IOT Based Smart Refrigerator

Internet of Things and Big Data Analytics - IT4021

IoT Implementation with Big Data Analytics

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ABSTRACT

Food spoilage due to suboptimal refrigeration remains a significant challenge in both domestic and commercial settings, contributing to global food waste, economic losses, and health hazards. This project presents the design and implementation of an IoT-based smart refrigeration monitoring system aimed at ensuring optimal food preservation through real-time environmental monitoring and analytics. The system utilizes an ESP32 microcontroller integrated with temperature, humidity, gas, and door sensors to collect data at regular intervals. This data is transmitted to an Azure Function, which securely stores it in an Azure SQL Database. Visualization is achieved using Power BI, enabling live dashboards with status indicators and real-time alerts. By analyzing environmental parameters and user behavior patterns, the system provides actionable insights to reduce food waste, improve energy efficiency, and enhance food safety. This solution offers a scalable, cloud-connected platform for intelligent refrigeration management, promoting sustainable storage practices and smarter consumer habits

ACKNOWLEDGMENT

We extend our sincere gratitude to Dr. Lakmini Abeywardhana, Lecturer and Module Coordinator for Internet of Things and Big Data Analytics at the Sri Lanka Institute of Information Technology (SLIIT), for her valuable guidance, encouragement, and expert support throughout this project. We would also like to thank our course coordinators, academic staff, and lab instructors at SLIIT for providing us with the technical direction and resources necessary for successful system development and testing.

Table of Contents

TABLE OF FIGURE

1 Introduction

Refrigerators are essential household and commercial appliances used to store perishable food items. However, food spoilage and inefficient storage remain significant challenges, leading to waste and increased energy consumption. According to the Food and Agriculture Organization (FAO), approximately 1.3 billion tons of food are wasted globally each year, with a significant portion attributed to improper storage conditions. In the United States alone, 30-40% of the food supply is wasted, costing an estimated $161 billion annually. Similarly, in developing countries, inefficient refrigeration leads to substantial food losses, impacting food security and economic stability.

Figure 1.1 spoil food images

Beyond financial losses, spoiled food can pose serious health risks. Consuming expired or improperly stored food increases the likelihood of foodborne illnesses, leading to conditions such as food poisoning, bacterial infections, and other health complications.

The Smart Refrigerator Monitoring System aims to provide real-time insights into temperature, humidity, food freshness, and door activity using IoT-based sensors. The collected data will be continuously stored on a cloud platform, visualized through Power BI, and analyzed to optimize storage conditions and minimize waste, ultimately promoting better food safety and sustainability.

2 Problem Statement

Food spoilage remains a significant concern in both domestic and commercial refrigeration, leading to substantial economic losses, resource waste, and potential health hazards. One of the primary causes of food deterioration is the failure to maintain optimal storage conditions within refrigerators and cold storage units. Factors such as fluctuating temperature, elevated humidity levels, and the emission of spoilage-related gases often go unnoticed until the food has already degraded. Traditional refrigeration systems typically lack the capability to monitor and respond to these changes in real-time, leaving users unaware of the gradual decline in food quality.

Moreover, user behavior, such as frequent or prolonged door openings, further exacerbates these issues by disrupting internal conditions, leading to increased energy consumption and reduced cooling efficiency. Over time, this not only accelerates food spoilage but also contributes to higher energy costs and carbon footprints.

Despite advancements in refrigeration technology, there is a noticeable gap in intelligent, automated solutions that can detect environmental anomalies and provide timely alerts to users. The absence of such systems limits the ability to implement proactive food management strategies.

To address these challenges, this project proposes the development of an Internet of Things (IoT)-based smart refrigeration monitoring system. The system will integrate sensors to continuously track key parameters such as temperature, humidity, and gas levels. By leveraging real-time data processing and alert mechanisms, the system aims to enhance food preservation, improve energy efficiency, and empower users with actionable insights. This solution is expected to contribute significantly to sustainable food storage practices and the reduction of food waste.

Figure 2.1 Problem statement image

3 Objective

The primary objective of this project is to design and develop an IoT-based smart monitoring system for refrigeration units that ensures optimal food preservation through real-time environmental monitoring and alert generation. Specifically, the system aims to

- Monitor key environmental parameters

The system will use sensors to continuously track critical conditions inside the refrigerator primarily temperature, humidity, and gas emissions (e.g., ethylene, CO_2, or other spoilage-indicating gases). Monitoring these parameters helps identify early signs of food spoilage or deviation from optimal storage conditions.

- Detect abnormal conditions

By setting threshold values for each parameter, the system can automatically detect anomalies. For instance, a sudden rise in temperature or a spike in gas concentration could indicate a malfunction or that certain food items are starting to spoil. Detecting these issues early allows users to take corrective action before the food becomes unsafe or inedible.

- Provide real-time alerts and notifications

The system will be connected to a mobile app or web dashboard that sends instant alerts to users when an abnormal condition is detected. These alerts may include warnings such as "Temperature too high," "Gas emission detected," or "Door left open for too long," helping users respond promptly and prevent spoilage.

- Analyze user behavior patterns

In addition to monitoring the internal environment, the system will track how often and how long the refrigerator door is opened, since this directly affects temperature and humidity stability. By analyzing these patterns, the system can inform users about behaviors that waste energy or compromise food preservation, encouraging more mindful usage.

- Support data logging and visualization

All monitored data will be logged over time and made accessible through charts or graphs in the user interface. This enables users to visualize trends, such as how temperature fluctuates throughout the day or how gas levels increase as food ages. Such insights can help users improve storage habits and reduce food waste over the long term.

4 Methodology

4.1 System Overview

This project employs a systematic approach to design and implement an IoT-based smart refrigeration monitoring system that enables real-time data visualization and food preservation insights. The methodology consists of six core stages: sensor integration, data transmission, cloud processing, database storage, data visualization, and dashboard deployment.

4.2 Sensor Integration and Data Collection

An ESP32 microcontroller is used as the central unit for collecting environmental data from multiple sensors embedded within the refrigerator:

- DHT11 and DHT22: Measure temperature and humidity at two different locations to ensure accurate environmental profiling.
- MQ135 Gas Sensor: Detects harmful gases and spoilage-related emissions such as ammonia or CO_2.
- Magnetic Reed Switch: Tracks the number of times the refrigerator door is opened.

The ESP32 collects sensor data at 1-minute intervals and formats it into a JSON payload including fields such as temperature, humidity, gas levels, doorCount, and timestamps.

4.3 Data Transmission via Azure Function

The ESP32 transmits data to the cloud using an HTTP POST request directed to an Azure Function App developed in Node.js. This function acts as a lightweight cloud gateway that:

- Receives the JSON payload.
- Parses the incoming data.
- Establishes a secure connection to an Azure SQL Database.
- Inserts the parsed data into a predefined table (Fridge Data).

To ensure data security, SQL credentials and connection strings are stored in the Azure Function’s App Settings environment.

4.4 Real-Time Storage in Azure SQL Database

The Azure SQL Database serves as the central storage for all sensor data. A structured table schema was created to align with incoming data fields:

- date, time

- temperature_dht11, humidity_dht11
- temperature_dht22, humidity_dht22
- gas1, gas2
- doorCount

This allows for efficient storage, indexing, and querying of large volumes of time-series data, which is essential for real-time analytics and visualization.

4.5 Visualization in Power BI Desktop

The sensor data stored in Azure SQL is connected to Power BI Desktop using DirectQuery mode, enabling live access without importing data. The visualization layer includes:

- Line charts for temperature, humidity, and gas levels over time.
- Real-time door activity tracking.
- DAX-based status indicators to classify readings (e.g., Good, Warning, Critical).
- Calculated measures to compute rolling averages (e.g., 30-minute mean values).

The report is configured with Auto Page Refresh set to 1 minute to reflect real-time updates.

4.6 Dashboard Deployment in Power BI Service

The report is published to the Power BI Service, making it accessible through a secure, shareable web link. Within the Power BI workspace:

- The SQL database credentials are reconfigured for cloud access.
- Scheduled refresh and DirectQuery are enabled for continuous data updates.
- Role-based access can be implemented to limit dashboard visibility.

This provides users with a web-based interface for monitoring fridge health in real time.

4.7 End-to-End Data Flow

This real-time, cloud-based methodology ensures continuous monitoring, fast response to environmental changes, and actionable insights for users to minimize food spoilage and improve energy efficiency.

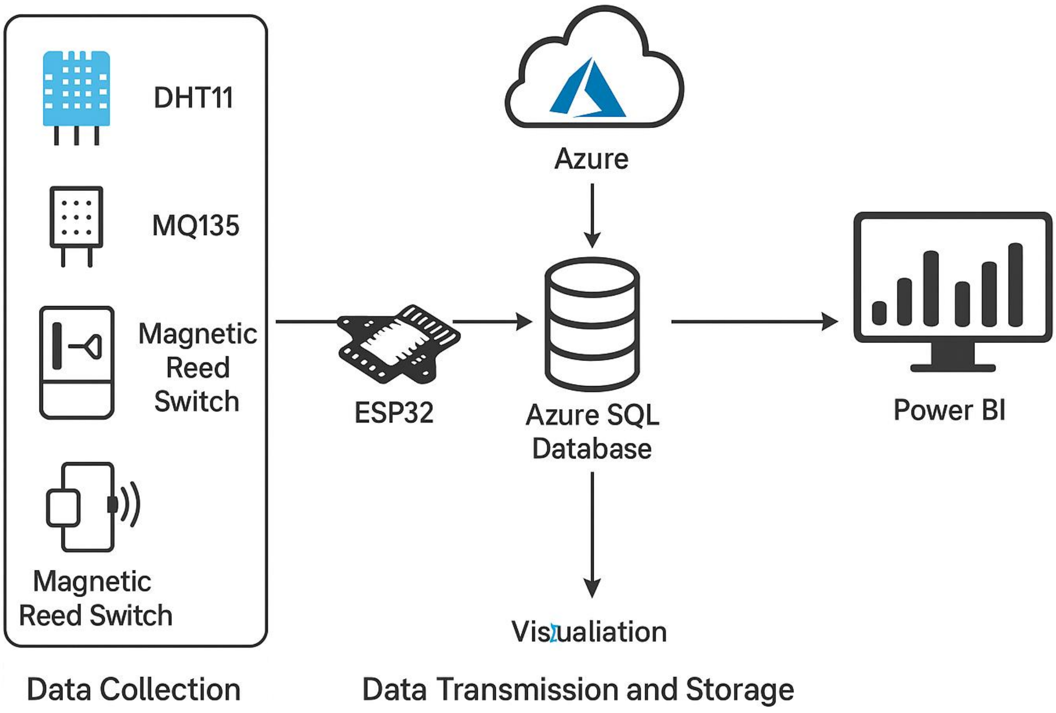

Figure 4.1 end to end data flow diagram

5 Overall Architecture diagram

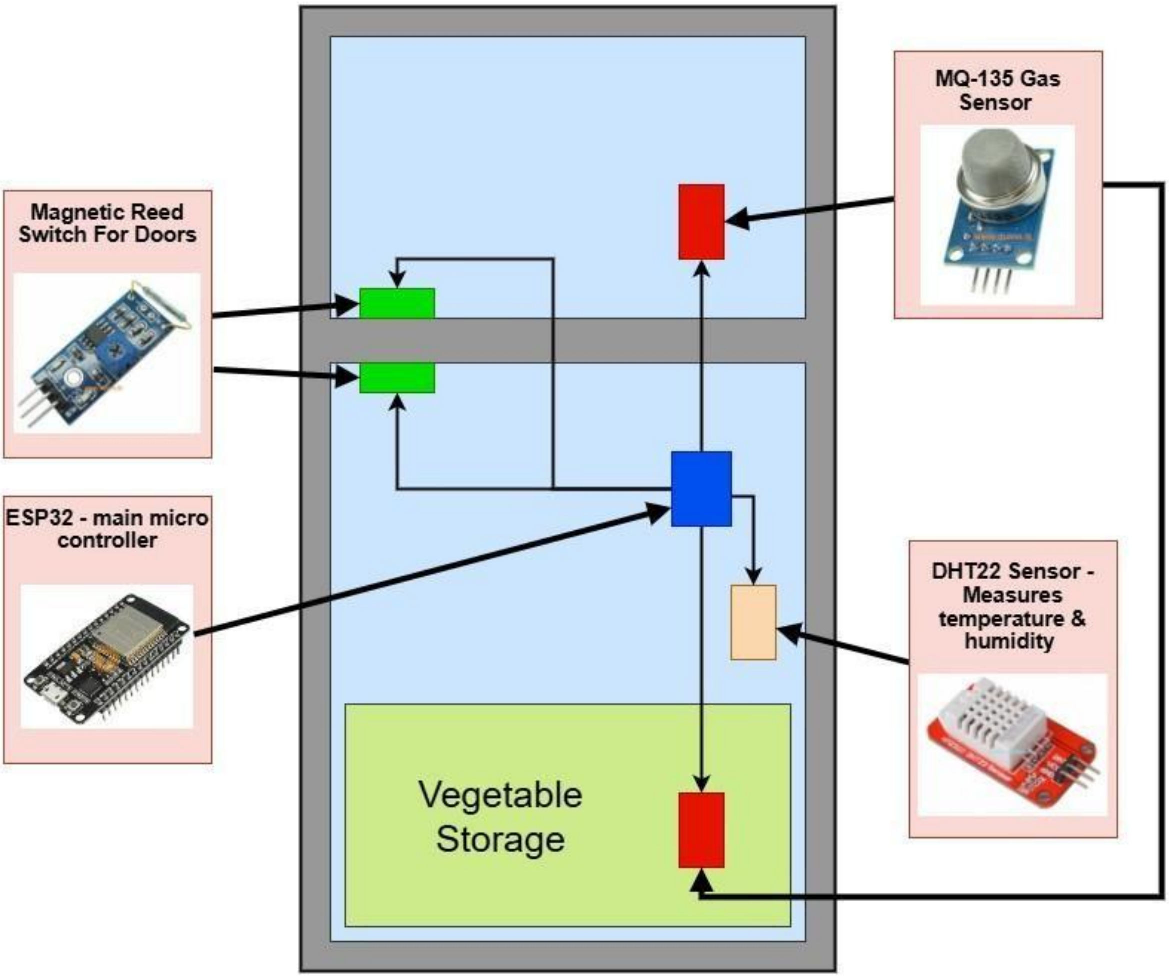

Figure 5.1 overall system diagram

The smart refrigeration system is powered by an ESP32 microcontroller, which collects, processes, and transmits real-time data from various sensors to the cloud. It also triggers alerts when abnormal conditions are detected. The MQ-135 gas sensor monitors air quality inside the fridge by detecting harmful gases like ammonia and CO_2, indicating potential food spoilage. The DHT22 sensor tracks temperature and humidity to ensure optimal storage conditions, triggering alerts if readings exceed safe limits. Additionally, a magnetic reed switch monitors door activity, helping to detect energy inefficiencies caused by frequent or prolonged door openings. All sensor data is analyzed and visualized through a cloud-connected dashboard for actionable insights.

5.1 Schematic diagram

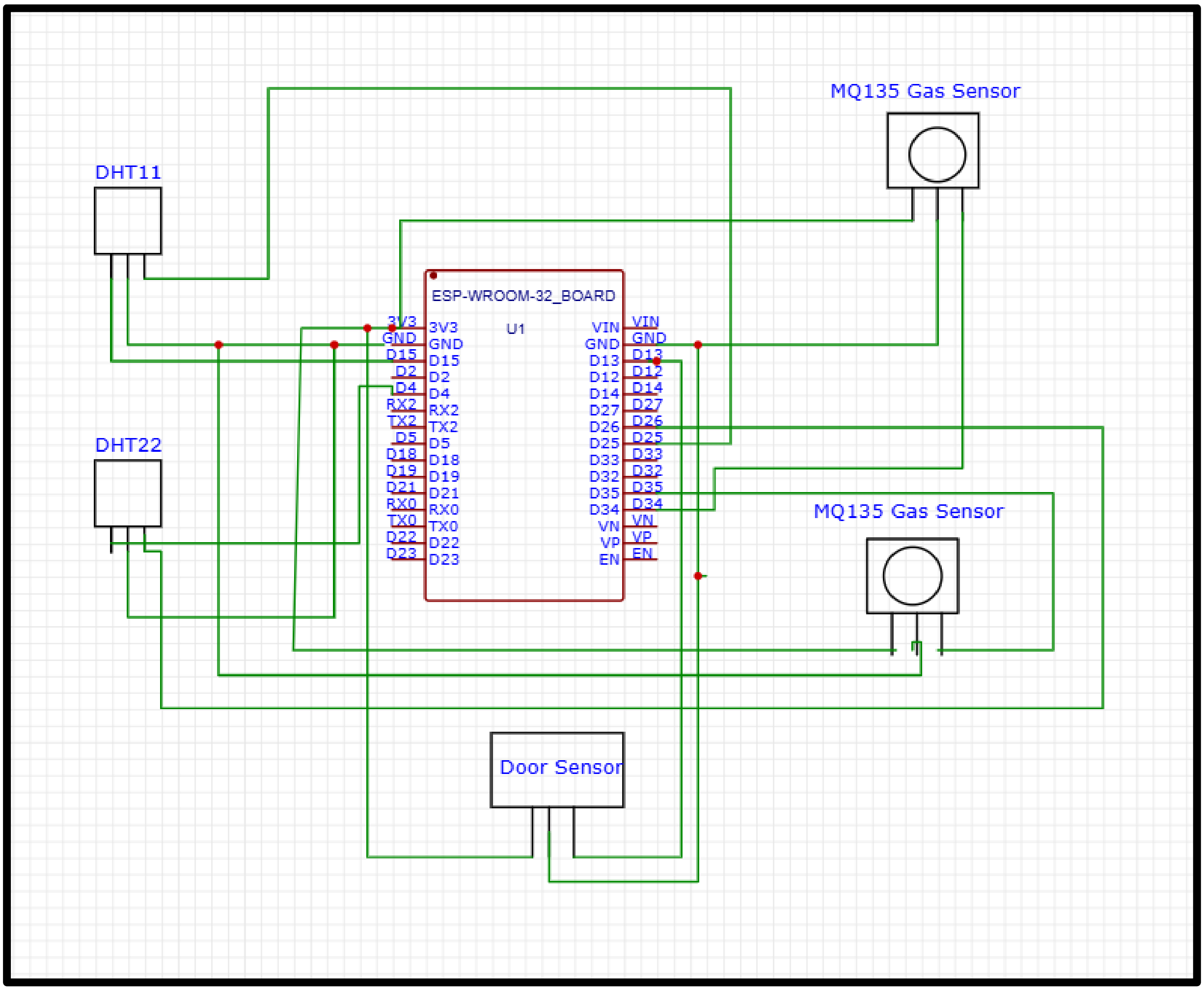

Figure 5.2 schematic diagram of Esp 32

This schematic diagram illustrates the hardware architecture, showing how each sensor is connected to the ESP32 microcontroller for data acquisition and transmission.

6 Data Analysis and Insights

6.1 Power BI Dashboard Design and Interpretation

As part of the smart refrigerator system, a series of interactive and visually structured dashboards were developed using Microsoft Power BI to transform raw sensor data into actionable insights. These dashboards serve as the primary medium for monitoring, analyzing, and understanding environmental conditions inside the refrigerator in real-time and over extended periods. The visualizations are built upon continuous data streams collected from embedded IoT sensors including temperature, humidity, gas concentration, and door activity sensors and are organized to provide both instantaneous feedback and historical analytics.

The dashboard system is divided into several dedicated views, each targeting a specific aspect of refrigerator performance and food preservation: real-time monitoring, historical analytics, fridge condition assessment, and food status tracking. Each view has been thoughtfully designed to present complex data in a simplified, user-friendly format while supporting advanced filtering, drill-down capabilities, and trend interpretation. The combination of summary indicators, time-series graphs, and contextual insights empowers users to make informed decisions regarding energy efficiency, food safety, and maintenance.

The following sections provide a detailed explanation of each dashboard view and its contribution to the overall system intelligence. Each metric displayed on the dashboard is based on the average value over the most recent 30-minute window, ensuring stability and accuracy in the assessment while still reflecting real-time behavior.

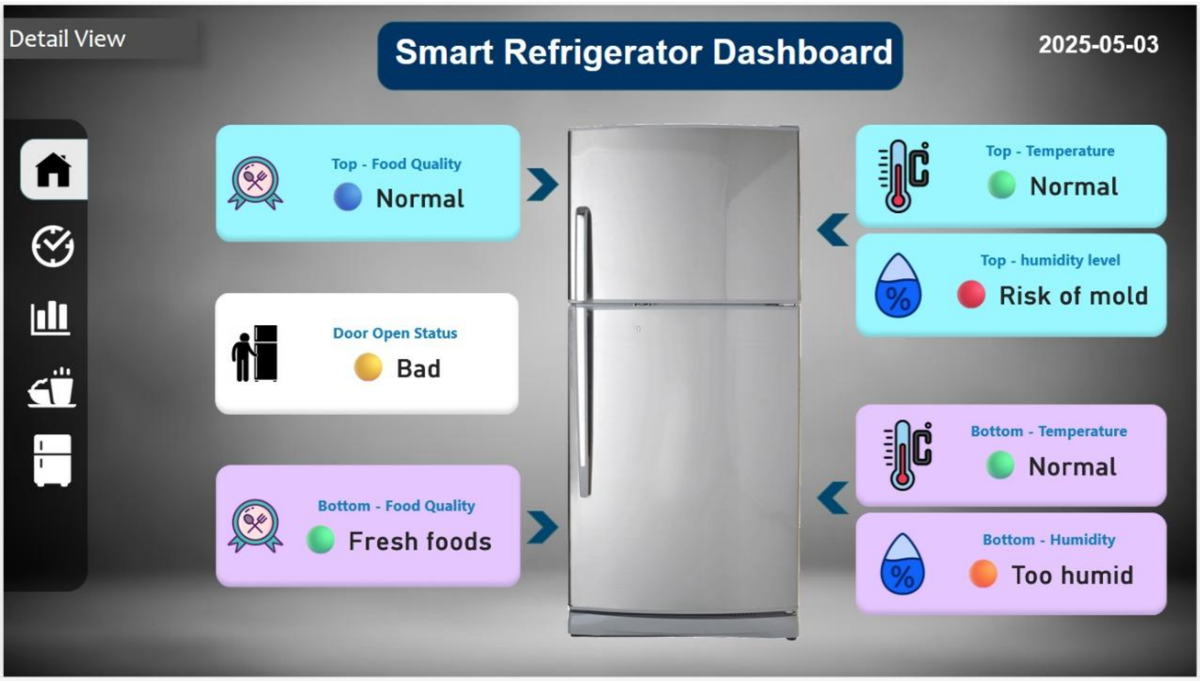

Figure 6.1 Home Page Of Smart Refrigerator Dashboard

Key Logical Components:

Food Quality Status: Food quality is estimated using gas concentration levels (from the MQ135 sensor), which indicate the presence of spoilage-related gases. If gas levels are low, the food is assumed to be fresh. Moderate levels suggest the start of spoilage, and high levels indicate likely food deterioration. The dashboard labels these statuses accordingly as “Good,” “Normal,” “Spoiling Detected,” or “Likely Spoiled.”

Humidity Level Analysis: The humidity levels inside the refrigerator compartments are classified based on thresholds that reflect mold risk and food preservation efficiency. Humidity above 80% is flagged as a “Risk of Mold,” while moderate levels indicate “Too Humid.” Ranges between 45% and 65% are considered “Normal,” and values below that indicate “Good Dry Air,” suitable for preserving food freshness.

Temperature Status: Temperature readings are evaluated separately for the top (fridge) and bottom (freezer) compartments using food safety guidelines. The fridge compartment is ideal when maintained between 1°C and 4°C, while the freezer section is optimal between -18°C and -22°C. Based on the detected temperature ranges, the system categorizes conditions from “Very Cold” to “Very Bad,” depending on how suitable the environment is for preserving different types of food.

Door Open Status: The frequency of refrigerator door openings is monitored continuously. A high number of openings over time indicates inefficient handling and potential exposure to ambient air. Based on the total door open count, the dashboard classifies the status from “Good” to “Very Bad,” highlighting operational efficiency and energy waste.

The dashboard uses a color-coded system and intuitive icons to make information digestible even at a glance. This enhances usability for both technical users and general audiences. By combining real-time sensor data with clearly defined classification logic, the dashboard enables proactive responses to spoilage risks, energy inefficiency, and storage safety concerns.

6.1.1 Real-Time Monitoring Dashboard

The real-time data is visualized using direct query connections to the cloud-based SQL database, enabling continuous updates without the need for manual refresh or scheduled synchronization. This setup ensures that users can observe the latest readings at any given moment, effectively transforming the system into a live monitoring tool.

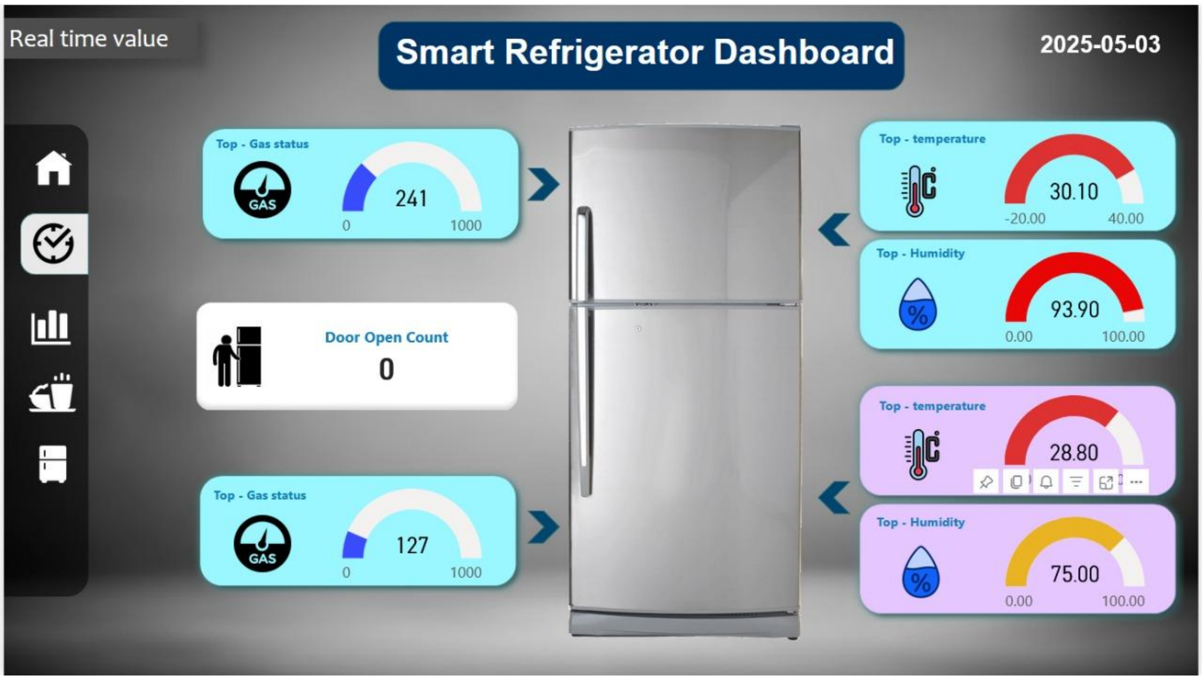

Figure 6.2 Real Time Data View DashboardKey parameters displayed include:

Gas Concentration Levels: Real-time gas status values from the MQ135 sensor are presented using radial gauges, representing current air quality conditions in both the top and bottom compartments. These values help identify early signs of food spoilage or chemical build-up.

Temperature Readings: Live temperature data is shown separately for the top (fridge) and bottom (freezer) compartments. Radial dials clearly indicate whether the current readings fall within acceptable food safety ranges, allowing immediate recognition of abnormal thermal conditions.

Humidity Levels: Humidity sensors continuously stream data to reflect moisture conditions. Excessive humidity is flagged visually, as it can lead to mold formation or accelerated spoilage. This real-time monitoring is crucial for maintaining optimal storage environments.

Door Open Count: The dashboard also includes a live door open counter, which reflects the number of times the refrigerator has been accessed. Monitoring this behavior helps evaluate energy efficiency and potential cooling disruptions due to frequent access.

The design emphasizes clarity and usability, using color-coded indicators and gauge visuals to convey sensor values in a manner that is both informative and intuitive. Real-time monitoring supports proactive interventions, such as adjusting temperature settings or checking food quality based on live gas readings.

6.1.2 Analytic View Dashboard and Insight Generation

The Analytic View Dashboard was developed to provide a deeper, data-driven understanding of the environmental behavior within the smart refrigerator system over an extended period. While the real-time dashboard offers momentary values, the analytic view focuses on historical trends and cumulative patterns, allowing for robust performance evaluation, anomaly detection, and usage diagnostics.

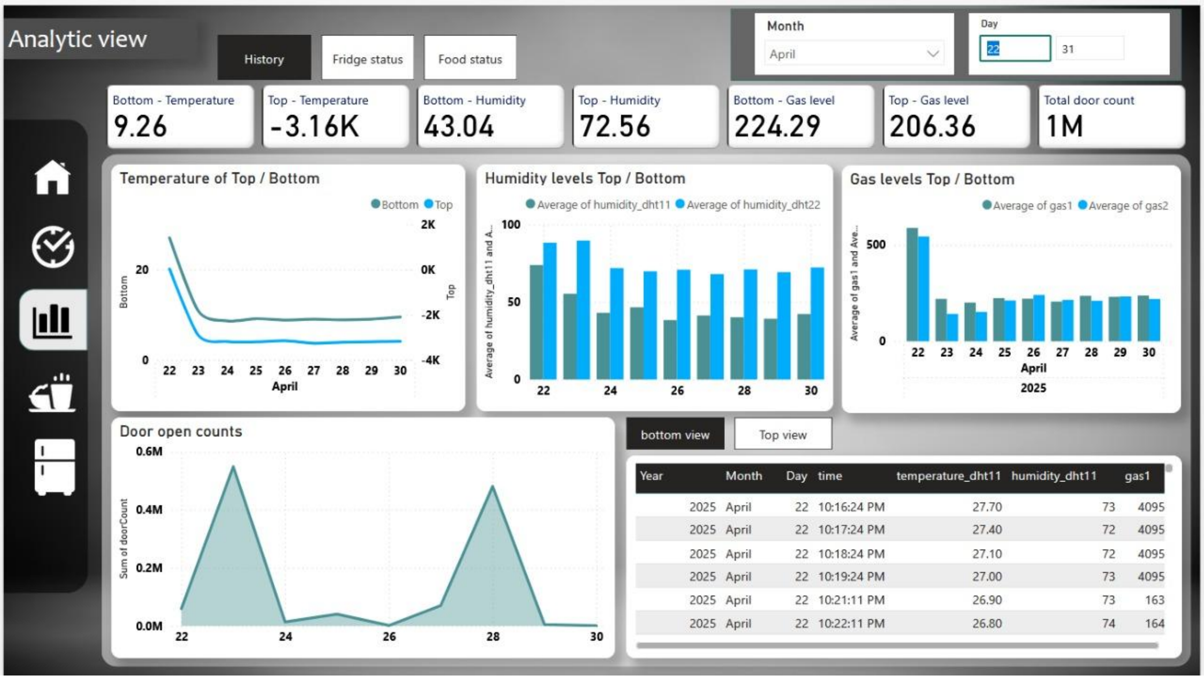

Figure 6.3 Analytic View Dashboard and Insight Generation

Purpose and Design Objectives

The core objective of this dashboard is to transform historical sensor data into meaningful visual insights, supporting both technical analysis and decision-making. It is designed to allow users to:

- Identify irregularities in temperature, humidity, or gas concentration over time.
- Understand long-term trends in fridge usage and environmental stability.
- Compare top (fridge compartment) and bottom (freezer compartment) conditions side by side.
- Drill down into specific windows (by day or hour) for precise incident tracking.

Key Components and Functionality

At the top, key summary cards display average values for:

- Top and bottom compartment temperatures.
- Humidity levels from both compartments.
- Gas concentration levels from the MQ135 sensors.
- Total cumulative door open count.

These indicators provide a quick snapshot of system behavior over the selected time period (e.g., April), helping to assess whether optimal storage conditions were consistently maintained.

Time-Series and Comparative Charts

- Temperature Chart (Top / Bottom)

A line graph compares temperature variations in both compartments over several days. This visualization reveals cooling trends and highlights any deviations that may suggest system inefficiencies or operational issues.

- Humidity Chart

A bar chart illustrates daily averages from both humidity sensors (DHT11 and DHT22), distinguishing top and bottom readings. This aids in identifying areas where humidity may be excessive, contributing to potential spoilage or mold risk.

- Gas Level Chart

Another bar chart displays average daily gas sensor readings from both compartments. Monitoring these values helps detect the onset of food spoilage based on volatile organic compound buildup, enhancing food safety oversight.

- Door Open Count Chart

This area chart visualizes the frequency of door openings over time, offering insights into user behavior and its impact on energy efficiency and internal temperature control.

- Interactive Drill-Down Filtering

The dashboard is equipped with date filters, allowing users to narrow down the analysis to specific months, days, and even hourly segments. This interactivity enables precise temporal analysis, such as pinpointing the exact time a condition started to deteriorate (e.g., humidity spike or temperature drop).

- Detailed Tabular View

At the bottom, a structured table displays raw sensor data entries in chronological order. Each row includes:

- Date and timestamp
- Temperature and humidity readings
- Gas sensor values

This detailed breakdown complements the charts by offering a granular view of the collected data, suitable for technical validation, debugging, or audit trails.

By presenting historical data through visually engaging and highly interactive elements, the Analytic View Dashboard bridges the gap between raw sensor data and actionable intelligence. Users can not only evaluate the performance consistency of the refrigerator system, but also derive insights to improve maintenance schedules, adjust storage practices, and enhance food preservation strategies. This dashboard plays a vital role in converting the sensor data into a comprehensive analytical framework. It supports proactive decision-making, facilitates root cause analysis in the event of spoilage or failure, and contributes to the overall efficiency and reliability of the smart refrigerator system.

6.1.3 Fridge Condition Dashboard

The Fridge Condition Dashboard was developed to provide a focused evaluation of the refrigerator's internal temperature performance, with a particular emphasis on food safety and cooling efficiency. This dashboard visualizes key temperature trends and anomalies using sensor data from the DHT11 and DHT22 temperature sensors, helping users assess whether the refrigerator has consistently maintained optimal storage conditions

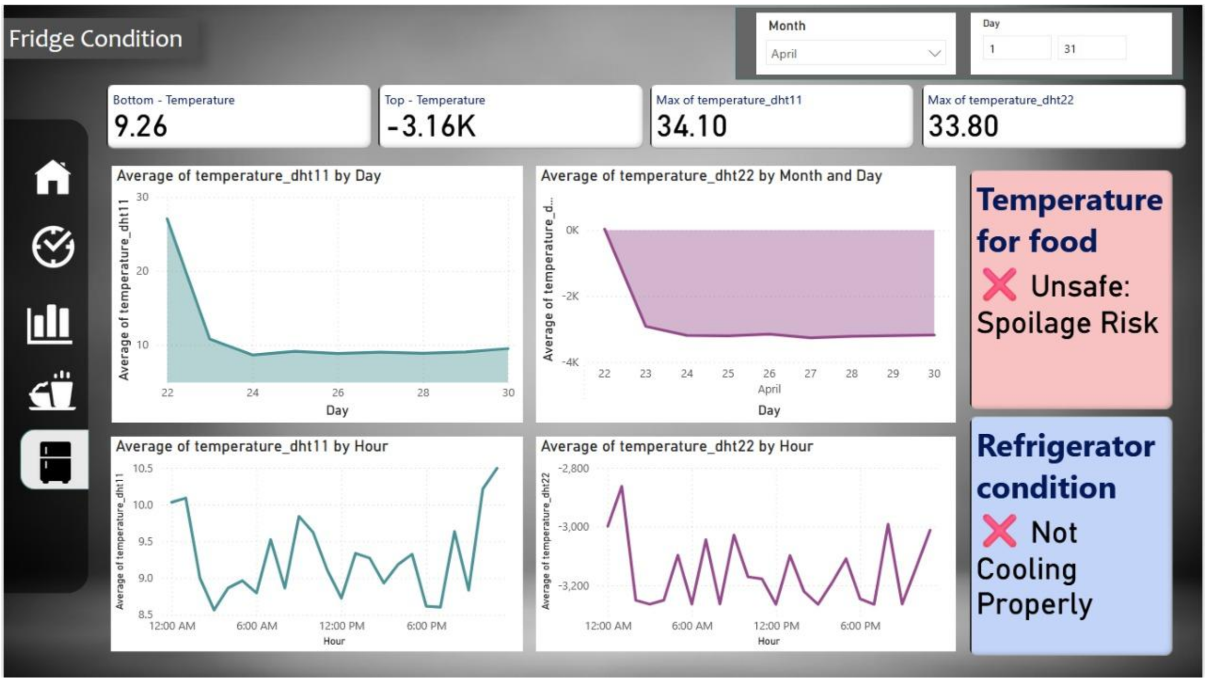

Figure 6.4 Fridge Condition Dashboard

Purpose and Insights

This dashboard aims to:

- Evaluate historical cooling behavior based on day-wise and hour-wise temperature readings.
- Identify risks of food spoilage due to sustained high internal temperatures.
- Highlight abnormal cooling patterns, indicating possible malfunctions in the refrigerator system.

Key Features and Components

The top section displays important metrics, such as the average top and bottom compartment temperatures, along with the maximum recorded temperatures for each sensor during the selected time range.These figures immediately alert the user to any temperature spikes that may indicate spoilage risk or system malfunction.

Daily and Hourly Temperature Trends:

Line graphs track the average temperature readings over time from both DHT11 (top) and DHT22 (bottom) sensors.

Separate charts are provided for daily trends and hourly fluctuations, offering both macro and micro perspectives of the refrigerator's cooling behavior.

The visual differentiation between sensors and compartments allows easy comparison of performance across the entire appliance.

Alert Panels:

- Two clearly labeled alert panels on the right side of the dashboard provide actionable insights:
- A Food Safety Alert, warning when sustained high temperatures may pose a spoilage risk.
- A Cooling Condition Alert, which flags that the refrigerator may not be cooling effectively based on persistent deviations from expected temperature ranges.

Analytical Value

The dashboard serves as a diagnostic tool for evaluating the operational integrity of the refrigerator. By visualizing long-term temperature behavior, it allows users to:

- Detect signs of inefficient cooling.
- Validate sensor consistency and system stability.
- Respond quickly to potential hazards such as food spoilage or equipment failure.

The inclusion of both hourly and daily resolution supports granular analysis and historical context, empowering users to make informed decisions regarding system maintenance and food storage practices.

6.1.4 Food Status Dashboard

The Food Status Dashboard focuses on analyzing the quality and freshness of stored food by monitoring gas concentration levels inside the refrigerator. Gas sensors (MQ135) installed in both the top and bottom compartments detect the presence of gases such as ammonia, carbon dioxide, and other volatile organic compounds (VOCs), which are commonly released as food begins to spoil. This dashboard visualizes those readings and helps identify spoilage risks through trend analysis.

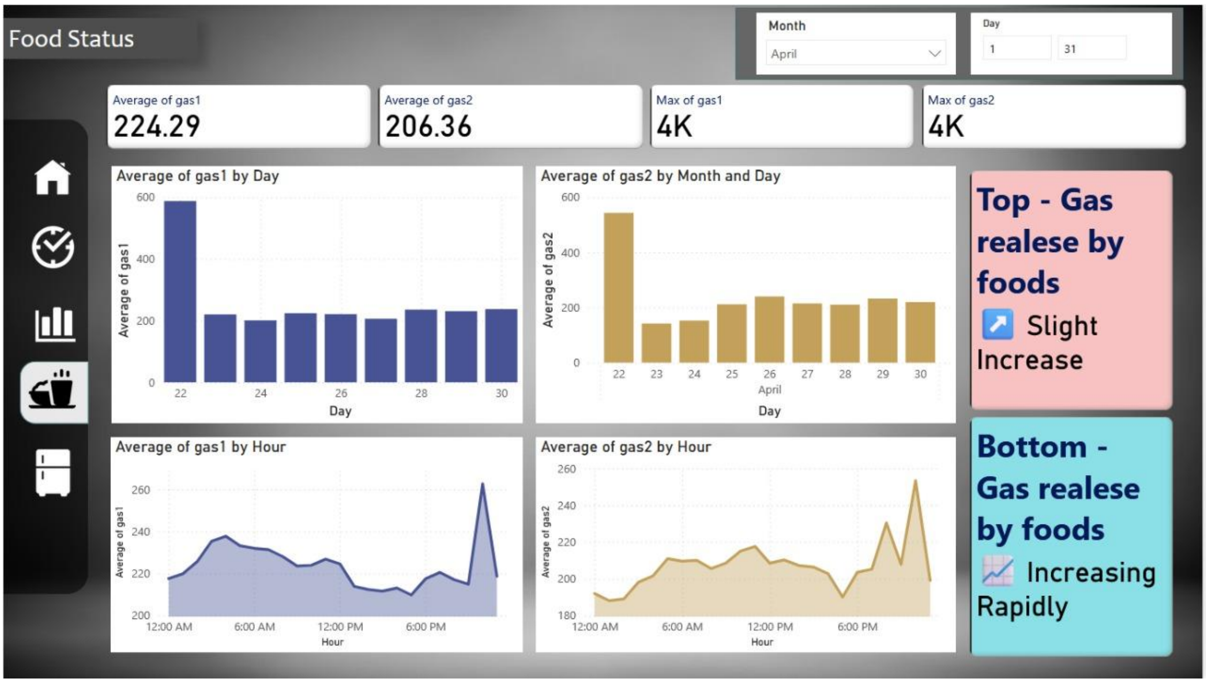

Figure 6.5 Food Status Dashboard

Purpose and Key Indicators

The objective of this dashboard is to

- Continuously monitor gas buildup over time.
- Identify early indicators of food spoilage.
- Compare gas concentration patterns between the fridge and freezer compartments.
- Detect abnormal or rapid increases in gas levels using trend analysis.

Dashboard Components

At the top of the dashboard, average gas values for the current date are displayed for both gas1 (top compartment) and gas2 (bottom compartment), along with their respective maximum recorded values. These help quickly assess the peak and average conditions for food preservation.

Daily and Hourly Trends:

Bar charts represent day-wise averages of gas concentration, allowing users to assess long-term spoilage behavior.

Area graphs show hour-wise gas level changes, offering short-term insight into how food freshness is evolving throughout the day.

By presenting data for both compartments side-by-side, users can evaluate where spoilage is occurring more rapidly and respond accordingly.

Trend Analysis Logic:

A custom logic was implemented to compare gas readings from the last 5 hours against the previous 5 hours.

If the difference is significantly positive, the dashboard classifies the trend as "Increasing Rapidly" or "Slight Increase", indicating active spoilage or environmental deterioration.

Conversely, a negative difference may show as "Decreasing", and minimal change is labeled as "Stable".

These trend summaries are visually represented with arrow symbols and color-coded alerts on the right side of the dashboard for clarity.

Interpretive Panels

Two interpretation panels summarize key findings:

- The top panel reflects gas trends in the refrigerator's upper compartment, where a slight increase in gas level may suggest the early stages of spoilage.
- The bottom panel shows that gas levels are increasing rapidly in the freezer compartment, signaling an urgent need to inspect or remove perishable items.

Analytical Value

This dashboard enhances the smart refrigerator system by enabling proactive food quality monitoring. Instead of relying solely on temperature and humidity, it incorporates a chemical-level dimension to assess spoilage risk. The trend-based classification approach allows users to detect spoilage before visual signs appear, making it a highly effective tool for maintaining food safety and minimizing waste.

By combining real-time readings, historical patterns, and dynamic trend detection, the Food Status Dashboard transforms gas sensor data into actionable insights, supporting both routine fridge management and timely intervention strategies.

Collectively, the dashboards developed for the smart refrigerator system provide a comprehensive framework for environmental monitoring, food quality analysis, and operational diagnostics. By leveraging real-time and historical data visualization through Power BI, the system enables users to observe trends, detect anomalies, and make proactive decisions based on live sensor feedback. The modular design—spanning condition tracking, food status, and usage analytics—ensures that each dashboard contributes uniquely to the goal of maintaining food safety, reducing waste, and optimizing refrigerator performance. This data-driven approach not only enhances user awareness but also demonstrates the practical integration of IoT and business intelligence in smart home applications.

6.2 Predictive Model for Food Spoilage Risk

6.2.1 Predictive Model Design and Risk Labeling Strategy

To enhance the intelligence of the smart refrigerator system, a predictive model was developed to estimate the spoilage risk of stored food based on real-time environmental data. The primary goal of this model was to classify the condition of food into three risk levels Safe, Warning, and High using sensor inputs such as temperature, humidity, and gas concentration. By enabling early detection of unfavorable storage conditions, the model supports informed decision-making to minimize food waste and ensure food safety.

The data used for training the model was collected through an ESP32-based IoT system that continuously recorded sensor readings at one-minute intervals. Specifically, the sensors captured ambient temperature and humidity using the DHT11 sensor and gas levels through the MQ135 sensor. This data was transmitted to an Azure SQL Database (SmartFridgeDB) and stored in the FridgeData table. Before proceeding with model development, the dataset underwent initial cleaning. Records containing invalid values, such as the default gas sensor output (4095), were removed. Additionally, entries from April 22, 2025, which were used for preliminary testing, were excluded to maintain the integrity of the training data.

As the dataset did not include predefined labels, a rule-based labeling mechanism was designed to assign spoilage risk categories. The labeling logic was grounded in empirical thresholds derived from food storage guidelines and practical observations. Entries with temperature values above 11°C or gas concentration exceeding 400 ppm were labeled as High, indicating significant risk of spoilage. If the temperature ranged between 9.5°C and 11°C, humidity between 70–75%, or gas levels between 300–400 ppm, the entry was labeled as Warning. All other entries that satisfied ideal ranges—temperature between 2°C and 9.5°C, humidity between 40–70%, and gas concentration at or below 300 ppm—were categorized as Safe. This approach enabled the construction of a meaningful and supervised classification model tailored to real-world refrigerator monitoring scenarios.

6.2.2 Data Preprocessing and Model Training

Following the data collection and labeling process, a structured preprocessing phase was conducted to ensure the quality and consistency of the dataset before feeding it into the classification model. The selected features for training included temperature (temperature_dht11), humidity (humidity_dht11), and gas concentration (gas1). To prevent anomalies from affecting the model's performance, the dataset was further filtered to exclude any remaining records with missing or abnormal values. The risk labels (Safe, Warning, High) were then encoded into numerical format using a label encoding technique, converting the categorical output into integer values suitable for supervised learning.

Once preprocessing was complete, multiple classification algorithms were evaluated to identify the most effective model for predicting spoilage risk. The training dataset was split into training and validation sets to allow for model evaluation and comparison. Initially, logistic regression was employed as a baseline model due to its simplicity and interpretability. Subsequently, more complex models such as Random Forest Classifier and Support Vector Machine (SVM) were trained and tested. The Random Forest model, in particular, demonstrated superior performance across evaluation metrics including accuracy, precision, recall, and F1-score, attributed to its robustness and ability to handle feature interactions.

To evaluate the performance of each model, a confusion matrix was generated, and cross-validation was used to assess generalizability. The model that achieved the highest balanced accuracy and minimal overfitting was selected for deployment. This selected model was then serialized using the pickle module and saved along with the fitted label encoder. These files were used later in the deployment phase to integrate the predictive capability into the live smart refrigerator system.

6.2.3 Model Deployment and Integration

After successful training and validation, the predictive model was integrated into the smart refrigerator system through the deployment of an automated Azure Function. This serverless function was designed to operate on a timer trigger, executing at five-minute intervals. Each time it was triggered, the function established a secure connection to the Azure SQL database (SmartFridgeDB) and retrieved the most recent sensor readings from the FridgeData table. The fetched data was preprocessed within the function to ensure compatibility with the trained model, and the model along with the label encoder both stored as serialized .pkl files were loaded dynamically during execution.

The Azure Function performed real-time predictions using the latest temperature, humidity, and gas readings and classified the current food condition into one of the three risk categories: Safe, Warning, or High. The predicted outcome, along with the corresponding sensor values and a timestamp converted to Sri Lanka Standard Time (UTC+5:30), was then inserted into a new table named PredictedFoodRisk in the same Azure SQL database. This approach ensured that prediction results were continuously recorded and available for monitoring.

To facilitate visualization and decision-making, the PredictedFoodRisk table was integrated into the Power BI dashboard using DirectQuery mode. This enabled real-time updates of prediction results on the user interface without manual refreshes or data imports. The dashboard presented the risk levels using color-coded indicators and status labels, allowing end users to quickly assess the current condition of food stored in the refrigerator. This seamless deployment not only enabled live inferencing of spoilage risk but also provided an end-to-end automated pipeline from sensor data collection to risk prediction and dashboard visualization.

6.2.4 Model Summary

The development of the predictive model played a crucial role in enhancing the intelligence and usability of the smart refrigerator system. By leveraging real-time sensor data and a rule-based labeling strategy, the model was able to accurately classify food spoilage risk levels using supervised learning techniques. Through a carefully designed pipeline that included preprocessing, model training, and evaluation, a high-performing classifier was selected and deployed using Azure Functions. This deployment enabled automated real-time predictions which were directly integrated into a dynamic Power BI dashboard. Overall, the predictive modeling component added a proactive layer of intelligence to the system, offering both analytical value and practical utility in food safety monitoring.

7 Conclusion

The IoT-based Smart Refrigeration Monitoring System has proven to be a robust, data-driven solution for enhancing food preservation, energy efficiency, and system reliability within refrigeration units. By integrating an ESP32 microcontroller with temperature, humidity, gas, and door sensors, the system enables continuous environmental monitoring and intelligent data capture. The seamless flow of sensor data into the cloud—processed via Azure Functions and stored in an Azure SQL Database—ensures real-time availability and historical traceability of critical parameters affecting food quality and storage performance.

A key highlight of the project is the advanced Power BI dashboard suite, which transforms raw sensor data into actionable insights through real-time monitoring and historical analytics. Four dedicated dashboards Real-Time Monitoring**,** Analytic View**,** Fridge Condition**,** and Food Status have been meticulously designed to simplify complex data into user-friendly visualizations. These dashboards allow users to monitor environmental trends, detect anomalies, and assess fridge conditions and food status with high precision.

The Real-Time Monitoring Dashboard empowers immediate responses by visualizing live temperature, humidity, gas levels, and door access frequency through intuitive, color-coded gauges. The Analytic View Dashboard provides a historical perspective on environmental behavior, enabling trend analysis, anomaly detection, and system usage diagnostics with interactive filtering and time-series charts. The Fridge Condition Dashboard focuses on evaluating temperature stability over daily and hourly intervals, highlighting risks of spoilage and cooling inefficiencies through alert panels and comparative trend graphs. Meanwhile, the Food Status Dashboard introduces a chemical-level monitoring dimension by tracking gas concentration trends that indicate spoilage risks, using dynamic logic to classify the severity of gas buildup over time.

Together, these dashboards form a comprehensive framework that not only enhances situational awareness but also supports proactive decision-making. By combining IoT sensing with cloud computing and business intelligence, the system exemplifies the potential of smart home technology in food safety, energy conservation, and environmental sustainability.

In conclusion, this project demonstrates a successful implementation of an integrated smart refrigeration system that leverages real-time sensor data, cloud architecture, and intelligent visualization to maintain food quality, minimize waste, and optimize operational efficiency. It serves as a scalable and impactful solution, laying the groundwork for future enhancements such as AI-based spoilage prediction, predictive maintenance, and automated control systems in smart refrigeration applications.

Code Repository Link

https://github.com/IOTBDA2025/iot-data-collection-and-analysis-project-2025_07.git

Link to Video Demonstration

IOTBDA Smart Refrigeration System