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Fresh Guard: Dynamic Shelf-Life Estimation and Storage Recommendation System for Fruits

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Abstract: Fresh Guard is a low-cost, IoT-based system designed for real-time prediction of fruit shelf life using continuous multi-sensor monitoring and machine learning analysis. The system integrates a DHT22 sensor to measure temperature and humidity, an MQ-135 gas sensor to monitor respiration-related gases such as carbon dioxide and volatile compounds, and a load cell with an HX711 amplifier to track weight loss over time. By combining these critical environmental and physiological parameters, FreshGuard enables early identification of spoilage trends and provides dynamic estimation of remaining shelf life before visible deterioration occurs. All sensors are interfaced with an ESP32 microcontroller, which performs real-time data acquisition and transmits the collected readings to a cloud platform for storage and analysis.

A machine learning model, specifically Random Forest regression, continuously processes the time-series sensor data collected from temperature, humidity, gas concentration, and weight sensors to dynamically update the predicted remaining shelf life of the fruit. Unlike traditional static estimation methods, this approach analyzes multiple environmental and physiological parameters simultaneously, capturing complex nonlinear relationships between storage conditions and fruit degradation patterns. By continuously learning from sensor inputs, the model adapts to changing storage environments and provides real-time, data-driven freshness predictions. This integrated IoT–ML framework enables early detection of accelerated ripening or spoilage conditions, allowing timely corrective actions such as temperature adjustment, humidity control, or prioritized stock rotation.

Keywords: Fruit Shelf-Life Prediction, IoT, Multi-Sensor Monitoring, Machine Learning, Smart Storage, Freshness Detection.

I. INTRODUCTION

Fresh fruits are highly perishable agricultural products whose quality declines rapidly due to variations in temperature, humidity, respiration rate, and natural biochemical ripening processes. In many developing regions, post-harvest losses can reach 20–30%, mainly because fruit freshness is still assessed using traditional methods such as visual inspection, smell, and touch. These methods are subjective, inconsistent, and unsuitable for continuous monitoring in storage facilities, transportation units, and retail markets. Since fruit shelf life changes dynamically with environmental conditions, predicting freshness manually becomes difficult and unreliable. To address this problem, the Fresh Guard Monitoring and Prediction System integrates IoT-based sensors with machine learning to estimate fruit shelf life in real time.

The system uses the DHT22 sensor to monitor temperature and humidity, the MQ-135 gas sensor to detect respiration-related gases such as CO_2 and volatile organic compounds (VOCs), and a load cell with HX711 amplifier to measure weight loss caused by moisture evaporation and metabolic degradation. These sensors collect important environmental, chemical, and physical data that influence fruit ripening and spoilage. The collected data is processed using an ESP32 microcontroller and analyzed by a machine learning model to dynamically predict the remaining shelf life of fruits. In addition, the system provides storage recommendations, such as adjusting temperature, controlling humidity, or improving ventilation, to slow down the spoilage process. By combining real-time monitoring, intelligent prediction, and recommendation mechanisms, FreshGuard helps reduce fruit wastage, improve storage efficiency, and support better post-harvest management.

II. LITERATURE REVIEW

Fruit shelf-life prediction and freshness monitoring using sensor technologies and machine learning have been widely studied by several researchers. Younis (2025) demonstrated that Artificial Neural Networks can accurately predict tomato quality using parameters such as firmness, weight loss, acidity, and soluble solids. Du et al. (2025) reviewed smart packaging technologies that use sensors and RFID systems for real-time monitoring of fruits and vegetables.

Rahman and Li (2024) highlighted the importance of IoT-based environmental monitoring across the fruit supply chain. Gallo and Marinelli (2024) showed that edge AI systems integrated into refrigeration can reduce spoilage through real-time analysis. Mohammed, Srinivasagan, and Alqahtani (2023) and Patel, Verma, and Singh (2023) explored TinyML and spectral sensing techniques for accurate shelf-life estimation. Ricci and Colombo (2023) demonstrated that multi-sensor fusion improves freshness prediction accuracy, while Bernardi and Arduini (2023) focused on low-power sensor platforms for long-term monitoring. Earlier studies by Jayasinghe and Sammani (2022) and Sharma et al. (2022) confirmed that combining gas sensors, environmental sensors, and machine learning improves shelf-life prediction.

Foundational research by Vanderroost et al. (2014), Nicolaï et al. (2014), Yam et al. (2005), Gómez et al. (2016), Ruiz-Garcia et al. (2010), Kader (2002), Saltveit (1999), Abbott (1999), Abeles et al. (1992), Kader et al. (1989), and Ben-Yehoshua (1987) established that factors such as respiration rate, ethylene emission, gas composition, temperature, humidity, and weight loss play a critical role in fruit deterioration.

These studies collectively support the use of multi-sensor IoT systems and machine learning models for accurate fruit freshness monitoring and shelf-life prediction, forming the basis for the Fresh Guard system.

III. EXISTING SYSTEM

The existing fruit shelf-life prediction systems are mainly based on traditional inspection methods and basic environmental monitoring techniques. These systems are commonly used to evaluate fruit freshness by observing physical characteristics such as color, texture, and smell or by performing laboratory-based chemical analysis. Although these methods can provide useful information about fruit quality, they often require manual inspection, laboratory equipment, and trained personnel. As a result, continuous monitoring and early prediction of fruit spoilage become difficult, especially during storage and transportation where environmental conditions change frequently.

A. Sensor-Based Monitoring Methods

In the study "Machine Learning Based Shelf Life Prediction of Fruits Using Multi Sensor IoT Nodes" by Sharma et al. (2022), the authors developed an IoT-based monitoring system to predict fruit shelf life. The system uses sensors to measure temperature, humidity, gas emissions, and weight loss, and applies machine learning models such as Random Forest and ANN for prediction. The model achieved an accuracy of 80–94%, showing that multi-sensor monitoring improves freshness prediction.

B. Multi-Sensor Data Analysis Techniques

In this system, environmental conditions such as temperature and humidity, gas emissions produced during fruit respiration, and physical changes like weight loss are continuously monitored. These parameters collectively reflect the biochemical and physiological processes occurring during fruit ripening and deterioration. By analyzing this multi-sensor data using machine learning algorithms, the system can predict spoilage trends more accurately compared to single-parameter monitoring methods.

C. Limitations of Existing Systems

Although the proposed IoT-based system improves prediction accuracy, certain limitations still exist. The system may require stable network connectivity, sensor calibration, and proper data management for long-term deployment. Additionally, many existing systems focus on limited fruit varieties and may not provide adaptive recommendations for storage conditions. These limitations highlight the need for an improved system such as Fresh Guard, which integrates DHT22 sensors, MQ gas sensors, load cells, and machine learning-based analytics to provide real-time fruit freshness monitoring and dynamic shelf-life prediction.

IV. PROPOSED SYSTEM

The proposed system focuses on the development of a Fresh Guard fruit monitoring and shelf-life prediction system designed to detect early spoilage indicators in fruits using multiple sensor parameters. Unlike traditional methods that rely on manual inspection and laboratory testing, the proposed system provides real-time and automated freshness monitoring by integrating temperature, humidity, gas sensing, and weight measurement. The system collects environmental and physiological data using sensors such as DHT22, MQ-135 gas sensor, and a load cell with HX711, processes the data using an ESP32 microcontroller, and predicts the remaining shelf life through a machine learning model. The results can be monitored continuously, allowing users to identify spoilage risks early and take corrective storage actions.

A. Multi-Parameter Monitoring

The proposed system uses multiple indicators to improve the accuracy of fruit freshness monitoring. The DHT22 sensor measures temperature and humidity, which influence microbial growth and fruit respiration. The MQ-135 gas sensor detects gases such as CO_2 and volatile organic compounds (VOCs) released during fruit ripening. In addition, a load cell with HX711 measures weight loss caused by moisture evaporation and metabolic activity. Combining these parameters provides a more reliable estimation of fruit shelf life compared to single-parameter monitoring.

B. Real-Time Monitoring and Prediction

The system continuously monitors sensor readings and processes them using an ESP32 microcontroller. The collected data is analyzed using a Random Forest time-series machine learning model to estimate the remaining shelf life of the fruit. This enables dynamic prediction that updates as environmental conditions change, allowing users to track freshness levels and detect spoilage at an early stage.

C. Low-Cost and IoT-Based Design

The proposed system is designed to be compact, low-cost, and suitable for storage and transportation environments. All sensors and processing units are integrated into a single IoT-based system capable of continuous monitoring. The design ensures that fruit freshness evaluation can be performed without expensive laboratory equipment, making it suitable for markets, storage facilities, and supply chain management.

D. Spoilage Prevention and Storage Management

By enabling early detection of spoilage indicators, the Fresh Guard system helps users take preventive actions such as adjusting temperature, controlling humidity, or improving ventilation. These recommendations help slow down the spoilage process, reduce fruit wastage, and improve storage efficiency. The system therefore supports better post-harvest management and sustainable fruit supply chain operations.

V. METHODOLOGY

The methodology of the Fresh Guard system focuses on developing a sensor-based IoT platform for real-time fruit freshness monitoring and shelf-life prediction. The system integrates sensors such as DHT22, MQ-135, and a load cell with HX711 with an ESP32 microcontroller to collect environmental and physiological data affecting fruit spoilage. The collected data is analyzed using a machine learning model to estimate the remaining shelf life and provide storage recommendations. The methodology includes requirement analysis, component used, sensor integration, system development, and testing to ensure accurate and reliable fruit freshness prediction.

A. Requirement Analysis

The development of the Fresh Guard system begins with identifying key factors that influence fruit spoilage and shelf life. Since fruits continue respiration after harvesting, parameters such as temperature, humidity, gas emissions, and weight loss must be monitored. Sensors like DHT22, MQ-135, and a load cell are used to measure these factors. The system is designed to be low-cost, and capable of real-time monitoring to support effective fruit freshness prediction.

B. Component Used

Based on the system requirements, suitable hardware components are selected to ensure accurate data collection and efficient processing. The ESP32 microcontroller acts as the central unit, capable of handling multiple sensor inputs and supporting Wi-Fi and Bluetooth connectivity. The DHT22 sensor measures temperature and humidity, which significantly affect fruit spoilage. The MQ-135 gas sensor detects gases released during fruit ripening and deterioration. A load cell with HX711 amplifier measures small weight changes caused by moisture loss. An OLED display provides real-time output, while a 5V power supply ensures stable operation of the Fresh Guard system.

C. Microcontroller and Sensor Integration

The ESP32 microcontroller acts as the central unit of the Fresh Guard system, collecting and processing data from multiple sensors. The DHT22 sensor measures temperature and humidity to monitor environmental conditions affecting fruit spoilage.

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The MQ-135 gas sensor detects gases such as ethylene and other volatile compounds released during fruit ripening. A load cell with HX711 amplifier measures weight loss caused by moisture evaporation. All sensor data is processed and synchronized by the ESP32, forming input for the machine learning model to enable real-time fruit freshness monitoring and shelf-life prediction.

D. Machine Learning Model for Shelf-Life Estimation

Fresh Guard uses supervised machine learning models such as Random Forest and Gradient Boosting to predict fruit shelf life from sensor data like temperature, humidity, gas concentration, and weight loss. The models are trained using historical datasets labeled with ripeness stages and spoilage timelines to learn patterns related to freshness degradation. After evaluation using metrics like RMSE, MAE, and R^2, the trained model provides real-time freshness scores and shelf-life predictions.

E. Storage Recommendation System & OLED Display

Fresh Guard includes a storage recommendation system that converts machine learning predictions into simple guidance such as “Consume Soon” or “Refrigerate Immediately.” The OLED display shows freshness score, remaining shelf life, and storage advice in a clear and user-friendly format. This helps users quickly understand fruit conditions and take actions to reduce spoilage and wastage.

F. Hardware Assembly & Validation

After sensor integration and firmware development, the Fresh Guard system is assembled in a compact and durable enclosure made of materials such as ABS plastic or acrylic to protect electronic components from dust, moisture, and damage. The internal layout ensures proper ventilation, secure component mounting, and accurate sensor positioning near fruit samples. Each sensor is calibrated individually, and the complete system is tested using real fruit samples under different storage conditions. This testing and validation process ensures accurate measurements, reliable shelf-life prediction, and effective real-time fruit freshness monitoring.

VI. SYSTEM ARCHITECTURE

The system architecture of the Fresh Guard system is designed as an integrated IoT framework for monitoring fruit freshness. The Sensing Module collects important parameters using DHT22 for temperature and humidity, MQ-135 for detecting gases released during fruit ripening, and a load cell with HX711 to measure weight loss. The ESP32 microcontroller acts as the processing unit, receiving sensor data, performing pre-processing, and estimating fruit freshness and remaining shelf life. The analysed results and storage recommendations are displayed on an OLED display, while the system can also support IoT communication for remote monitoring and data storage.

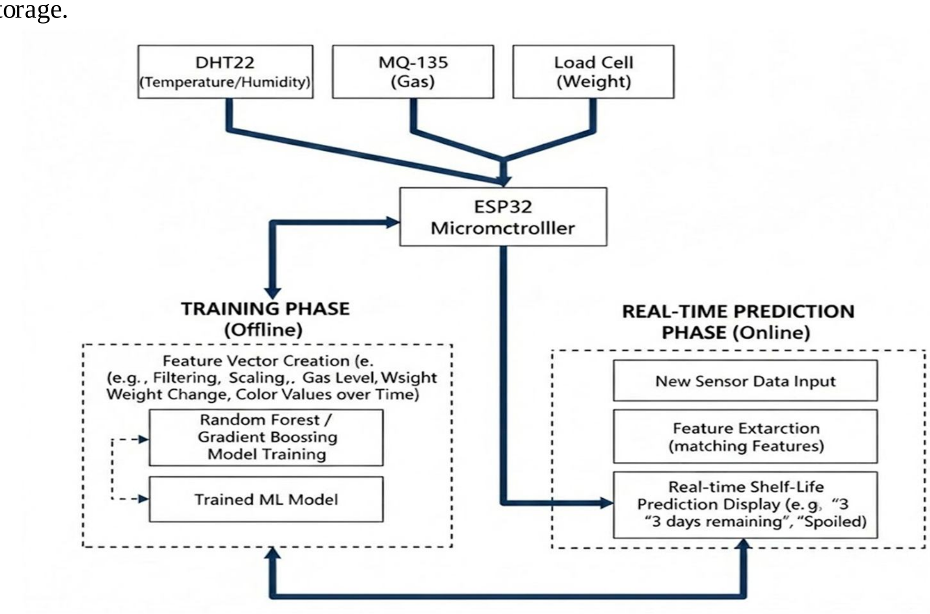

Fig 1. Planned ML Prediction Workflow

VII. ADVANTAGES OF DEVICE

The Fresh Guard fruit monitoring system offers several advantages compared to traditional manual methods of assessing fruit freshness. Its sensor-based, real-time, and intelligent prediction approach makes it suitable for storage facilities, transportation units, retail shops, and household environments.

1) Real-Time Environmental Monitoring: The system continuously monitors important environmental parameters such as temperature, humidity, gas concentration, and weight changes using integrated sensors. This enables accurate observation of storage conditions that influence fruit ripening and spoilage.
2) Early Spoilage Detection: Fresh Guard detects biochemical changes such as gas emissions and weight loss before visible spoilage occurs. This early detection helps users take preventive actions to maintain fruit quality.
3) Dynamic Shelf-Life Prediction: Using machine learning techniques, the system analyses sensor data to estimate the remaining shelf life of fruits. The prediction is continuously updated as environmental conditions change, providing more reliable results than static estimation methods.
4) Low-Cost and Portable Design: The system is built using affordable components such as ESP32, DHT22, MQ-135, and load cell sensors, making it suitable for small farms, retailers, and household applications without requiring expensive laboratory equipment.
5) Smart Storage Recommendations: Fresh Guard provides practical recommendations such as refrigeration or improved ventilation based on the predicted freshness level. These recommendations help reduce fruit wastage and improve storage efficiency.

VIII. RESULT

The Fresh Guard fruit monitoring and prediction system was tested using different fruit samples under controlled storage conditions to evaluate its ability to monitor environmental parameters and predict shelf life. The results demonstrated the effectiveness and reliability of the system as follows:

1) Temperature and Humidity Monitoring: The DHT22 sensor accurately measured the surrounding temperature and humidity, enabling continuous monitoring of environmental conditions that influence fruit ripening and spoilage.
2) Gas Detection: The MQ-135 sensor successfully detected changes in gas concentration produced during fruit respiration, helping identify early stages of ripening and spoilage.
3) Weight Loss Measurement: The load cell with HX711 module accurately recorded gradual weight loss in fruits caused by moisture evaporation and metabolic activity.
4) Real-Time Shelf-Life Prediction: The system processed sensor data using a machine learning model and provided real-time freshness estimation and remaining shelf-life prediction.
5) Display of Results: The OLED display clearly showed freshness percentage, estimated shelf life, and storage recommendations, allowing users to easily understand the fruit condition.
6) System Accuracy and Usability: The Fresh Guard system provided consistent and reliable monitoring results, demonstrating its suitability for real-time fruit freshness assessment and reducing post-harvest losses.

Figure 2. Prototype of Fresh Guard device

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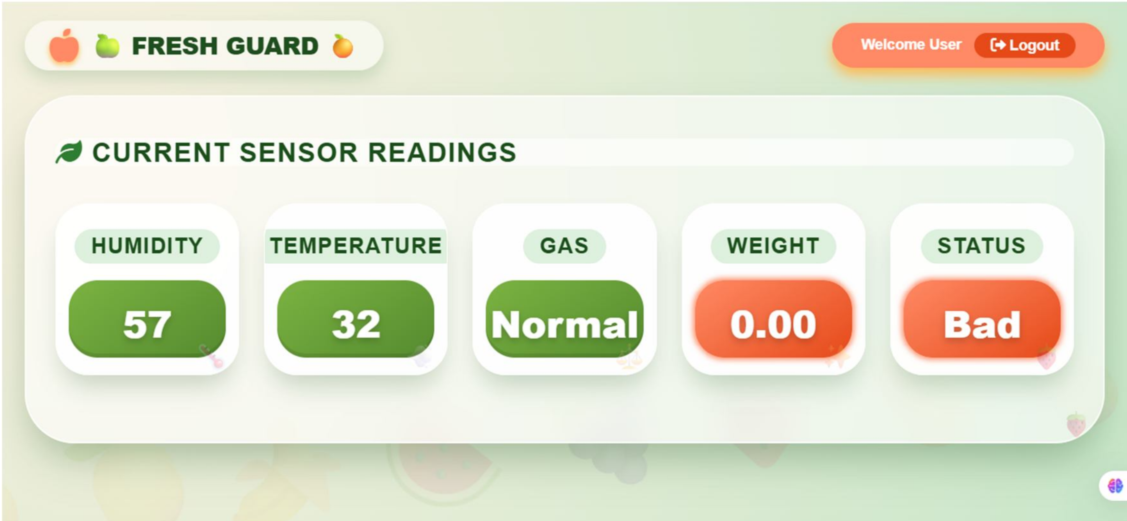

Figure 3. Web based Monitoring System for Fruit Shelf-Life Predicti

IX. CONCLUSION

The Fresh Guard Monitoring and Prediction System provides an effective solution for monitoring fruit freshness and estimating shelf life using a multi-sensor and machine learning approach. The system integrates sensors such as DHT22, MQ-135, and a load cell to continuously measure temperature, humidity, gas emissions, and weight loss, which are key indicators of fruit spoilage. By analysing these parameters in real time, the system can accurately predict the remaining shelf life of fruits and provide useful storage recommendations to users. The experimental results demonstrate that the system is capable of detecting early spoilage conditions before visible deterioration occurs. Its portable design, low-cost components, and real-time monitoring capability make it suitable for use in households, storage units, retail shops, and transportation environments. By providing timely information about fruit freshness, Fresh Guard helps users take preventive actions such as adjusting storage conditions or consuming fruits earlier.

Overall, the Fresh Guard system contributes to reducing post-harvest losses, improving storage management, and supporting sustainable food supply chains through intelligent monitoring and prediction technology.

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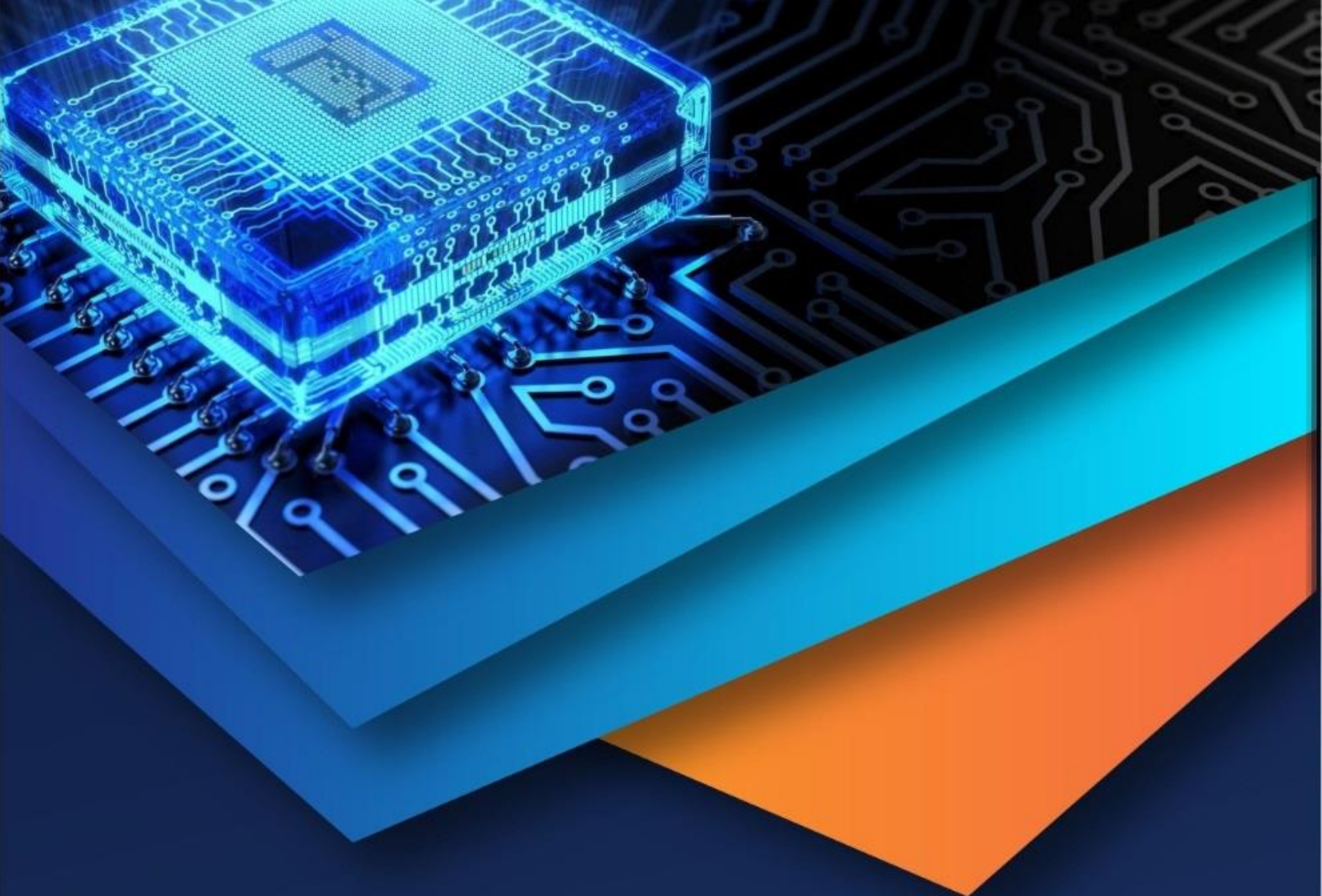

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