IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Nutri Fusion X: A Smart Non-Destructive Multi-Sensor System For Fruit And Vegetable Quality Inspection System

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Abstract: The quality assessment of fruits and vegetables is essential for ensuring food safety and reducing post-harvest losses. Traditional methods such as visual inspection and laboratory testing have several limitations. Visual inspection can only evaluate the external appearance and cannot detect internal spoilage, hidden damage, or contamination, while laboratory testing is costly, destructive, and time-consuming. This paper presents Nutri Fusion X, a smart non-destructive fruit and vegetable quality inspection system based on multi-sensor technology and IoT. The system integrates gas, optical, UV, NIR sensors, ultrasonic sensing, and image analysis to evaluate fruit freshness, ripeness, spoilage, pesticide contamination, and internal damage (e.g., bruises or soft spots) without cutting the fruit. An ESP32 microcontroller processes sensor data and transmits results in real time to a mobile application via Wi-Fi. The application displays quality indicators, including freshness percentage, ripeness level, spoilage risk, and safety alerts. The proposed system is portable, low-cost, and user-friendly, making it suitable for farmers, vendors, and the food industry while helping to reduce food waste and improve food quality monitoring.

I. INTRODUCTION

Agriculture plays a vital role in supporting global food supply and economic development. Fruits and vegetables are essential agricultural products that provide nutrients, including vitamins, minerals, antioxidants, and dietary fiber, essential for human health. However, maintaining the quality and safety of these products throughout harvesting, transportation, storage, and distribution remains a major challenge in the agricultural supply chain.

One of the major issues faced in agriculture is post-harvest loss, which significantly affects farmers and food availability. According to reports by the Food and Agriculture Organization, approximately 30–40% of fruits and vegetables produced worldwide are wasted each year due to improper quality assessment, poor storage conditions, and damage during transportation. Such losses not only reduce farmers' income but also contribute to global food security concerns.

In countries such as India, large quantities of fruits and vegetables are rejected in markets because of spoilage, contamination, or poor quality. Many of these losses could be minimized if efficient and reliable quality inspection systems were available directly at the farm level or market level. Currently, fruit quality is primarily evaluated through visual inspection, in which farmers and vendors observe the color, size, shape, and texture of fruits to estimate freshness and ripeness. Although this method is simple and inexpensive, it has several limitations because it only evaluates the external appearance of the fruit.

Visual inspection cannot effectively detect internal quality problems such as internal bruising, hidden spoilage, pesticide contamination, or internal moisture loss. These issues often remain undetected until the fruit is cut open or consumed, which can lead to food wastage and potential health risks. Another commonly used approach for accurate quality analysis is laboratory-based testing. These methods involve advanced chemical analysis techniques such as chromatography, spectroscopy, and other analytical tools to detect chemical residues or internal changes. While these laboratory techniques provide highly accurate results, they are expensive, time-consuming, and destructive, meaning the fruit sample is damaged during testing. Furthermore, laboratory facilities are usually located in research institutions or large cities, making them inaccessible to small farmers and local vendors.

This research proposes NutriFusion X, a smart and portable fruit and vegetable quality inspection system that uses multi-sensor technology to evaluate both internal and external quality parameters. The system integrates gas sensors, optical sensors, ultrasonic sensing, ultraviolet (UV) sensing, near-infrared (NIR) sensing, and image processing techniques to analyze freshness, ripeness, spoilage, and possible pesticide contamination without cutting or damaging the fruit. By combining multiple sensing techniques with IoT communication, the system provides rapid and reliable quality assessment that can assist farmers, vendors, and the food industry in making better decisions.

The major objectives of the proposed system are:

• To develop a non-destructive fruit and vegetable quality inspection system.
• To integrate multiple sensors for accurate quality detection.
• To detect internal damage and spoilage without cutting the fruit.
• To provide real-time results using IoT-based communication.
• To design a portable and affordable system suitable for farmers and vendors.
• To help reduce food wastage through better quality monitoring.

The proposed system has the potential to significantly improve traditional quality inspection methods and support the development of smart agriculture technologies that enhance food safety, reduce post-harvest losses, and improve decision-making in agricultural markets.

II. REVIEW OF LITERATURE

Research on fruit quality evaluation has evolved significantly with the advancement of sensing and imaging technologies. Early studies mainly focused on computer vision–based systems that analyze external characteristics of fruits such as color, texture, size, and shape. These systems use cameras along with image processing algorithms to classify and grade fruits automatically. Researchers like José Blasco developed machine vision techniques for grading citrus fruits based on surface color distribution and visible defects. Although computer vision methods provide fast and non-contact inspection, they are mainly limited to surface-level analysis and cannot accurately identify internal damage or chemical contamination inside fruits.

Another widely explored approach for monitoring fruit quality is gas sensing technology. During the ripening and spoilage stages, fruits naturally release gases such as ethylene. The concentration of ethylene increases as fruits mature and eventually begin to decay. Gas sensors, particularly metal oxide semiconductor sensors, can measure the level of these gases and help determine the ripening stage of fruits during storage and transportation. Many studies have used gas sensing systems to monitor fruit freshness in warehouses and storage facilities. However, gas sensing alone cannot provide complete information about internal structure or physical damage.

Near-infrared spectroscopy (NIR) has also been investigated as a reliable technique for analyzing internal fruit properties. NIR sensors work by measuring the absorption and reflection of infrared light within the fruit tissue, which helps estimate parameters such as moisture content, sugar level, and internal defects. Similarly, ultrasonic sensing techniques transmit sound waves through the fruit and analyze changes in wave speed or amplitude to detect variations in density and internal structure. These technologies are capable of identifying internal issues without cutting the fruit, but they are generally used in industrial environments due to their high equipment cost and complex setup.

Recent developments in smart agriculture emphasize the use of Internet of Things (IoT)–based monitoring systems. IoT devices enable real-time data collection from various sensors and transmit the information to cloud platforms or mobile applications for analysis. These systems are widely used for monitoring environmental conditions such as soil moisture, temperature, crop health, and storage conditions. Despite these advancements, most existing fruit quality detection systems rely on a single sensing method, which reduces overall accuracy and reliability. The proposed NutriFusion X system overcomes these limitations by integrating multiple sensing technologies with IoT connectivity in a portable and low-cost device capable of detecting freshness, ripeness, and internal damage without cutting the fruit.

III. LIMITATIONS OF EXISTING SYSTEM

Current fruit and vegetable quality inspection methods have several limitations that reduce their effectiveness in real agricultural environments. Most farmers and vendors still rely on visual inspection, which only evaluates the external appearance of fruits, such as color, size, and shape. Although this method is simple and low-cost, it cannot detect internal spoilage, hidden bruises, chemical contamination, or early stages of decay. As a result, fruits that appear healthy from the outside may still contain internal damage, which can lead to food wastage and safety risks.

Another commonly used approach is laboratory-based quality testing, which includes chemical analysis, spectroscopy, and other scientific techniques. While these methods provide accurate results, they have major drawbacks. Laboratory tests are expensive, time-consuming, and destructive, meaning the fruit sample is damaged during testing and cannot be sold or consumed afterward. In addition, laboratory facilities require specialized equipment and trained personnel, making them inaccessible to farmers and small vendors who need quick quality assessment directly in the field or market.

Major limitations of existing systems include:

- Dependence on visual inspection, which only evaluates external fruit appearance
- Inability to detect internal damage, bruising, or hidden spoilage
- Difficulty in identifying pesticide residues or chemical contamination
- Laboratory testing is destructive, expensive, and time-consuming
- Lack of portable and real-time quality inspection systems
- Existing industrial grading machines are bulky and costly
- Limited accessibility for small farmers and local markets
- Most systems rely on single-sensor technology, reducing detection accuracy

These limitations highlight the need for a smart, portable, and multi-sensor-based quality inspection system that can evaluate both internal and external fruit quality in real time without damaging the produce.

IV. PROPOSED SYSTEM ARCHITECTURE

The proposed NutriFusion X system is designed to perform non-destructive quality inspection of fruits and vegetables using a combination of multiple sensors and IoT technology. The system architecture comprises hardware components and software modules that work together to collect, process, and analyze fruit-quality data in real time. The main objective of the system architecture is to detect parameters such as freshness, ripeness, internal damage, spoilage level, and possible pesticide contamination without cutting or damaging the fruit. The architecture integrates different sensing technologies, including gas sensing, optical sensing, ultrasonic sensing, ultraviolet sensing, near-infrared sensing, and image processing.

The entire system operates by placing the fruit sample inside a controlled inspection chamber, where multiple sensors collect data related to external and internal characteristics of the fruit. The collected data is processed by the ESP32 microcontroller, which acts as the central processing unit. The processed information is then transmitted wirelessly to a mobile application through Wi-Fi communication, allowing users to monitor fruit quality instantly.

The architecture of the proposed system is divided into two main components:

- Hardware Architecture
- Software Architecture

A. Hardware Architecture:

The hardware architecture of the proposed system includes several sensing modules and electronic components that work together to collect information from the fruit sample. Each sensor performs a specific task in detecting fruit quality parameters.

1. ESP32 Microcontroller

The ESP32 microcontroller serves as the main control unit of the system. It is responsible for acquiring sensor data, performing initial signal processing, and transmitting results to the mobile application. The ESP32 is selected due to its high processing capability, integrated Wi-Fi module, and multiple input/output pins that allow connection with various sensors simultaneously.

The main functions of the ESP32 microcontroller include:

• Reading analog and digital signals from sensors
• Converting analog signals into digital data using ADC
• Processing sensor data using threshold-based algorithms
• Managing wireless communication with the mobile application

2. Gas Sensor (MQ-135)

The MQ-135 gas sensor is used to detect gases released by fruits during the ripening and spoilage process. Fruits naturally emit gases such as ethylene, ammonia, and carbon dioxide as part of their biological metabolism.

The concentration of these gases increases during fruit ripening and decay. The MQ-135 sensor measures gas concentration and provides an analog voltage output proportional to the gas level.

The sensor helps in determining:

• Fruit ripeness stage
• Spoilage detection
• Gas emission patterns

3. Color Sensor (TCS34725)

The TCS34725 color sensor is used to analyze the color characteristics of fruits. Color is an important indicator of fruit maturity and ripeness. During ripening, fruits undergo noticeable color changes due to biochemical reactions.

The sensor detects red, green, and blue (RGB) light reflected from the fruit surface and converts it into digital data that can be processed by the ESP32.

This sensor helps in:

• Identifying fruit ripeness
• Detecting color abnormalities
• Monitoring surface quality

4. Ultrasonic Sensor (HC-SR04)

The HC-SR04 ultrasonic sensor is used to analyze the internal structural properties of fruits. The sensor emits ultrasonic sound waves that travel through the fruit surface and reflect. This method enables non-destructive internal inspection, allowing quality evaluation without cutting the fruit.

Changes in the reflected signal indicate variations in fruit firmness and internal density. These variations can help identify:

• Internal bruising
• Soft spots
• Structural damage

5. UV Sensor

The Ultraviolet (UV) sensor is used to detect fluorescence patterns that may indicate pesticide residues or chemical contamination on fruit surfaces. Some chemical substances react with ultraviolet light and produce fluorescence signals. By measuring UV light reflection or emission, the system can identify potential contamination on the fruit surface.

The UV sensor helps in:

• Detecting pesticide contamination
• Monitoring surface chemical residues
• Enhancing food safety analysis

6. Near-Infrared (NIR) Sensor

The Near-Infrared sensor is used to analyze internal fruit properties using infrared light absorption characteristics. NIR technology allows the detection of internal fruit conditions such as moisture content, sugar concentration, and tissue density. Infrared light penetrates the fruit tissue, and the reflected light pattern is analyzed to detect variations in internal structure.

This sensor helps in identifying:

• Internal bruising
• Moisture loss
• Hidden spoilage

7. Camera Module (ESP32-CAM)

The ESP32-CAM module captures images of fruits placed inside the inspection chamber. These images are processed using image analysis techniques to detect surface defects and texture variations. Combining camera analysis with sensor data improves the overall accuracy of fruit quality detection

Image processing algorithms analyze features such as:

• Color distribution
• Surface defects
• Shape irregularities
• Texture patterns

B. Software Architecture

The software architecture is responsible for processing sensor data, analyzing fruit characteristics, and displaying results to the user.

1. Sensor Data Processing

The ESP32 receives raw signals from all sensors and converts analog signals into digital values using its ADC module. These values are then processed using threshold-based algorithms to interpret fruit quality parameters.

For example:

If gas level > threshold → possible spoilage

If RGB values match the ripeness range → fruit is classified as ripe

2. Image Processing

Images captured by the ESP32-CAM are processed using image analysis techniques to detect visual features such as color variations, surface damage, and texture patterns. These features help in identifying external defects and improving classification accuracy.

3. IoT Communication

The system uses Wi-Fi connectivity to transmit processed sensor data to a mobile application. Data is transmitted in JSON format for efficient communication. The ESP32 sends data using IoT communication protocols such as:

- HTTP protocol
- MQTT protocol
- Firebase cloud database

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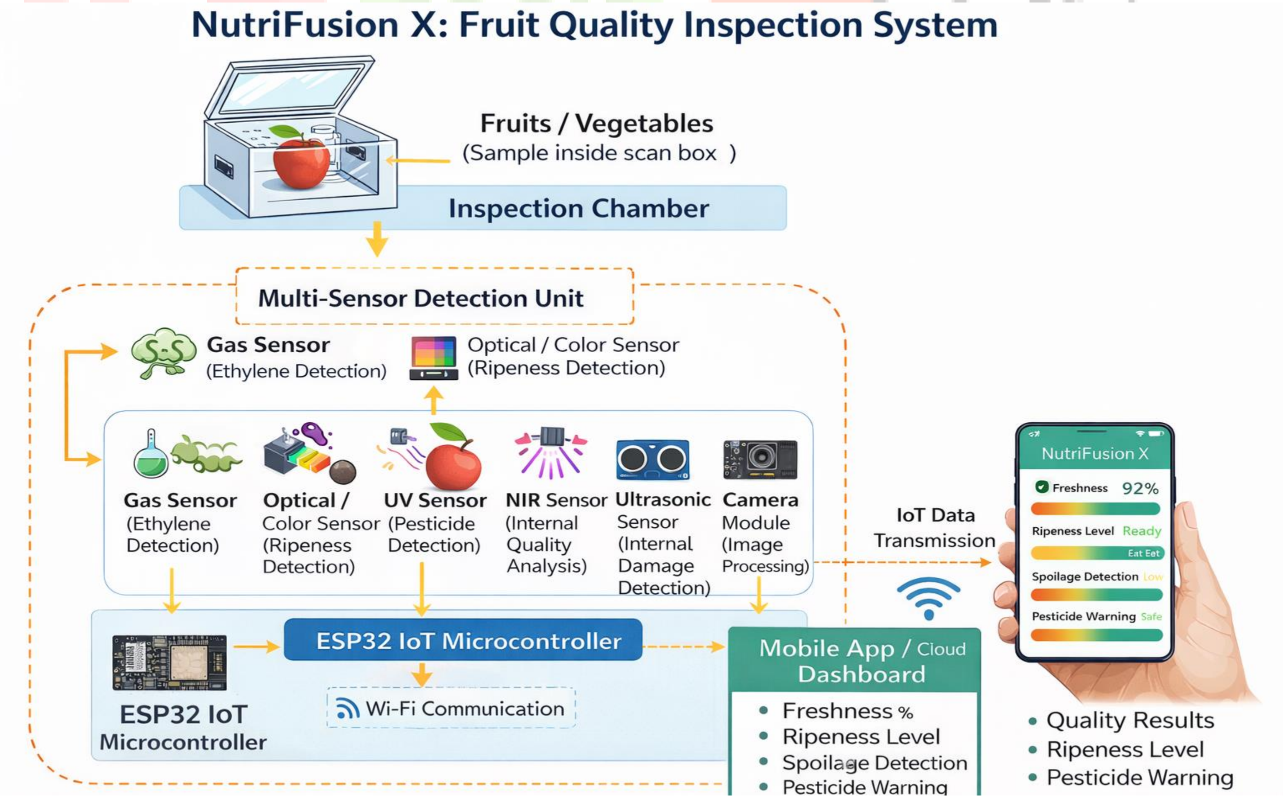

Fig. 1: Architecture of Proposed System

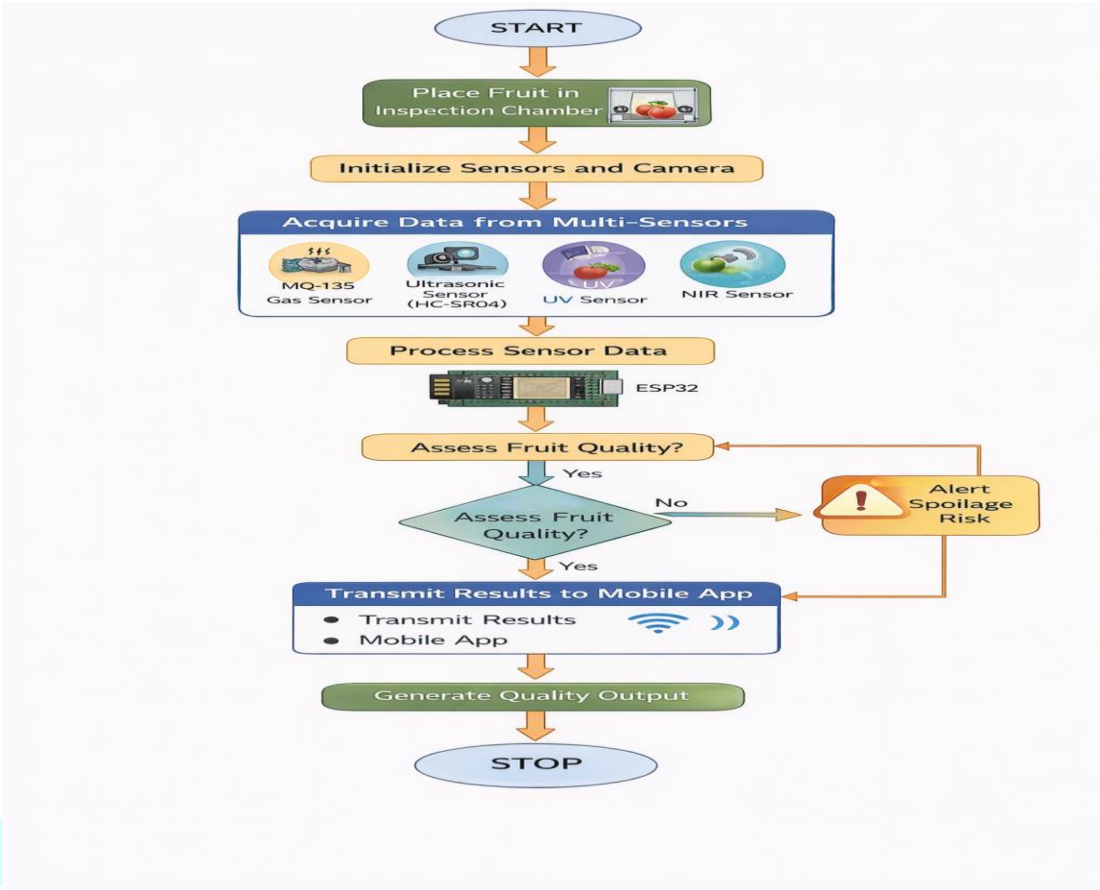

Fig. 2: Flowchart of Proposed System

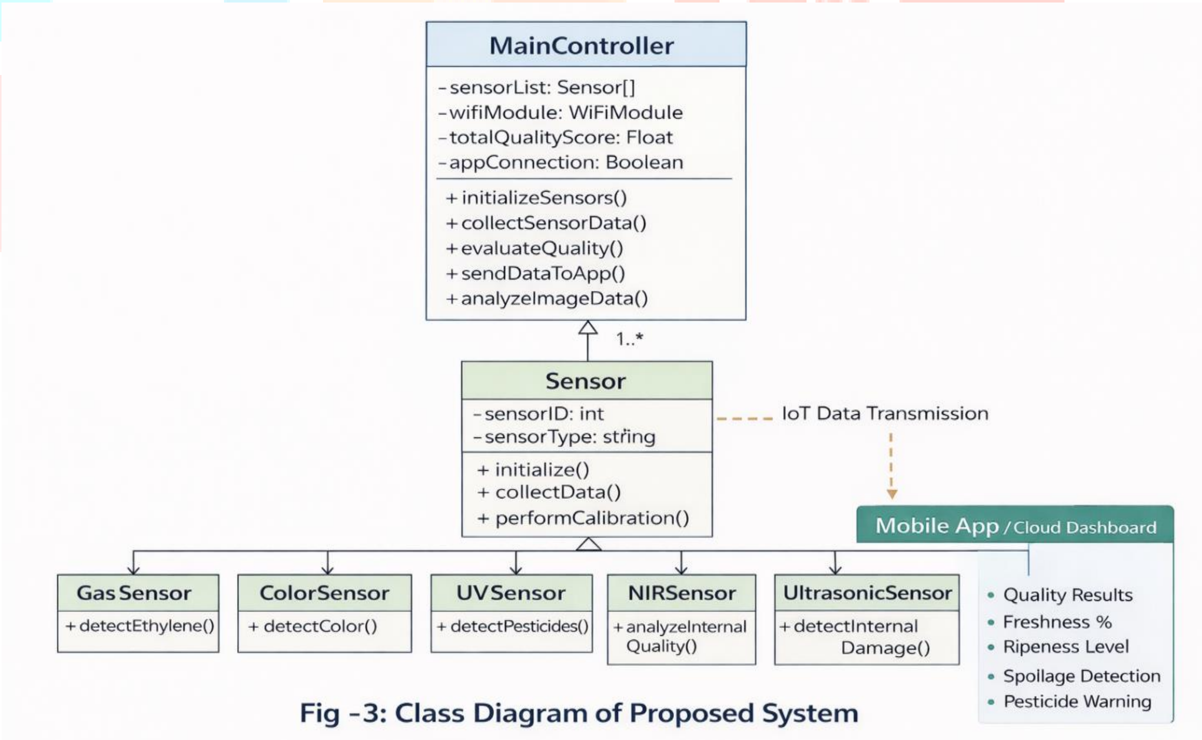

Fig -3: Class Diagram of Proposed System

4.1 Models of Proposed System

Mainly, there are 5 types of entities involved:

1. Sensor Model
2. Processing Model
3. Communication Model
4. IoT Communication (Wi-Fi) Model
5. User Interface Model
6. Decision Model

4.2Applications of the Proposed System

1.Smart Agriculture

- Helps farmers evaluate fruit quality before harvesting.
- Assists in determining the optimal harvesting time.
- Reduces post-harvest losses.

2. Agricultural Markets

- Vendors and traders can inspect fruits before purchasing.
- Detects internal damage without cutting the fruit.
- Improves fair trading and quality grading.

3. Food Processing Industry

- Used for automatic quality inspection before fruit processing.
- Ensures only high-quality fruits are used for food production.
- Improves efficiency in juice, jam, and food manufacturing industries.

4. Supermarkets and Retail Stores

- Helps check fruit freshness before selling to consumers.
- Improves food safety monitoring.

5. Food Safety and Research

- Can be used by food safety authorities and agricultural researchers.
- Helps study fruit ripening patterns and spoilage behavior.

6. Cold Storage and Supply Chain Monitoring

- Used to monitor fruit quality during storage and transportation.
- Helps prevent spoilage and food wastage.

4.2 Future Scope of Proposed System

1. Integration with Artificial Intelligence for Smart Prediction.
2. Smart Refrigerator Integration.
3. Application in Cold Storage Systems.
4. Automated Sorting and Grading Using AI.
5. AI-Based Smart Supply Chain Monitoring.
6. Advanced Mobile Application for Real-Time Monitoring.
7. Integration with Blockchain for Data Security and Traceability.
8. Development of Low-Cost AI-Based Portable Devices.

Fig. 4: Prototype Model of Proposed System

V. CONCLUSION

The proposed NutriFusion X system presents an innovative and efficient approach for non-destructive fruit quality assessment using a multi-sensor and IoT-based framework. By integrating sensors such as gas sensors, ultrasonic sensors, UV sensors, and NIR sensors with an ESP32 microcontroller, the system is capable of analyzing multiple parameters related to fruit freshness, ripeness, and spoilage. The collected sensor data is processed using sensor fusion techniques to provide an accurate quality evaluation without physically damaging the fruit. Experimental results demonstrate that the proposed system achieves high accuracy in detecting fruit quality, making it a reliable tool for farmers, traders, food industries, and consumers. Furthermore, the IoT-based communication enables real-time monitoring through a mobile application, improving decision-making in agricultural and food supply chain management. Overall, the proposed system contributes to reducing food wastage, improving fruit quality inspection, and supporting the development of smart agriculture technologies.

VI. ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the faculty members and project supervisors for their continuous guidance, valuable suggestions, and encouragement throughout the development of this research work. We also extend our appreciation to the department and institution for providing the necessary resources, laboratory facilities, and technical support required to complete this project. Their support and motivation were instrumental in researching the NutriFusion X: Smart IoT-Based Fruit Quality Detection and Analysis System. Finally, we thank all those who directly or indirectly contributed to the successful completion of this research work.

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