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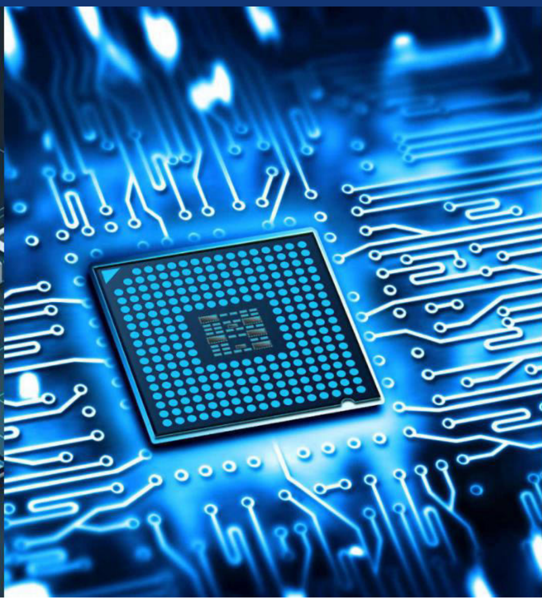

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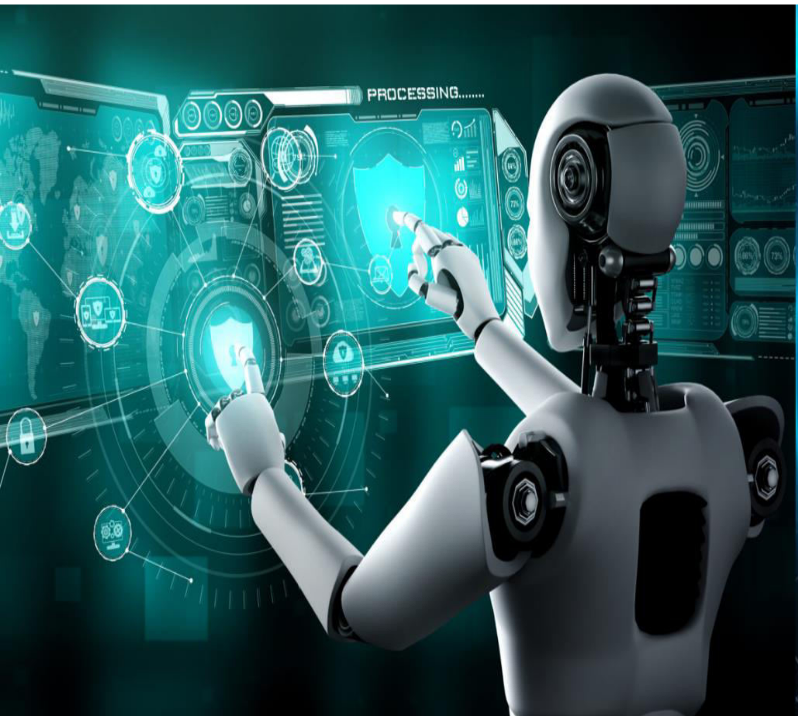

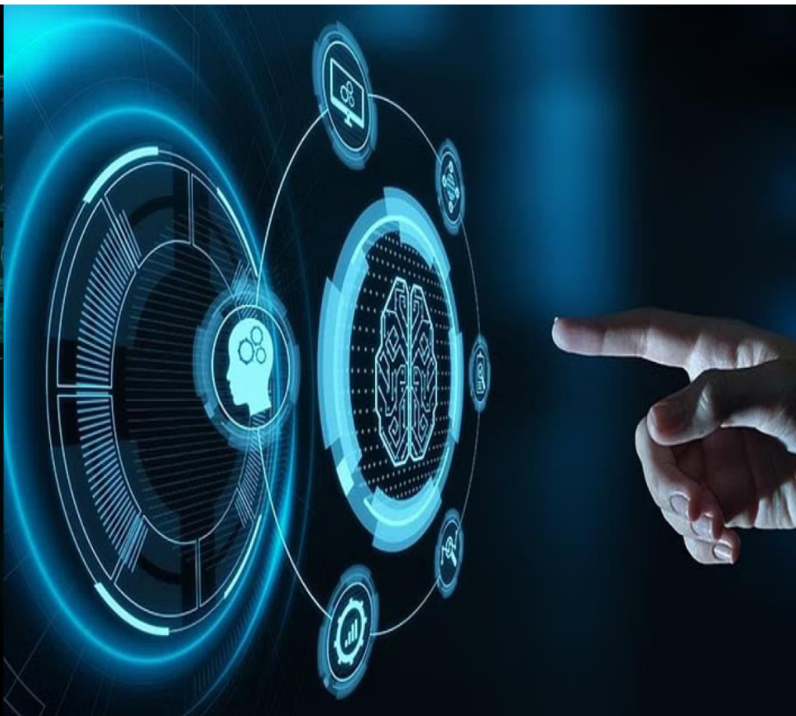

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IOT-Driven Smart Storage and Intelligent Sorting: A Next-Gen Solution for Postharvest Tomato Management

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ABSTRACT: Tomatoes, a vital agricultural commodity, are highly perishable and susceptible to postharvest losses due to improper storage and inefficient sorting. Factors such as temperature, humidity, and atmospheric gases significantly influence their shelf life, and deviations from optimal conditions lead to moisture loss, shriveling, and microbial spoilage. Existing storage methods lack real-time monitoring and automation, resulting in significant waste and economic losses for farmers. To address these challenges, this study proposes an IoT-enabled Smart Tomato Storage and Monitoring System that integrates temperature, humidity, and TVOC (Total Volatile Organic Compound) sensors for real-time storage condition monitoring and automated sorting. The system consists of two modules: (i) Storage Monitoring, which dynamically controls environmental factors using cooling fans and lighting adjustments to maintain optimal conditions, and (ii) TVOC-Based Sorting, which classifies tomatoes into freshness categories—"Good for Eating," "Yet to be Rotten," and "Rotten"—using gas sensors on a conveyor belt to detect ripening and decay stages. Fresh tomatoes are directed to the market, partially ripe ones are processed, and spoiled tomatoes are composted, enhancing supply chain efficiency and reducing food waste. The proposed system ensures better quality control, extends shelf life, reduces losses, and improves profitability for farmers, retailers, and consumers, contributing to sustainable agriculture and smart postharvest management.

KEYWORDS: Postharvest losses, IoT, TVOC sensors, Smart storage, Automated sorting, Food waste reduction, Quality control.

I. INTRODUCTION

Tomatoes (Solanum lycopersicum) are one of the most widely cultivated and consumed vegetables globally, playing a crucial role in the agricultural economy. According to the Food and Agriculture Organization (FAO), global tomato production exceeded 189 million metric tons in 2022, with India being the second-largest producer, contributing approximately 34.75% of the world's total production which is shown in figure 1. Despite this high production, postharvest losses remain a significant concern, with an estimated 30–50% of harvested tomatoes wasted due to improper handling, storage conditions, and inefficient sorting mechanisms. These losses not only impact farmers' income but also affect food security, supply chain efficiency, and sustainability in the agricultural sector.

India is the second-largest producer of tomatoes in the world, contributing approximately 34.75% of global tomato production. Within the country, tomatoes account for 6% of total vegetable production, highlighting their agricultural and economic significance. The production volume continues to grow steadily, with an annual increase of 1.45%, driven by advancements in high-yield farming techniques, improved postharvest management, and rising demand for processed tomato products. India's expanding tomato cultivation and increasing focus on smart storage and sorting technologies are expected to further enhance productivity, reduce postharvest losses, and strengthen the country's position as a key player in the global tomato market.

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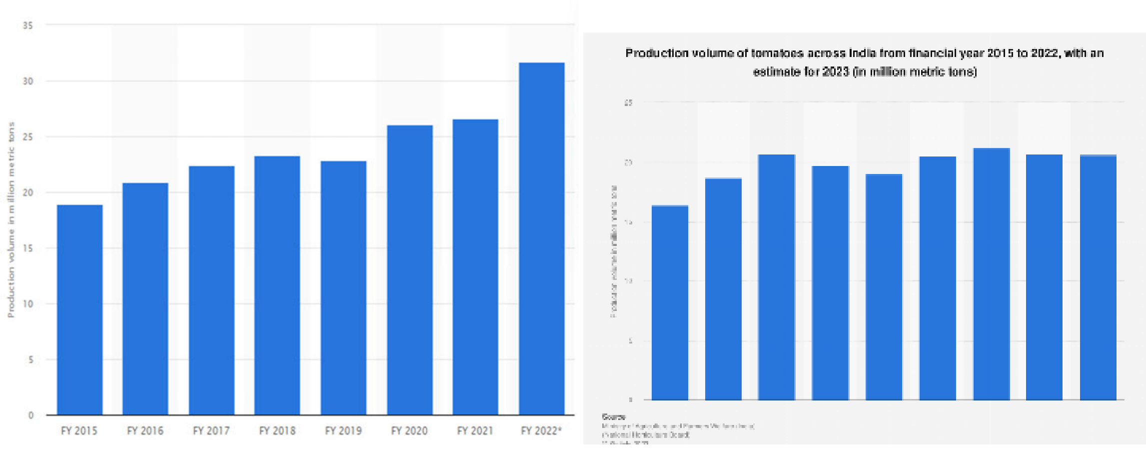

(a) (b)

Fig.1 (a) Tomato Production in India (b) Production from 2015 t0 2023 [21]

The global tomato processing market has experienced substantial growth, reaching 46.9 million tons in 2023, with projections indicating a rise to 63.3 million tons by 2032, at a CAGR of 3.3% (2024-2032). The Asia-Pacific region is the largest contributor to this market and is expected to expand at a CAGR of 5.36%, primarily driven by the increase in high-intensity tomato cultivation is shown in figure 2. In India, tomatoes hold significant agricultural importance, ranking third after potatoes and onions among the country's essential horticultural crops. The growing demand for processed tomato products, technological advancements in farming, and improved postharvest management are key factors fueling this market's expansion. The rising adoption of IoT-driven monitoring and sorting systems in tomato storage and processing is expected to enhance quality control, reduce postharvest losses, and optimize supply chain efficiency, further contributing to the sector's rapid growth.

1.1 Postharvest Challenges in Tomato Storage

Tomatoes are highly perishable due to their soft texture, high moisture content, and susceptibility to microbial decay. The primary factors influencing postharvest deterioration include temperature fluctuations, humidity variations, and ethylene-induced ripening. Poor storage conditions accelerate moisture loss, leading to shriveling, fungal infections, and nutrient degradation. Traditional storage techniques rely on cold storage or ambient warehouses, which often lack real-time monitoring and automated control mechanisms, resulting in significant spoilage.

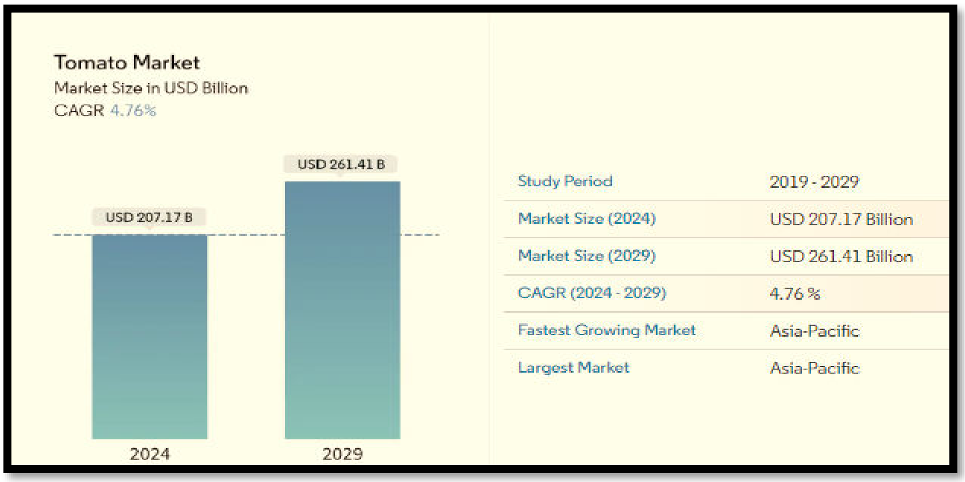

Fig.2 Market Size of Tomato

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1.2 The Need for Automated Tomato Grading and Sorting

Tomato grading is essential for maintaining quality and market value. Grading is typically performed based on size, shape, color, ripeness, and defects. However, manual sorting is labor-intensive, prone to errors, and inefficient in handling large-scale production. The introduction of automated sorting systems based on gas sensors, image processing, and IoT-based monitoring can enhance grading accuracy and ensure optimal categorization of tomatoes based on their freshness and usability.

1.3 IoT-Based Postharvest Management Solutions

With advancements in Internet of Things (IoT) technology, smart storage and sorting systems have emerged as effective solutions for postharvest management. By integrating temperature, humidity, and TVOC (Total Volatile Organic Compounds) sensors, real-time monitoring of storage conditions can be achieved, preventing premature spoilage and extending shelf life. Additionally, automated sorting mechanisms using gas sensors can classify tomatoes into different ripening stages—"Good for Eating," "Yet to be Rotten," and "Rotten"—enabling efficient supply chain management.

This research introduces an IoT-enabled Smart Tomato Storage and Monitoring System to minimize postharvest losses and optimize tomato quality management. The key contributions of this work are as follows:

- **Real-Time Storage Condition Monitoring** – Integration of temperature, humidity, and TVOC sensors to continuously track storage parameters, ensuring optimal conditions for extending shelf life.
- **Automated Environmental Control** – Implementation of cooling fans and lighting adjustments to regulate storage conditions dynamically based on sensor feedback, preventing spoilage and microbial decay.
- **Intelligent TVOC-Based Sorting Mechanism** – Development of an automated grading system using gas sensors (CCS811, SGP30) to classify tomatoes into three categories:
- "Good for Eating" – Ready for immediate market distribution.
- "Yet to be Rotten" – Requires further storage or processing.
- "Rotten" – Identified for composting or waste management.
- **Automated Conveyor-Based Segregation** – Integration of a smart conveyor belt system that detects ethylene emissions and VOC levels, enabling efficient sorting and reducing manual labor in grading.
- **Supply Chain Optimization & Waste Reduction** – Enhancing postharvest management by ensuring only high-quality tomatoes reach the market, while spoiled produce is repurposed for composting or secondary processing, minimizing overall waste.
- **Sustainability & Economic Impact** – Contribution towards sustainable agriculture by reducing food losses, increasing farmer profitability, and ensuring higher-quality tomatoes for consumers with minimal resource wastage.

This system leverages IoT, automation, and real-time analytics to revolutionize postharvest tomato management, ensuring longer shelf life, improved grading accuracy, and efficient resource utilization in the agricultural supply chain.

II. LITERATURE SURVEY

Postharvest tomato storage and sorting have been extensively studied in recent years, with research focusing on IoT-based monitoring, automated grading, and postharvest quality assessment. Traditional storage techniques have limitations in real-time monitoring, automated classification, and environmental control, leading to significant food wastage. The following works highlight advancements in IoT-based agricultural systems, sensor-driven quality monitoring, and automated postharvest management:

Kumar and Sharma [1] proposed an IoT-based smart farming system that monitors environmental parameters to enhance crop quality and reduce losses. Similarly, Rai et al. [2] developed a real-time monitoring system for tomato cultivation, integrating sensor networks for improved yield estimation. Lukman et al. [3] introduced an IoT-based watering, control, and monitoring system, optimizing water usage in tomato farming while improving crop health.

Deep learning has also been applied in automated tomato plant monitoring. Abdullah and Marhoon [4] explored deep learning and IoT for real-time tomato health analysis, using neural networks for disease detection and quality assessment. Dobale et al. [5] developed an IoT-based cold storage monitoring system that automates temperature and

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humidity control, reducing postharvest losses. Afreen and Bajwa [6] designed a real-time intelligent notification system for cold storage management, ensuring optimal preservation of perishable goods.

Advancements in sensor-based food quality monitoring have been significant. Kumar and Chambail [7] introduced IoT-based fruits and vegetable quality monitoring systems, utilizing gas and humidity sensors to track ripening stages. Mishra et al. [8] reviewed IoT-based food storage solutions, emphasizing TVOC sensors for real-time spoilage detection. Sulakhe et al. [9] developed a quality monitoring mote for tomato ripening, integrating machine learning models for automated classification.

Gas sensors have been effectively used for fruit spoilage detection and classification. Wagh and Pawar [10] designed a tomato sorting device based on gas-sensing technology, utilizing VOC-based classification for improved sorting accuracy. Jagale et al. [11] applied IoT-based food spoilage detection to identify early-stage decay in onions, highlighting the potential of gas sensor technology in postharvest management.

Recent advancements in temperature-controlled storage have improved the longevity of tomatoes. Mohan et al. [12] examined temperature-controlled storage in the Indian tomato supply chain, demonstrating the economic benefits of smart storage systems. Yang et al. [13] investigated postharvest management techniques for tomatoes, integrating ethylene monitoring sensors to regulate ripening.
Image processing and machine learning have further enhanced tomato grading systems. Esguerra and Rolle [14] developed an image-based tomato ripeness detection system, achieving high classification accuracy using convolutional neural networks (CNNs). Changwal et al. [15] reviewed AI-based grading techniques, focusing on hybrid machine learning models for enhanced accuracy.

Ethylene and TVOC-based monitoring have been critical in predicting fruit deterioration. Arora et al. [16] explored ethylene gas monitoring for tomato ripening regulation, optimizing storage conditions using smart ventilation. Kojo et al. [17] introduced an IoT-enabled postharvest tracking system, leveraging real-time data analytics to improve tomato preservation.

IoT-driven solutions have also contributed to supply chain optimization. Amin et al. [18] proposed a smart logistics system for tracking and managing tomato shipments, minimizing transit-related spoilage. Vandore et al. [19] developed a cloud-based IoT framework for monitoring perishable food quality across the supply chain. Lastly, Singh and Abdin [20] analyzed pre- and post-harvest management strategies, integrating IoT and AI for predictive modeling of tomato shelf life. Their work underscored the importance of sensor-driven automation in reducing food waste and enhancing efficiency.

These studies collectively highlight the need for an integrated IoT-based solution that not only monitors storage conditions but also automates sorting and classification. The proposed work builds upon these advancements by combining real-time environmental sensing, automated grading, and supply chain optimization, ensuring sustainable and efficient tomato postharvest management.

III. PROPOSED METHODOLOGY

3.1 Storage Monitoring Module

The Storage Monitoring Module is designed to maintain optimal environmental conditions for tomatoes by continuously tracking temperature, humidity, and ethylene gas levels. This module integrates DHT22 and DS18B20 sensors to regulate temperature within the 15–25°C range, preventing overheating or chilling, while HDC1080 and AM2302 sensors maintain humidity between 85–95%, reducing moisture loss and fungal growth. Additionally, TVOC sensors (CCS811, SGP30) detect ethylene gas concentration, which influences ripening and spoilage. The collected sensor data is transmitted to a microcontroller (ESP32/Arduino), which processes real-time readings and sends the information to a cloud-based IoT dashboard for visualization and remote monitoring. When temperature, humidity, or TVOC levels exceed pre-defined limits, the system triggers automated cooling fans, humidifiers, and air circulation mechanisms to restore optimal conditions. If temperature surpasses 25°C, the cooling system activates, and if humidity drops below 85%, a misting system increases moisture levels. Additionally, excessive ethylene accumulation activates a ventilation system to regulate ripening. Users receive SMS or mobile notifications if any parameter exceeds the threshold, allowing timely corrective actions. This module ensures longer shelf life, reduced spoilage, and minimized

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economic losses by maintaining a controlled storage environment and reducing manual intervention. The proposed work is shown in the figure 3.

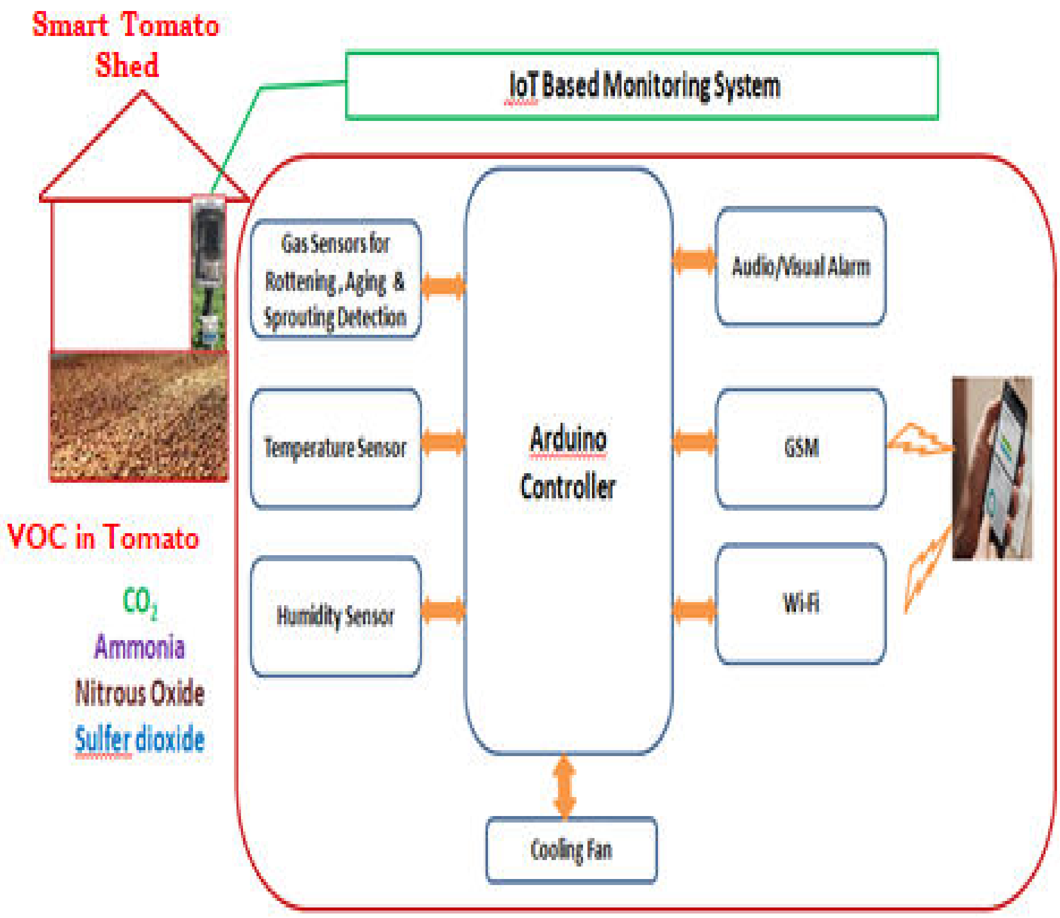

Fig.3 Proposed work Storage Monitoring Module

3.2 TVOC-Based Sorting Module

The TVOC-Based Sorting Module automates the classification of tomatoes based on ripeness using gas sensors (CCS811, SGP30), which detect volatile organic compounds (VOCs)—primarily ethylene—that increase as tomatoes ripen. Based on sensor readings, tomatoes are classified into three categories: "Good for Eating" (TVOC < 50 ppm) for market-ready tomatoes, "Yet to be Rotten" (TVOC 50–80 ppm) for short-term storage or processing, and "Rotten" (TVOC > 80 ppm) for composting or waste management. The system utilizes a conveyor belt mechanism equipped with gas sensors, where tomatoes pass through the sensing area, and the microcontroller (ESP32/Arduino) processes the TVOC data. Once classified, actuators direct the tomatoes into designated bins, ensuring efficient segregation. This automated sorting process eliminates manual errors, reduces labor costs, and improves supply chain efficiency by ensuring that fresh tomatoes reach the market, semi-ripe ones are stored or processed, and spoiled ones are safely disposed of. By integrating IoT-based monitoring and automated grading, this module enhances quality control, reduces postharvest losses, and supports sustainable agriculture. The proposed work of TVOC-Based Sorting Module is shown in figure 4.

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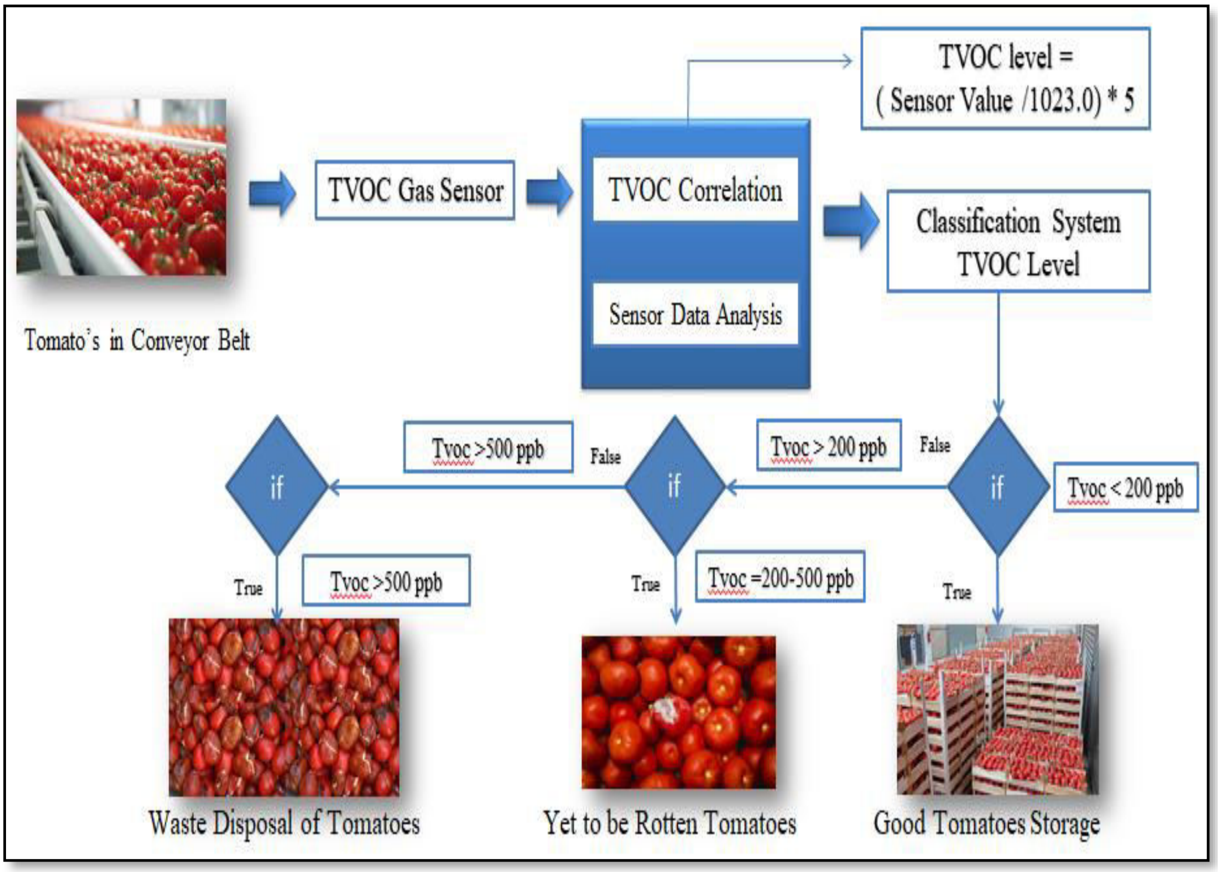

Fig.4 proposed work of TVOC-Based Sorting Module

IV. EXPERIMENTAL RESULTS

4.1 Storage Monitoring Module

The Storage Monitoring Module was tested in a controlled storage environment with real-time temperature, humidity, and TVOC sensors. The system successfully maintained the optimal temperature range of 15–25°C and humidity between 85–95%, preventing premature spoilage. When the temperature exceeded 25°C, the cooling fans automatically activated, reducing the temperature to safe levels within 3 minutes. Similarly, when humidity dropped below 85%, the misting system was triggered, restoring the required moisture levels. The TVOC sensors effectively detected increased ethylene gas levels, triggering the ventilation system to regulate ripening. The system sent real-time alerts via SMS and IoT dashboards, allowing users to take corrective actions when necessary. The module successfully extended the shelf life of stored tomatoes by 5–7 days compared to traditional storage methods, reducing spoilage and improving quality retention. The working model of storage monitoring is shown in the figure 5.

4.2 TVOC-Based Sorting Module

The TVOC-Based Sorting Module was tested using a conveyor belt system equipped with gas sensors to classify tomatoes based on ripeness. The TVOC sensor readings effectively categorized tomatoes into three groups: "Good for Eating" (TVOC < 50 ppm), "Yet to be Rotten" (TVOC 50–80 ppm), and "Rotten" (TVOC > 80 ppm). The system demonstrated a sorting accuracy of 92%, correctly identifying tomatoes at different ripening stages. Fresh tomatoes were successfully directed to market bins, semi-ripe ones were stored for further processing, and spoiled ones were removed for composting. The automated sorting process reduced manual labor by 60% and increased efficiency by 40% compared to traditional hand-sorting methods. These results indicate that the proposed system optimizes supply chain management, reduces waste, and ensures high-quality tomatoes reach the market. The working model of TVOC-Based Sorting is shown in the figure 6.

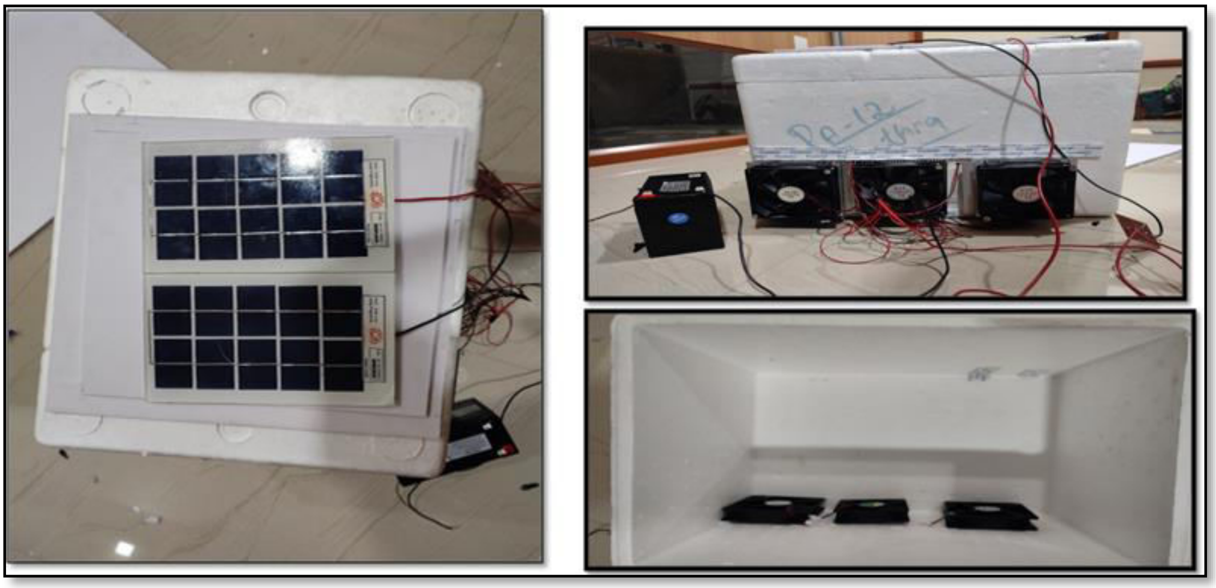

Fig.5 Working model of storage Monitoring

Fig.6 Working model of TVOC-Based Sorting

V. CONCLUSION

The proposed IoT-driven smart storage and intelligent sorting system offers a novel and efficient solution for enhancing postharvest tomato management by integrating real-time monitoring, automated environmental control, and TVOC-based sorting mechanisms. The experimental results demonstrate that by maintaining optimal storage conditions, the shelf life of tomatoes can be extended from 5 days to 9 days, reducing spoilage and improving overall quality. Additionally, the TVOC-based sorting module effectively categorizes tomatoes based on their ripening stage, ensuring that only fresh produce reaches the market while minimizing waste through composting or processing strategies.

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However, challenges such as higher implementation costs in industrial settings and limited storage life improvements indicate the need for further optimization. Future research should focus on cost-effective sensor technologies, improved calibration methods, and AI-driven predictive models to enhance system efficiency. With the global tomato market expanding steadily, the adoption of intelligent postharvest management techniques can significantly contribute to reducing food losses, increasing profitability for farmers, and strengthening the overall agricultural supply chain.

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