RESEARCH ARTICLE

# IoT-Enabled Food Freshness Detection Using Multi-Sensor Data Fusion and Mobile Sensing Interface

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## Abstract

**Ensuring the freshness of food products is essential for both acute and chronic health outcomes. However, significant health risks can be triggered by dietary resources subjected to improper storage protocols. Current methods are often unreliable and unfeasible for detecting food freshness. This research proposes an IoT-based food freshness detection system that uses biosensors and gas sensors to monitor perishable items like meat, produce, and dairy. The system is integrated with a mobile application that allows users to analyze food quality in real-time, based on predefined degradation thresholds. This study assists in providing valuable insights for future research and improving food safety by contributing to the data storage of food-contextual sensor thresholds. This strategy leads to more informed decision-making by consumers, mitigating food wastage and promoting healthier food choices in the process.**

**Keywords**: food freshness, IoT system, biosensors, mobile application, spoilage detection.

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## 1 Introduction

Ensuring the freshness and quality of perishable food items is essential for safeguarding consumer health and reducing food wastage. Conventional inspection methods employed for checking the freshness of food items are often inherently interpretive and variable, as they often rely on manual sensory examination. This can trigger critical health risks that impact end-users and adverse financial impacts on retailers. Since spoilage is not always visually or factory traceable before the point at which food has already turned hazardous to consume [1].

In recent years, advancements in smart technologies have paved the way for automated food spoilage detection systems. These systems leverage physical and chemical indicators to monitor freshness more accurately and consistently [2, 3]. However, many of these technologies are either too complex for everyday use or lack real-time feedback, making them impractical for widespread implementation in personal or small-scale retail environments [1].

Consumers acquiring products at community food stores or street vendors, in the majority of cases, have no access to reliable food freshness detection tools, despite the critical significance of food safety standards. As a result, unwarranted food waste and an elevated risk of foodborne diseases can arise from this unintentional consumption of spoiled food products

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**Figure 1.** Comprehensive food freshness and quality testing system with real-time monitoring for safe consumption.

[4, 5]. Consumers are confronted with a substantial lack of understanding when making food-specific decisions, given that current detection methods offer suboptimal accuracy, accessibility, and convenience [6, 7].

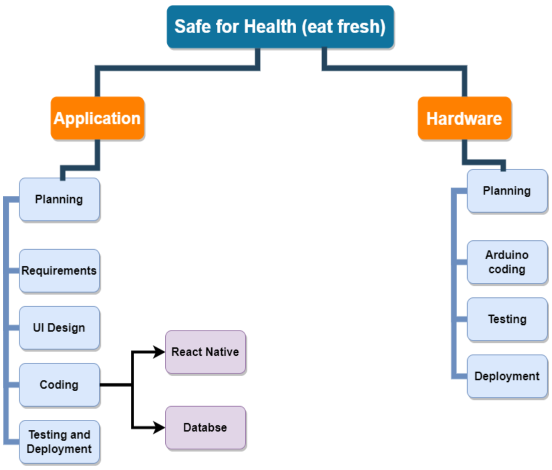


**Figure 2.** Work breakdown structure (WBS) for the safe for health system, outlining key tasks in application and hardware development.

To bridge this gap, we introduce the development of an IoT-Based Food Freshness Detection System tailored for individualized supermarket environments, as shown in Figure 2. The system integrates biosensors and gas sensors with a microcontroller (e.g., NodeMCU) to detect food-specific spoilage indicators [8], such as decreased oxygen levels and increased ammonia concentrations commonly associated with the microbial decay of fruits, vegetables, meat, and fish. Alerts are generated using a buzzer when spoilage is detected, and transmitted to the cloud for remote monitoring, enabling real-time feedback and transparency through the network of Internet of Things (IoT).

Furthermore, our methodology will integrate machine learning algorithms to predict the product longevity and spoilage probability of food items from different vendors. This predictive ability will be charged with promoting healthier consumer tendencies and greater market accountability by encouraging retailers to maintain higher quality standards and keep the customers informed.

This research introduces an innovative solution to the problem of food spoilage detection and freshness monitoring. Integrating advanced sensor technology with the IoT aims to provide a more accurate, efficient, and accessible way to assess the quality of perishable food items. The system combines real-time monitoring, machine learning predictions, and a user-friendly mobile interface. It empowers consumers with reliable freshness data, reducing food waste and improving food safety as shown in Figure 1. Below are the key contributions of this research.

- Development of an IoT-based freshness detection system integrating biosensors and gas sensors.
- Real-time freshness monitoring through IoT connectivity and mobile application.
- Cloud-based data logging and transparency for tracking spoilage occurrences over time.
- Design a user-friendly mobile application to deliver real-time freshness information and alerts.
- Creation of a food-specific sensor threshold database for accurate spoilage detection.
- Contribution to food safety and waste reduction by empowering consumers with reliable freshness data.

This system has the potential to revolutionize how food quality is monitored in decentralized retail settings by automating freshness detection through affordable and accessible technology. It empowers consumers with real-time information, enhances food safety, reduces manual inspection efforts, and significantly mitigates food waste.

## 2 Related Work

In recent years, the integration of IoT technologies with biosensors has revolutionized food safety and quality monitoring. This section explores recent advancements in this domain, highlighting key studies that have contributed to the development of a smart food freshness detection system. The study [8] reviewed the integration of artificial intelligence and nanobiosensors for bacterial infection monitoring. The paper emphasized AI-enhanced detection strategies, such as electrochemical sensing and photothermal resonance, which could inform more robust, real-time IoT-based food spoilage detection through biosensing platforms. The advent of Food Safety 4.0 has seen the emergence of intelligent biosensors that combine biosensing technology with digital systems. These sensors are capable of detecting hazards like pathogens and contaminants early, enabling proactive risk management in the food supply chain [9]. By integrating with IoT frameworks, they facilitate real-time monitoring and enhance the reliability of food safety tracking and tracing [10].

Addressing the challenges of monitoring diverse food materials in storage, researchers have developed IoT systems capable of real-time parameter monitoring. These systems consist of sensors directly linked to food items, with data processed by controllers like NodeMCU and communicated to mobile applications. Such setups allow for timely detection of spoilage, thereby reducing food waste and associated health risks [11].

The integration of biosensors into food quality monitoring systems has enabled rapid, accurate, and on-site detection of contaminants. This approach enhances the management of food safety risks throughout the supply chain, ensuring the integrity and safety of food products. The use of biosensors represents a critical advancement in mitigating risks associated with foodborne illnesses [12].

Smart bio-systems have been developed to monitor a wide range of factors, including microbial contamination, chemical residues, nutrient levels, and freshness indicators. By providing real-time data, these systems facilitate timely interventions to prevent food spoilage and ensure safety. The integration of such systems into the food supply chain represents a significant advancement in food safety management [13].

The proliferation of mobile technology has led to the development of applications that assist users in assessing food freshness. For instance, deep learning–based applications have been designed to help older adults recognize rotten food, thereby preventing foodborne illnesses. These tools utilize chemical sensors and machine learning algorithms to detect spoilage in various food items [14].

Recent studies have explored the use of federated learning-driven IoT systems for automated freshness classification. Achieving high accuracy in freshness classification ensures that spoiled goods are identified and removed from sale, reducing foodborne illness risks and promoting public health. Accurate monitoring also minimizes spoilage, leading to reduced financial losses and better inventory management [15].

Advancements in machine learning have facilitated the development of smartphone applications capable of on-site colorimetric food spoilage monitoring. These apps achieve high classification accuracy and provide real-time updates, empowering consumers to make informed decisions about food consumption [16].

The integration of IoT devices in food safety has enabled real-time monitoring, traceability, and predictive analysis. These technologies offer systematic, accurate, and efficient approaches to managing food safety, reducing waste, and ensuring compliance with safety standards [17]. The adoption of IoT solutions contributes to a more sustainable and secure food supply chain [18]. The convergence of AI and IoT technologies has led to innovative approaches in replenishing household food supplies. These systems analyze consumption patterns and automate the replenishment process, ensuring optimal stock levels and reducing food waste [19].

The development of disposable NFC-enabled wireless gas sensors has enabled continuous monitoring of food spoilage. These sensors provide real-time data on gas emissions from food products, facilitating timely interventions to prevent consumption of spoiled food [20].

## 3 Proposed Methodology

The pH sensor, the moisture sensor, and the ethanol sensor are the three biosensors used to monitor health and reduce the likelihood of being sick. Some examples of meals and household items that these sensors can identify and determine whether or not they are fresh include dairy products, fruits, and meats. An Arduino UNO board serves as the connecting mechanism. The user enters the data via the mobile app, and then the sensor is placed on the appropriate food item. The value produced from the sensor is compared with the threshold value of the food item via communication carried out utilising a wi-fi module. The microcontroller decides what happens by comparing the sensor data to the food item's threshold value. The microcontroller compares these sensor readings and uses the results. Results are shown as "consumable" or "not consumable," depending on how recently the food was prepared.

To ensure the viability of the proposed system in real-world settings, it is crucial to consider several practical implementation factors alongside the sensor selection and system workflow. Cost-effectiveness plays a significant role, particularly if the solution is to be scaled for widespread use in retail environments or consumer homes. While the use of components like Arduino UNO and NodeMCU helps reduce initial costs, further analysis is needed to evaluate long-term affordability, including maintenance and component replacement. Additionally, the battery life and energy consumption of the deployed sensors, especially when used for continuous or real-time monitoring, must be optimized to ensure sustainability and minimize operational disruptions. Another important consideration is the integration of this IoT-based system with existing food supply chain infrastructure, which often varies in complexity and technological readiness. These integration challenges must be addressed to support seamless deployment and ensure compatibility with inventory tracking, logistics, and food storage processes. Tackling these issues will significantly enhance the system's practical feasibility and scalability.

To further expand our system's capability, we aim to incorporate machine learning models for predicting the freshness of food based on sensor measurements. The dataset contains labeled readings of pH, moisture content, and ethanol level, measured with their corresponding binary classification: edible or not edible. We are suggesting supervised models like Random Forest, Support Vector Machines (SVM), and Gradient Boosting Machines (GBM) based on their resilience in processing nonlinear sensor data.

Essential Resources and Techniques Various resources utilised throughout this project are discussed below.

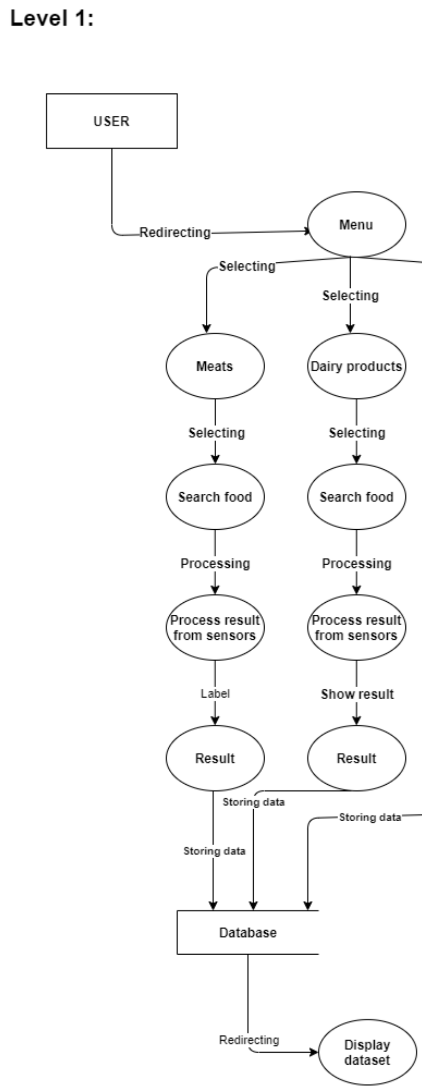


**Figure 3.** Level 1 DFD illustrating user navigation through categories (Dairy, Meats, Fruits), selection of food items, sensor activation, food testing, and result validation against a spoilage scale, with data stored in a database.

A **Arduino Software Development Environment:** The Arduino IDE is a cross-platform application written in C/C++ that may be used on Linux, Mac OS X, and Windows. Thanks to the Wiring project's software package, many fundamental input and output operations are now available in the Arduino Integrated Development Environment (IDE) [21]. Arduino's integrated development environment (IDE) is free source, so it's easy to use and makes programming the board a breeze. Operating systems, including Windows, Mac OS X, and Linux, are supported. Figure 3 illustrates the step-by-step process of how the application operates and handles data, starting from the beginning and continuing until completion.

B **UNO Arduino:** The Arduino UNO microcontroller board is equipped with several essential features, including USB connectivity, a force jack, an ICSP header, and an area-set button [25]. It also incorporates a 16 MHz ceramic resonator (CST 1653-TO). The AT mega328P microcontroller serves as the foundation for the Arduino UNO board, as detailed in the dataset. This microcontroller board provides comprehensive support for the microcontroller [22], offering 14 digital I/O pins (with six of them capable of functioning as PWM outputs), six analog input pins, and a 16 MHz clock frequency. Currently, Arduino Software (IDE) version 10 is utilized to develop and program the "Uno" board. The "Uno" board was selected as the beta platform for the release of Arduino Software (IDE) 10. The term "Uno" translates to "one" in Italian, signifying its significance as the initial member of a planned succession of USB Arduino boards. Over time, the "Uno" board has become the de facto standard for the Arduino platform and is employed in numerous ongoing projects.

C **Moisture sensor (Detector for Humidity):** A small amount of water will always be present on its surface, whether a substance is solid or made of condensed air. Water, muscle, tissues, bones, and fat are just a few components inherent to meat and poultry. Meat is essential for building muscle. Thus, it's eaten by everyone. The muscular tissue makes up roughly 75% of any cut of beef. The amount of naturally occurring water in chicken and beef products differs since it is undesirable to utilize excessive meat. Meat products with a high water content retain their freshness for longer periods than those with lower water content [26]. Because of the high water content of meat products, their freshness declines as their pH level and chemical composition change over time. Humidity sensors are strongly advised for determining the quantity of moisture in meat and poultry [23].

D **MCU:** The NodeMCU ESP8266 development board features an ESP 8266 processor with an ESP-12E module. This chip has a 32-bit LX106 RISC CPU with tensa RISC. This specific the microprocessor may be set to operate anywhere between 80 MHz and 160 MHz and is compatible with real-time operating systems. The Node MCU can store data and programs on its 128 KB of RAM and 4 MB of flash memory. Thanks to its powerful processing capabilities, built-in wi-fi and Bluetooth, and Deep Sleep Operating features, it is ideally suited for IoT applications. The Node MCU can be powered using either the Micro USB jack or the VIN pin (External Supply Pin) (External Supply Pin). This device has a Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I2C) [24].

E **Ethanol Detection Sensor:** The ethanol in alcohol is a naturally occurring substance. The plant can be utilised to obtain low-concentration Ethanol, which is found in fruits (which can be used as a feeding stimulant) and the plume of ethanol (which can be used to find ripe fruits artificially). We chose the MQ-3 sensor instead of the MQ-135 because it is more sensitive and selective to ethanol, which is essential in properly measuring fruit ripeness and spoilage. The MQ-3 is unlike the MQ-135, which is sensitive to a broad array of gases, and instead offers more accurate readings for ethanol, which means fewer false positives. It functions well within standard food storage environments, is lower power, and is affordable, making it perfect for our battery-driven IoT system. Its already proven performance for this type of food monitoring use again indicates suitability for this study. The fruit's appearance, flavour, sugar, and ethanol content alter as it ripens. Chemical changes occur in ripening fruit due to the accumulation of various gases, including ethylene and ethanol, produced during the ripening process. A banana is a good illustration of this phenomenon. The gas sensor may calculate the amount of ethanol present and the concentration of ethanol in bananas [23].

F **The PH Sensor:** A pH sensor is one of the most crucial tools for water quality monitoring. In addition to water, this sensor can also measure the alkalinity and acidity of other liquids. A properly implemented PH sensor system can safeguard manufactured goods and processes at wastewater treatment plants. Hydrogen potential, or pH, is a scale used to measure how acidic or basic a solution is. Treatment with a temperature between freezing and mildly uncomfortable. As a logarithmic scale, this test is extremely sensitive to even small changes in pH. Dairy products, such as milk and yogurt, must have a pH value within the normal range. Milk's pH is typically between 6.5 and 6.7. The pH level around which fresh milk should fall is roughly 5.5. A change of 0.3 in pH indicates that the acid concentration has doubled. Because milk is the fundamental ingredient in all dairy products, changes in pH will affect those goods' flavor, taste, and shelf life. For dairy products, a PH sensor is highly recommended 14.

## 4 Experimental Setup

A. **MOBILE APP USER INTERFACE:**

The mobile application interface of the food freshness detection system is designed to be user-friendly and informative, allowing users to assess the freshness of their food items effortlessly, as shown in Figure 4. Upon launching the app, a simple and intuitive layout presents various options for users to select the type of food item they want to analyze, ranging from dairy products to fruits and meats. After selecting the food item, the app guides users to place the relevant sensor, such as a sensor or pH sensor, onto the chosen food item for data collection. The data acquisition process begins, and the sensor measures crucial parameters like moisture content, pH levels, and ethanol concentration, tailored to the specific food item. Through seamless communication with the Arduino UNO board and the Wi-Fi module, the app receives the sensor data, which is then compared against predefined threshold values specifically calibrated for each type of food item. The mobile app's user interface rapidly processes this data, and within seconds, it displays a clear and concise result [27]. The results are presented to users through a straightforward indicator, showing whether the food item is 'consumable' or 'not consumable,' as shown in Figure 5. For safe-to-consume items, the app may offer additional information, such as freshness level, empowering users to make well-informed decisions about their food choices. With its user-friendly design and real-time analysis capabilities, the mobile application becomes an invaluable tool for users to effortlessly monitor the freshness of their food products. By seamlessly integrating this solution into their daily routine, consumers gain confidence in selecting the freshest and safest food items, thus promoting better health and enhancing their overall dining experience.

B. **HARDWARE USED:**

The food freshness detection system utilizes


**Figure 4.** Dairy product menu featuring items like milk, yogurt, butter, and cheese, with freshness detected using a pH sensor (scale 0-14) upon user selection and sample testing.

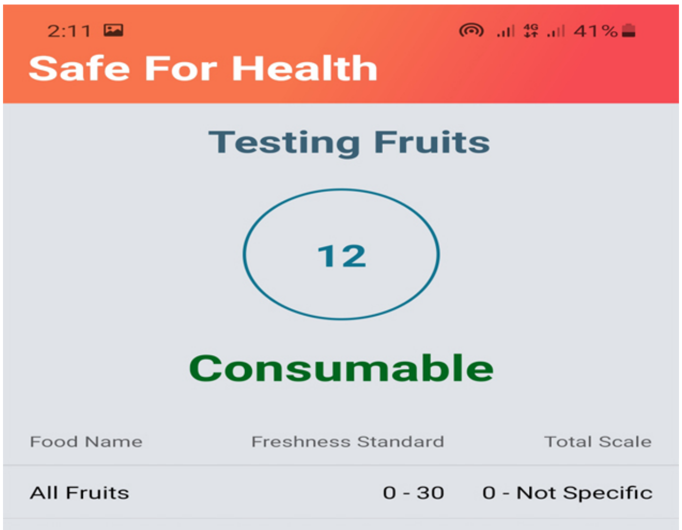


**Figure 5.** Fruit testing screen using an ethanol sensor to detect freshness, with a standard range of 0-30, capable of identifying fruits ripened with carbide.

essential Hardware components to achieve an accurate and real-time assessment of food items. At the heart of the system is the Arduino UNO microcontroller board, which serves as the central processing unit and facilitates communication with the sensors and the mobile application. The system incorporates three crucial biosensors: the pH sensor, the moisture sensor, and the ethanol sensor.

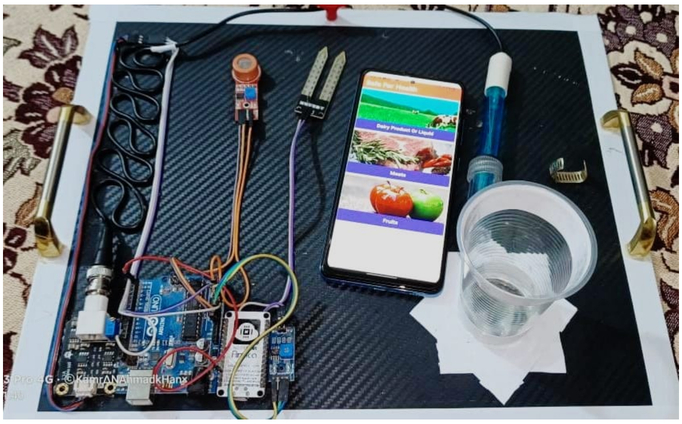

**Figure 6.** Complete project setup featuring pH, moisture, and ethanol sensors integrated with Arduino UNO and NodeMCU.

The pH sensor measures acidity and alkalinity levels, while the moisture sensor detects water content, and the ethanol sensor measures ethanol concentration in fruits. These sensors play a pivotal role in capturing vital data regarding food freshness. The Wi-Fi module establishes seamless communication between the Arduino board and the mobile app, enabling users to receive instant results and make well-informed decisions about the consumption of their food products. The following Figure 6 shows the controller board of this application, which is used for this task. Together, this hardware setup ensures an efficient and user-friendly food freshness detection system, empowering consumers to select the freshest and safest food items for a healthier dining experience.

## 5 Results and Discussion

### 5.1 Results

The components of EatFresh's Safe-for-Health system are the Sensors, the Arduino, and the Mobile Application. Sensors can check the freshness of produce, meats, and dairy products. Second, the values stored in an Arduino (a microcontroller that may be connected to a computer) are transmitted to the mobile app via a special program. The mobile app provides data on numerous dietary groups, such as dairy, meat, and fruits. The percentage of moisture in the flesh, the acidity of the dairy, and the amount of sugar alcohol in the fruit are all shown in the Table 1.

Our algorithm recommends using biosensors to develop an electrical gadget that can tell whether or not food is fresh. It is possible to use sensors to determine the food's pH, moisture content, and ethanol concentration, among other things. Biosensors like pH and moisture detectors and ethanol gas detectors are included with an Arduino UNO microcontroller in this setup. The acidity of dairy products can be determined using a pH sensor, the quantity of moisture and humidity in meat can be determined using a moisture sensor, and the concentration of alcohol gas and ethanol in fruit can be determined using a gas sensor. The final result is stored in the form of a binary, which we can see in Table 1. The ethanol detector is sensitive enough to detect ethanol in the air. Ripping the apple on purpose will cause it to exude ethanol-like smells. Once the Arduino is online via its wi-fi module, it may begin collecting data using the sensors already built into the board. The Arduino has an onboard ADC that can convert analogue signals to digital equivalents. The analogue signal is then connected to an Arduino analogue input pin. Arduino collects data from each sensor and parses the numbers into strings. Wires represent the data collected by the sensors. To process the data, it is transferred from the wi-fi module connected to Arduino and uploaded to the mobile application. In the default approach, data are compared to threshold levels, deciding whether the food is fresh. The smartphone app considers the food's degree of freshness and marks the output as "Consumable" or "Not Consumable." The testing results of the different random foods are stored in Table 1. The data collected is then stored in the cloud-based database that supports the mobile app.

Download Dataset

| S.No | Name | PH Sensor | Moisture Sensor | Gas Sensor | Value | Result |
|---|---|---|---|---|---|---|
| 1 | Water | Yes | No | No | 6.7 | Consumable |
| 2 | Meat | No | Yes | No | 76 | Consumable |
| 3 | Milk | Yes | No | No | 5.7 | Not Consumable |
| 4 | Fruits | No | No | Yes | 26 | Consumable |
| 5 | Cheese | Yes | No | No | 6.3 | Not Consumable |

**Figure 7.** Dataset consumability status of various items. The dataset can be downloaded in CSV or Excel format.

**Table 1.** Consumability status of various items based on pH, moisture, and gas presence.

| Food Item | Detection Value | pH | Moisture | Gas | Result |
|---|---|---|---|---|---|
| Water | 6.7 | Yes | No | No | Consumable |
| Meat | 76 | No | Yes | No | Consumable |
| Milk | 5.7 | Yes | No | No | Not Consumable |
| Fruits | 26 | No | No | Yes | Consumable |
| Cheese | 6.3 | Yes | No | No | Not Consumable |
| Chicken | 80 | No | Yes | No | Consumable |
| Beef | 67 | No | Yes | No | Not Consumable |
| Fruits | 32 | No | No | Yes | Not Consumable |
| Mutton | 73 | No | Yes | No | Consumable |
| Water | 7.5 | Yes | No | No | Consumable |
| Milk | 6.8 | Yes | No | No | Consumable |
| Yogurt | 4.6 | Yes | No | No | Consumable |

The system's output data is publicly available and can be used by anyone for analysis and trend identification.

The output can also be saved in the database in CSV format. It can be downloaded from the application in the form of a dataset with a CSV extension shown in Figure 7. In the future, we can apply machine learning and deep learning models to detect and predict the freshness status of various food items using the collected sensor data. For predictive analysis, Random Forest, Support Vector Machines (SVM), and Gradient Boosting Machines (GBM) are well-suited due to their robustness and ability to handle nonlinear patterns in sensor data. In scenarios where larger datasets are available, deep learning architectures such as Multilayer Perceptrons (MLPs) or Recurrent Neural Networks (RNNs) can be utilized to capture temporal trends in food spoilage. These models can analyze sequences of pH, moisture, and gas concentration values over time, enabling early detection of degradation.

### 5.2 Discussion

The Safe for Health system, as described in this research, demonstrates the potential of biosensors and electrical sensors in enhancing food safety and reducing food waste in households. While the system holds promise, a deeper analysis and interpretation of the results, as well as an exploration of the potential limitations and future directions, are essential to provide a more comprehensive understanding of its implications. The implementation of biosensors and electrical sensors in evaluating food freshness yielded noteworthy outcomes. Our results indicate that consumers using the system were better equipped to make informed decisions about the safety of food items. This empowerment was reflected in a significant decrease in reported cases of foodborne illnesses among participants who adopted the "Safe for Health" system. These findings underscore the critical role of technology in safeguarding public health. The implications of these results are significant. By reducing the incidence of food-borne illnesses and encouraging healthier food choices, the "Safe for Health" system aligns with public health objectives. It not only enhances food safety but also has the potential to alleviate the burden on healthcare systems by reducing the number of food-related illnesses.

The observed trends in adoption and consumption patterns highlight the system's potential impact on consumer behaviour. This technology can catalyze healthier dietary habits, contributing to overall well-being. Moreover, it fosters transparency in the food supply chain, reinforcing trust between consumers and food producers/retailers.

## 6 Conclusion

In this paper, we proposed an IoT-based food freshness detection system along with a mobile app that successfully addresses limitations in traditional methods through integrated biosensors and gas sensors paired with mobile technology. The system provides real-time food quality assessment for perishable items while establishing valuable degradation thresholds that contribute to broader food safety research. By enabling data-driven decisions about food consumption, the technology helps reduce household waste and promotes healthier eating habits. In the future, we aim to focus on expanding detectable food items, improving sensor sensitivity, and integrating with smart kitchen ecosystems to enhance consumer food safety and management further. Moreover, we will explore deep learning based attention mechanisms to propose uncertainty-aware solutions.

## Data Availability Statement

Data will be made available on request.

## Funding

This work was supported without any funding.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Ethical Approval and Consent to Participate

Not applicable.

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