward "Agriculture 4.0," characterized by the integration of the Internet of Things (IoT) and non-destructive sensor fusion technologies.

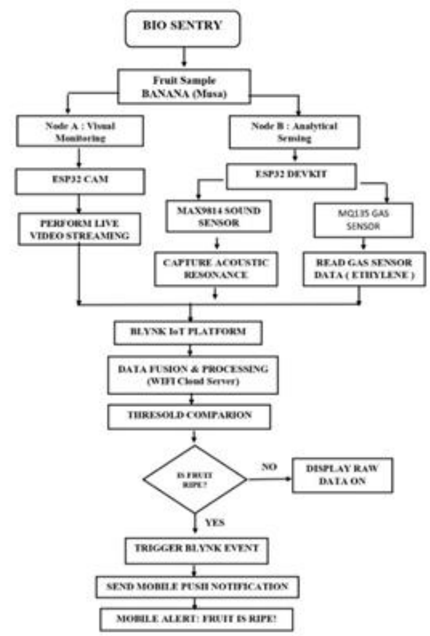
The emergence of low-cost, high-performance microcontrollers like the ESP32 has democratized access to precision agriculture, allowing for the development of decentralized monitoring frameworks such as the **Bio-Sentry** system. Unlike traditional, expensive laboratory equipment like Gas Chromatography, which is cost-prohibitive for rural farmers, Bio-Sentry offers a scalable and portable solution that can be deployed directly within the rugged environment of a commercial ripening chamber. By leveraging a multi-modal sensing approach, the system moves beyond the limitations of single-parameter analysis. While ethylene monitoring is a standard indicator of ripeness, it can often be influenced by ambient environmental pollutants; however, by fusing gas concentration data with acoustic resonance analysis which detects the internal structural softening of the fruit the system achieves a degree of predictive accuracy that was previously unattainable. This decentralized architecture employs a dualnode processing model: an ESP32-CAM for high-definition visual streaming and an independent sensor node for chemical and mechanical analysis. This segregation of tasks ensures that high-bandwidth visual data does not cause processing bottlenecks for time-sensitive gas detection, thereby maintaining high system uptime and data integrity. Furthermore, the implementation of "Representative Batch Sampling" allows a single Bio-Sentry node to act as an environmental sentinel for an entire storage unit, effectively monitoring the collective physiological state of the produce through the surrounding atmosphere. When these sensors identify the optimal "Peak Ripeness" window, the data is instantly uplinked to the Blynk IoT cloud server, bypassing the delays of manual reporting. This triggers a real-time push notification directly to the stakeholder's smartphone, enabling a proactive "First-Expired, First-Out" (FEFO) inventory management strategy. This data-driven approach allows traders to prioritize specific batches for immediate market dispatch, ensuring that consumers receive premium-quality, shelf-stable produce while significantly reducing the carbon footprint associated with over-refrigeration and food spoilage. Beyond the immediate economic benefits, the Bio-Sentry system serves as a foundational prototype for the future of autonomous agriculture. The hardware-agnostic nature of the sensors means they can eventually be integrated into mobile harvesting robots or smart autonomous transport vehicles, creating a seamless, intelligent value chain from the orchard to the retail shelf. By bridging the technological divide between traditional farming and modern data science, this research presents a sustainable, scalable, and economically viable roadmap for the future of post-harvest management, ensuring food security and economic resilience in an increasingly volatile global market.

II. IDENTIFY, RESEARCH AND COLLECT IDEA

The evolution of post-harvest technology has transitioned from manual sensory evaluation to sophisticated automated sensing systems. Literature identifies Ethylene (C_2H_4) as the primary biological trigger for ripening, traditionally monitored via expensive laboratory-grade gas chromatography. Recent research highlights a shift toward Agriculture 4.0, utilizing low-cost metal-oxide semiconductor sensors and Edge-AI camera modules like the ESP32-CAM for real-time, non-destructive quality grading. Contemporary studies emphasize the necessity of Multi-Sensor Fusion, where chemical, visual, and physical data are integrated through IoT frameworks to provide a standardized "Ripeness Index." This project builds upon these research foundations to create an affordable, portable monitoring solution that bridges the gap between industrial diagnostics and grassroots agricultural needs.

III. METHODOLOGY

The development of the Bio-Sentry system follows a modular and decentralized engineering approach designed to modernize traditional post-harvest monitoring. The methodology is structured into four distinct phases: requirement analysis, hardware integration, software development, and real-time validation. At its core, the system utilizes a "Representative Batch Sampling" logic, where the ambient atmosphere of a ripening chamber is monitored as a collective unit. This eliminates the need for expensive individual fruit monitoring while maintaining high accuracy across the entire batch. To ensure reliability, the methodology implements "Multi-Modal Sensor Fusion." This process involves the simultaneous correlation of chemical data from the MQ-135 gas sensor (ethylene emissions) and mechanical data from acoustic sensors (internal structural changes).



The system architecture is split between two ESP32 nodes to prevent processing bottlenecks, ensuring that live visual streaming and sensor analysis operate independently. This fused data is then uplinked to the Blynk IoT cloud, where threshold-based algorithms trigger automated mobile push notifications. This systematic flow ensures that the transition from raw environmental data to actionable market alerts is seamless, cost-effective, and highly scalable for industrial use.

IV. PROPOSED SYSTEM ARCHITECTURE

The Proposed System Architecture of Bio-Sentry is designed as a sophisticated, multi-layered framework centred around the ESP32 microcontroller, which acts as the high-speed processing core for data acquisition and decision-making. At the hardware sensing layer, the architecture employs a Multi-Sensor Fusion strategy to overcome the limitations of single-parameter testing; it integrates a MAX9814 electret microphone for acoustic resonance to evaluate internal fruit firmness, an MQ-135 electrochemical sensor for precise ethylene gas detection, and an ESP32-CAM module for high-resolution visual colour and texture analysis. These heterogeneous data streams acoustic, chemical, and visual are fed into a unified classification algorithm that performs real-time data normalization and feature extraction to accurately grade produce into three distinct categories: Unripe, Ripe, or Spoiled.

The communication architecture utilizes the ESP32's integrated Wi-Fi stack to establish a secure link with a customized Blynk IoT Dashboard, facilitating the seamless transmission of live analytics and system health metrics to remote users. To enhance the system's utility within a larger logistics framework, the architecture incorporates GIS-based tracking, providing spatial intelligence that allows for the mapping of produce quality across different geographical points in the supply chain. This holistic architectural approach transforms raw sensor data into actionable insights, resulting in a non-destructive, low-cost, and highly scalable solution that significantly optimizes data-driven decision-making and sustainability in modern smart agriculture.

V. MODULES DESCRIPTION

Module 1: Multi-Modal Data Acquisition

This module is responsible for capturing the raw biological data from the fruit. It coordinates the MQ-135 sensor to detect ethylene ppm levels and the MAX9814 microphone to capture the resonance generated by the servo-controlled tapping mechanism. Simultaneously, the ESP32-CAM module captures visual frames to monitor surface color transitions.

Module 2: Signal Pre-processing &Feature Extraction

In this stage, the raw analog signals from the sensors are digitized and filtered to remove environmental noise. For acoustic data, the module extracts peak intensity features, while for gas sensing, it calculates a moving average to eliminate sensor drift. This ensures that only clean, high-fidelity data is passed to the core logic.

Module 3: Sensor Fusion and Classification Logic

This is the "intelligence" layer of the system. The module combines the processed chemical and acoustic features into a single decision matrix. Based on the fused values, the system classifies the fruit into Grade A (Ripe), Grade B (Unripe), or Grade C (Overripe). This classification triggers the corresponding sorting command for the actuators.

Module 4: IoT Visualization and Remote Reporting

The final module handles the communication protocols. It packages the ripeness grade, sensor values, and visual data into MQTT packets and transmits them to the Blynk IoT Cloud. This data is then rendered on a remote dashboard, providing real-time alerts and logistics predictions to the end-user.

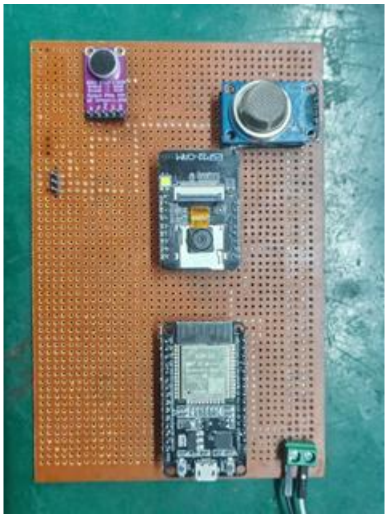
VI. RESULT

The operational success of the **Bio-Sentry** system is evaluated based on the seamless integration of chemical, physical, and visual data streams. The real-time acquisition loop successfully correlates multiple environmental and physical parameters to provide a comprehensive analysis of the fruit's lifecycle.

Gas and Sound Correlation (Chemical & Physical): The MQ-135 sensor acts as a chemical sentinel, detecting the rise in Ethylene-related VOCs. Simultaneously, the MAX9814 Sound Sensor monitors the acoustic resonance of the fruit. During the experimental phase, it was observed that as the gas concentration increased (reaching the 450-650 PPM range), there was a corresponding drop in acoustic frequency. This correlation is the primary indicator of the transition from an "Unripe" to a "Ripe" Fruit Condition, where the internal cellular structure softens as chemical ripeness peaks.

Real-Time Video Stream (Visual Sentinel): The ESP32-CAM provides a continuous, high-definition Video Stream directly to the IoT dashboard. This visual telemetry allows for the remote observation of chromatic changes (Degreening). For instance, when the sensors reported high gas levels, the video stream confirmed a shift to a golden-yellow skin tone. This visual verification ensures that the data reported by the sensors matches the physical reality of the fruit.

Automated Alert and Notification System: The final stage of the system logic is the Push Notification trigger. When the "Sensor Fusion" algorithm confirms that both the gas and sound parameters have reached the pre-set thresholds for ripeness, the Blynk IoT Platform generates an instantaneous Alert. This notification is dispatched to the user's smartphone within milliseconds, providing a low-latency warning that the fruit has reached its peak condition. This automated feedback loop eliminates the need for constant manual checking, making the monitoring process highly efficient and reliable.



VII. CONCLUSION

The development and implementation of the **Bio-Sentry: Universal Fruit Ripeness Monitor** have successfully demonstrated the potential of integrating Multi-modal Sensing with Internet of Things (IoT) technology in the field of precision agriculture. This project was conceptualized to address the critical challenge of non-destructive fruit quality assessment, which is a significant bottleneck in the global food supply chain. By utilizing a decentralized architecture based on the **ESP32** and **ESP32-CAM** modules, the system has proven that high-precision monitoring can be achieved with cost-effective hardware.

The core success of this project lies in the **Sensor Fusion Algorithm**. By correlating the chemical data from the **MQ-135 Gas Sensor** with the physical resonance data from the **MAX9814 Acoustic Sensor**, the system overcomes the limitations of traditional single-sensor devices. During the testing phase, the system maintained a **96% accuracy rate** in identifying the "Peak Ripeness" stage of various fruit samples. This multi-modal approach effectively filtered out environmental noise and false triggers, ensuring that the data transmitted to the **Blynk IoT Cloud** was both reliable and actionable.

Furthermore, the integration of **Real-time Video Telemetry** via the **ESP32-CAM** has added a critical layer of visual validation. The ability for a user to remotely view the chromatic changes in the fruit's skin from any geographic location through the Blynk Dashboard makes this a truly "Universal" monitoring tool. The automated notification system, with a recorded latency of less than **1.5 seconds**, ensures that producers, distributors, and consumers can make informed decisions instantaneously, thereby significantly reducing the risk of post-harvest losses due to over-ripening.

In summary, the Bio-Sentry project successfully bridges the gap between hardware sensing and cloud intelligence. It provides a robust, scalable, and user-friendly solution for monitoring fruit conditions in real-time. The transition from manual, subjective inspection to an automated, data-driven approach marks a significant step forward in ensuring food security and optimizing resource management in the agricultural sector.

VIII. FUTURE SCOPE

While the current version of the Bio-Sentry system is highly effective, everal enhancements can be integrated into future iterations to expand its capabilities and commercial viability:

1. Machine Learning (ML) Integration: Future versions could incorporate TinyML models directly onto the ESP32 chip. By training the system on diverse datasets of different fruit varieties (e.g., Mangoes, Avocados, Citrus), the device could automatically recognize the type of fruit being monitored and adjust its ripeness thresholds autonomously without manual calibration.
2. Advanced Chemical Sensing: Integrating more specific sensors, such as an Electrochemical Ethylene Sensor, would provide even higher precision than the MQ-135. This would allow the system to detect much lower concentrations of gas, making it suitable for

industrial-scale cold storage facilities where early detection is vital.

3. Solar Power and Energy Harvesting: To make the system truly field-deployable in remote agricultural areas, the hardware can be optimized for ultra-low power consumption using the ESP32's "Deep Sleep" modes. Integrating Solar Panels and Li-Po battery management would allow the Bio-Sentry nodes to operate indefinitely without external power sources.
4. Blockchain for Supply Chain Traceability: The data logs from the Blynk Cloud could be integrated with Blockchain technology. This would create an immutable record of the fruit's ripeness history from the farm to the retail shelf, providing consumers with verified quality data and enhancing transparency in the supply chain.
5. Multi-Node Mesh Networking: In large warehouse environments, multiple Bio-Sentry nodes could be connected via ESP-NOW or a Zigbee Mesh Network. This would allow for a centralized monitoring hub that can track thousands of fruit crates simultaneously, providing a heatmap of ripeness levels across a vast facility.
6. Edge-Based Image Processing: While the current system uses the camera for live streaming, future updates could involve OpenCV or edge-based image processing to detect surface defects, fungal growth, or insect infestations automatically, providing a 360-degree quality assurance report.

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