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Research paper

Revolutionary IoT Cold Chain Monitoring for Freshness Preservation

Sarankumar R [1] *, Chairman M [2], Sooriya Prabha S [3], Manojkumar B [4]

[1] Professor, Department of Electronics and Communication Engineering, Karpagam College of Engineering, Coimbatore, Tamilnadu, India.
[2] Assistant Professor, Department of Electronics and Communication Engineering Dr. Mahalingam College of Engineering and Technology, Pollachi, Tamilnadu, India.
[3] Associate Professor, Department of Electrical and Electronics Engineering, Mother Theresa Institute of Engineering and Technology, Palamaner, Andhra Pradesh, India.
[4] Assistant Professor, Department of Electronics and Communication Engineering, KGiSL Institute of Technology, Coimbatore, Tamilnadu, India.
*Corresponding author E-mail: rmsarankumar@gmail.com

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Abstract

Cold chain development is essential for preserving perishable agricultural products and reducing post-harvest losses. An estimated one-third of the food produced for human consumption is lost or wasted worldwide, resulting in significant negative environmental and economic impacts. This article highlights cutting-edge technologies that improve cold chain efficiency, focusing on key elements of a successful cold chain, including distribution, transportation, and storage. A properly established cold chain can enhance food security, lower waste, and promote sustainable agricultural practices by guaranteeing the integrity of food products from farm to table.

Keywords: *Blynk IoT, ESP32microcontroller, Humidifier, Perishable Goods, Real-Time Monitoring, Sensors, Supply Chain Management, ThingSpeak Cloud platform*

1. Introduction

People eventually start to appreciate the variety, quality, and nutrition of food as human living standards rise. The market is expected to grow significantly as demand for meat, fish, fruits, vegetables, and other goods increases [1]. Food is also susceptible to deterioration and corruption, which results in significant food waste is defined as “the loss of food that occurs at the end of the food”. The United Nations Food and Agriculture Organisation reports that up to 1.6 billion tonnes of food are wasted annually worldwide, with the edible portion accounting for approximately 1.3 billion tonnes. According to the “2022 world food security and nutrition status” report, which five United Nations organisations jointly released in July 2022, there are 828 million hungry people worldwide, which is more than 10 percent of the world’s total population. The severe food crisis affected over 258 million people in 58 nations and areas, compared to 193 million in 53 countries and regions in 2021 [2].

Improper storage and transportation conditions are responsible for a large amount of food deterioration. A key remedy that keeps food safe and fresh from manufacturing to consumption is cold chain monitoring. Cold chain monitoring can increase productivity, reduce spoilage, and enhance food security by incorporating cutting-edge technologies such as blockchain systems, IoT sensors, and AI-powered analytics. The goal of this project is to provide a dependable cold chain monitoring system that helps with sustainable food management by minimising waste and maintaining ideal storage conditions.

A vital part of the supply chain that guarantees the preservation of perishable items from the point of origin to the customer is cold chain logistics. The demand for safe and fresh food products, medications, and other temperature-sensitive goods has increased globally, thereby increasing the importance of cold chain logistics. Predictive algorithms for cold chain logistics have also opened up new opportunities to improve decision-making, reduce waste, and ensure product quality. The integration of multi-temperature delivery systems, distribution route optimization, and the trade-off between product quality and transportation costs are just a few of the industry's always-evolving issues that the report acknowledges the crucial role these technologies play in addressing [3]. Figure 1) represents the perishable goods in a container.

Fig. 1: Perishable goods

2. Related Work:

A supply chain consists of numerous connections and activities. Depending on the type of chain being discussed, everything is different. The type of items transported through that network also affects it. Some products must be handled differently from others, such as those that require maintaining a specific temperature throughout storage and distribution [4]. We refer to such a chain as a cold supply chain. Cold chain management refers to the development of an integrated distribution model centered on three essential elements: product quality, performance characteristics, distribution channels, and product origin and destination locations. The product property factor refers to the physical attributes and unique temperature and humidity requirements during handling, storage, and transportation [5]. The following indicates the product's place of origin and destination, which characterizes the final production and consumption location of temperature-sensitive products. Their interaction enables a comprehensive description of the cold chain, separating it into its following subdivisions. Fruits and vegetables, meat and fish, floriculture, dairy products, confections, and pharmaceuticals are among the industries that use a cold supply chain. (Brzozowska and others, 2016). [4]

Several key elements form the Smart Cold Chain Monitoring System. The GPS mouse, air quality, and temperature and humidity sensors are acquired by a microcontroller for real-time data transmission via WiFi and Bluetooth. The device is mounted in a stationary container truck to monitor environmental parameters during transportation [6]. Fans and humidifiers are used to adjust the relative humidity and temperature to the range set by the Thermostat. Relays and MOSFETs are used to control the fans and humidifiers based on the actuator's sensor readings. Remote environmental data collection is made possible using cloud software (ThingSpeak) while an LCD screen allows for real-time output of fetched data [7].

Lower layers of the system comprise lower-level data manipulation, visualization, alarm, and automation applications, as well as communication and data collection at a peripheral level through sensors. Data stored in a cloud server is accessible from anywhere, making it easier for stakeholders to respond to environmental changes [8]. Cloud storage also enhances data integrity by preventing data loss, improves ease of access for regulatory and analytical purposes, and ensures traceability regarding data destruction.[9] The architecture provides opportunities for enhanced system prominence and major expansion, which permits the Addition of multiple Stakeholders. Figure 2) represents the full hardware kit with components, which is set up with the Blynk IOT app data monitoring.

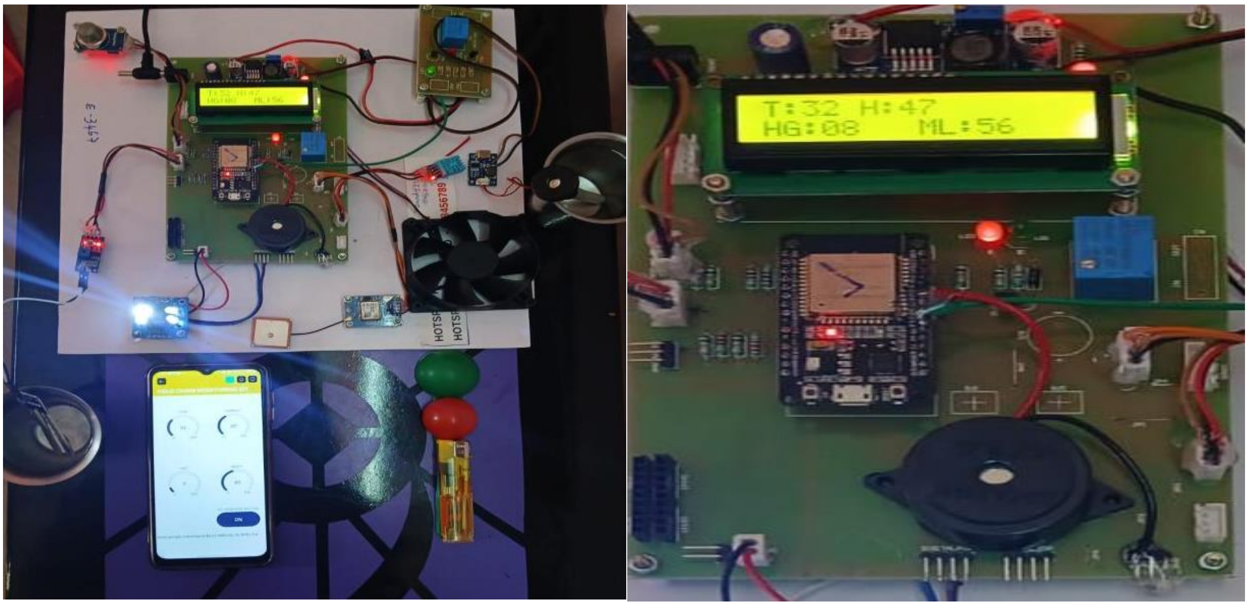


Fig. 2: Cold chain Monitoring system prototype

3. Methodology

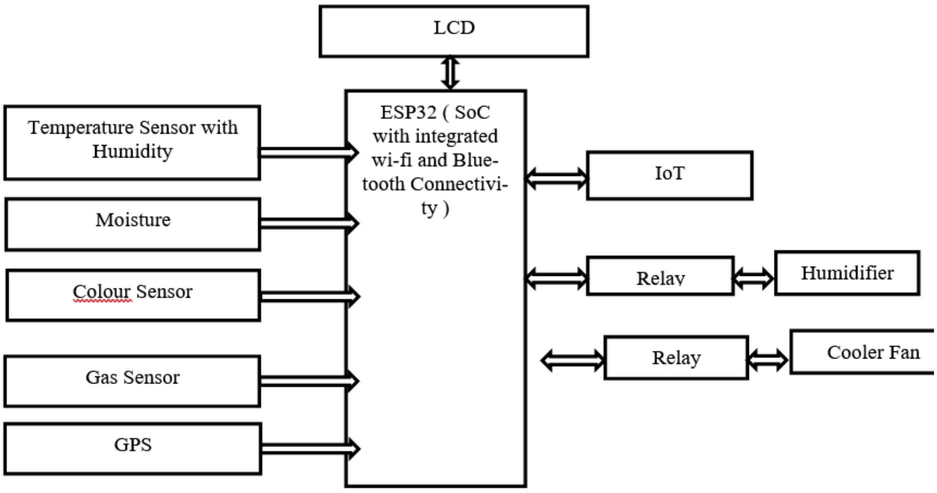


Fig. 3: Block Diagram

The outcome of perishable food products is determined as crucial by logistics. Indeed, producers must provide an efficient logistics system with appropriate handling procedures to guarantee high product quality.During the logistics process, about 35% of chilled foods are damaged due to exposure to inappropriate temperatures and packaging [10]. Figure [3] depicts the block diagram of the methodology. The system makes use of the ESP32 microcontroller, which has a dual-core processor that can operate at up to 240 MHz and has low-power modes that provide a good balance between processing power and power efficiency. Its integrated Bluetooth and 2.4 GHz Wi-Fi allow for smooth wireless connectivity, which makes it perfect for Internet of Things applications at a lower cost than competitors like the Raspberry Pi, which uses more power and needs extra parts. A temperature sensor with an accuracy of ±0.5°C, a gas sensor with tuned detection thresholds that is sensitive to spoilage gases like ethylene, a humidity sensor that measures ambient moisture accurately, and a color sensor that evaluates the quality of products without invasive methods are among the sensors chosen.

Cold processing (primary chilling and secondary cooling), cold storage (storing at controlled temperatures), and cold transportation and distribution (sorting, distributing, and transporting within a specified duration) are the three procedures that can be generally grouped under the umbrella of cold chain logistics. Automation and continuous environmental monitoring are key functionalities in the system's operation [11]. The sensors installed in the container-truck are responsible for continuous monitoring of internal temperature, humidity, and gas concentration. They are integrated with an ESP32 microcontroller and upload their readings to a cloud-based monitoring platform. Automated alerts are triggered in the event that any one of the parameters breaches a specified threshold and are sent to all stakeholders via SMS, email, or push notifications. The system also initiates corrective action, including switching on the fan for temperature or a humidifier to stabilize humidity in a predefined range if needed. The outlet of GPS integration facilitates real-time assessment of environmental conditions and tracking of the transport route for goods being transported. thus ensuring compliance with food safety regulations [12]. Real-time tracking provides supply chain managers with an opportunity to redirect shipments and make modifications to their plans based on environmental conditions—decision-making becomes much more informed. The system will work automatically to bring in nonhuman-dependent control, leaving reliable environment monitoring under any conditions [13]. Figure[4] represents the BlynkIOT App

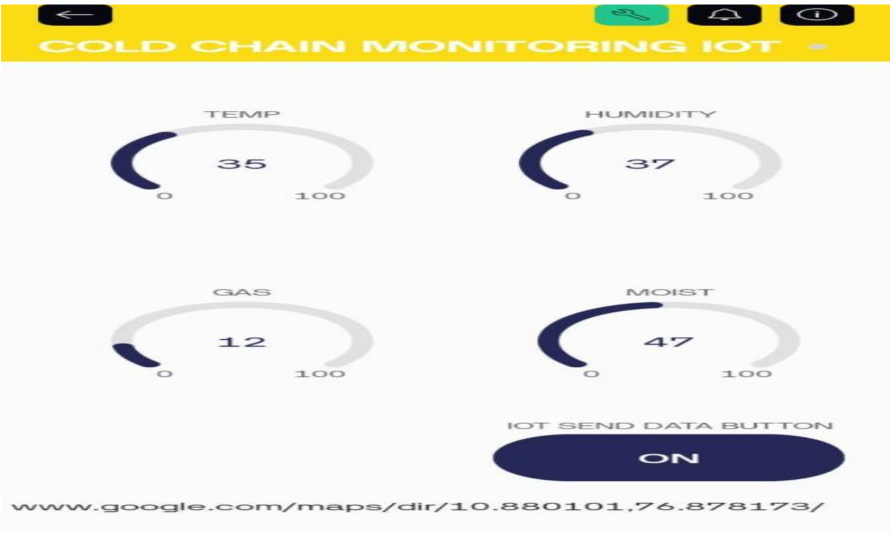
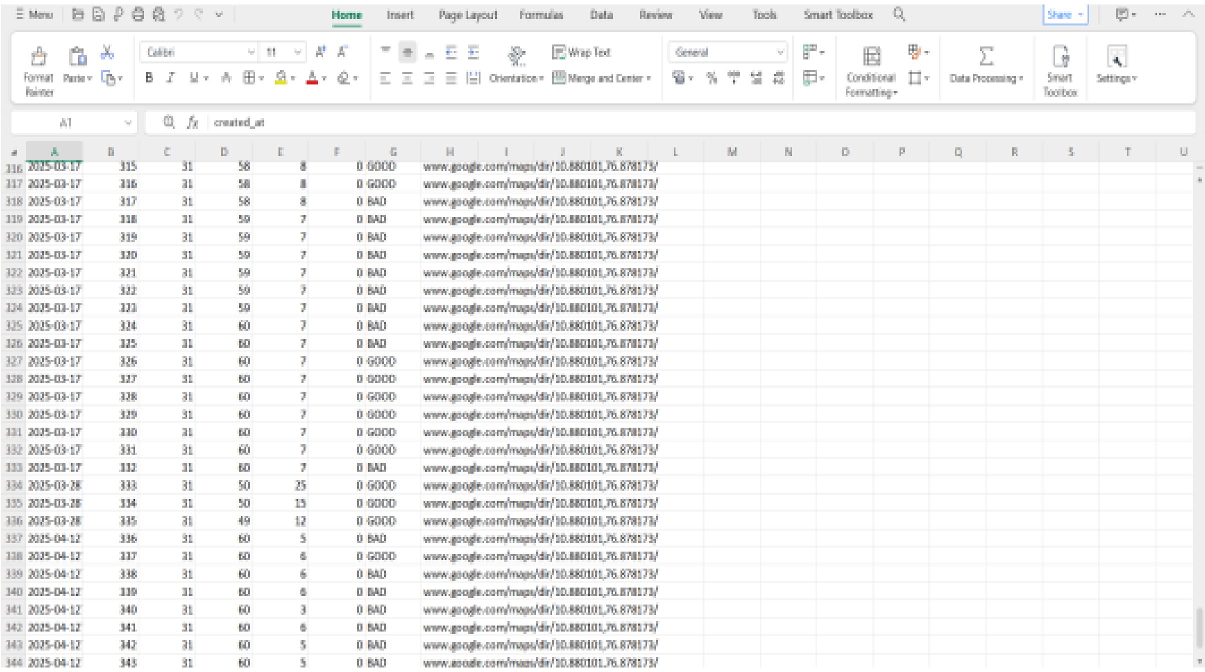


Fig.4: Monitoring the Data In Blynk IOT Represents ThingSpeak cloud Datas



#	A	B	C	D	E	F	G	H
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317	2025-03-17	316	31	58	8	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
318	2025-03-17	317	31	58	8	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
319	2025-03-17	318	31	59	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
320	2025-03-17	319	31	59	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
321	2025-03-17	320	31	59	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
322	2025-03-17	321	31	59	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
323	2025-03-17	322	31	59	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
324	2025-03-17	323	31	59	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
325	2025-03-17	324	31	60	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
326	2025-03-17	325	31	60	7	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
327	2025-03-17	326	31	60	7	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
328	2025-03-17	327	31	60	7	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
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334	2025-03-28	333	31	50	25	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
335	2025-03-28	334	31	50	15	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
336	2025-03-28	335	31	49	12	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
337	2025-04-12	336	31	60	5	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
338	2025-04-12	337	31	60	6	0	GOOD	www.google.com/maps/dir/10.880101,76.878173/
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343	2025-04-12	342	31	60	5	0	BAD	www.google.com/maps/dir/10.880101,76.878173/
344	2025-04-12	343	31	60	5	0	BAD	www.google.com/maps/dir/10.880101,76.878173/

Fig.5: Imported Data viewing in an Excel sheet

A container truck was used to create and test a prototype in a cold storage environment. The system ensured perfect conditions for perishable commodities by tracking and managing environmental factors and calling for alerts at the right time [14]. The performance study revealed greater compliance with standards, a reduction in rotting, and increased efficiency. Figure [5] shows the data in an Excel sheet to view the perishable items. The system was able to turn on cooling systems according to temperature ever since it was tested under various climatic conditions. Efficient transportation of a shipment is necessitated by time and coordination, and adverse consequences can result from any delay, especially if the goods are perishable. Businesses in the food, pharmaceutical, and medical sectors are depending more and more on the cold chain to guarantee the safe transportation of goods. In the cold chain, monitoring is thought to be a crucial component that provides clear proof of responsibility, temperature conditions during transportation, and other logistical tasks. Significant investments are made in recognition of the many advantages of monitoring. However, it is observed that redelivery costs are significantly higher when the product is of poor quality. As a result, it is expected that monitoring will be used more widely and become an even more crucial component of the cold chain. ThingSpeak data logs provided precise environmental condition tracking and visualization, enabling stakeholders to make more informed decisions. Because the warnings were timely, immediate action was taken to avert the expected degradation, which made it possible to reduce waste virtually to zero through

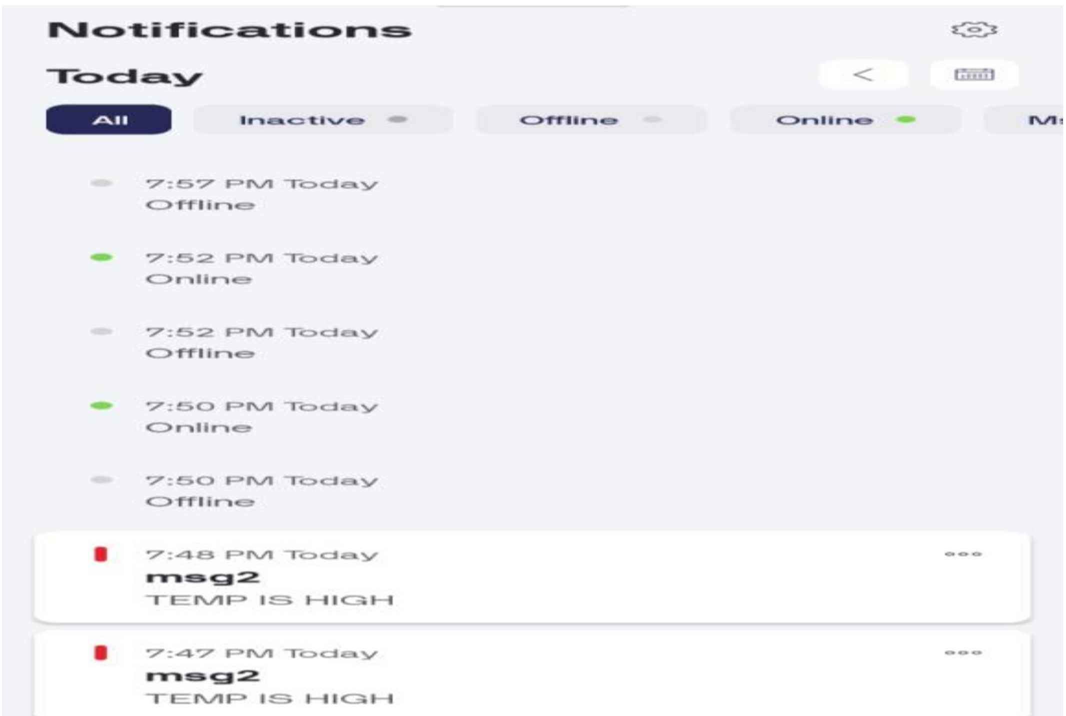

Fig. 6: Notification Message

IoT-based system implementation. The system's reliability in real-world situations was virtually proven by its significant accuracy in monitoring parameters and ensuring proper settings. Figure [6] shows the notification to the system to make a prevention. The improved stakeholders' faith in supply chain performance and product safety validated the applicability of the suggested approach.

These sensors were picked because of their outstanding cost-performance ratio, appropriate measurement ranges, and accuracy. The temperature sensor's precision of ±0.5°C and its ability to reliably detect gases at levels significant to spoiling were validated by prototype testing. In addition to maintaining a quick alert response time of less than two seconds via the Blynk app, which allowed for timely remote monitoring and notifications, pilot storage testing showed a 28% decrease in spoiling rates. Performance, cost, and efficiency are all balanced in the overall design, which makes use of the ESP32's built-in wireless capabilities and the accuracy of the selected sensors to efficiently monitor and lessen spoiling in storage settings.

4. Results and Discussion:

The advantages of a system usable in the food and pharmaceutical supply chain highlighted include real-time tracking, automated alerts, and actionable responses. With an array of real-time insights, enhanced efficiency, and improved safety regulations, IoT-based monitoring solutions have a bright ray of hope in transforming supply chain management. One future addition may be AI-propelled predictive analytics with capabilities for early intervention in the event of deviations. This model is designed to establish a location model for a cold chain logistics distribution center, which involves multiple distribution centers and multiple demand points, using frozen or refrigerated trucks as a means of transportation to deliver a single type of fresh product. The customer demand and geographical location are known, and several addresses are selected from the alternative addresses for the construction of distribution centers, in order to optimize the system's overall service reliability and lower the overall cost of delivering items to customers at these distribution hubs. When considering the associated costs, it is assumed that the system's total cost does not include warehouse storage costs and that the products' delivery temperature can be maintained during transit. As a result, it is possible to assume that the rate at which the delivered fresh products spoil is constant without The system's installation costs are fairly low, and a thorough analysis reveals savings when compared to more sophisticated options like Raspberry-Pi-based solutions, which come with greater power and hardware costs. However, there are scaling issues when implementing this system in remote areas or small-scale farms, especially because of spotty or limited network connectivity. The ESP32's deep sleep mode and intrinsic low-power architecture greatly reduce overall consumption to address energy efficiency, making it appropriate for prolonged field use. The use of solar-powered sensors to guarantee continuous operation without frequent battery changes, modular system designs for flexible scaling, and reasonably priced data plans to sustain connectivity in places with limited network infrastructure are some mitigation techniques to get past deployment obstacles. Together, these strategies improve the system's sustainability, cost-effectiveness, and adaptability in a range of agricultural contexts.

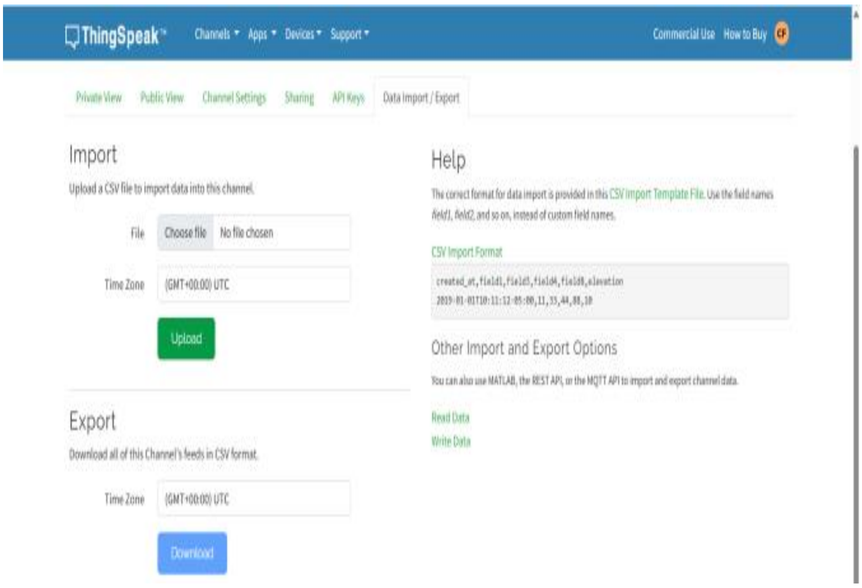

Fig.7: Cloud computing to store data

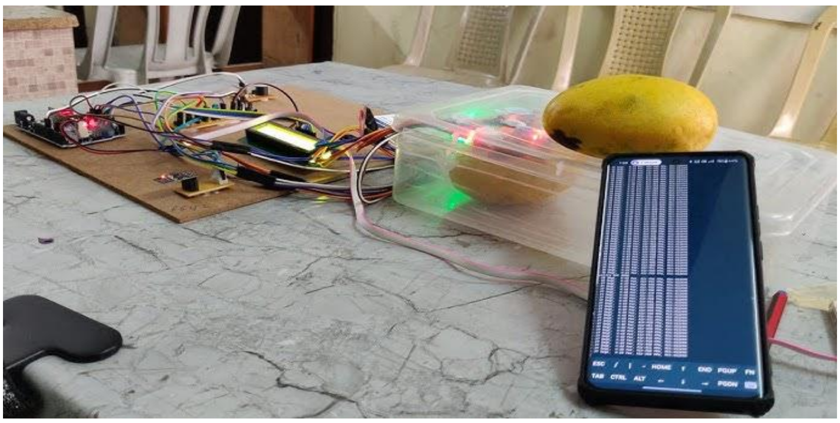

Fig. 8: Viewing the exported data in mobile/System

The Internet of Things-based cold chain monitoring system is a perfect way to ensure visibility in the supply chain, reduce losses, and maintain the quality of perishable products by offering real-time tracking, automated alerts, and corrective actions. It enhances operational efficiency and minimizes human interventions using IoT technologies. Figures 7 and 8 show the viewing of data in the cloud platform through the ThingSpeak platform. Future iterations may embrace blockchain integration for secure and transparent cold chain logistics. Another area for improvement could be based on energy-efficient power sources, such as solar-powered systems. Intelligent cold chain monitoring systems will become common in supply chain management, based on the ongoing growth of IoT and smart monitoring technologies. Figure [9] shows a food check with fresh vegetables. The cooling burden of a few chosen fruits and vegetables is determined using MATLAB. Mango, watermelon, cauliflower, potato, and onion are chosen for this trial, and the daily storage rate is set at 1000 kg. Mangoes and watermelons have a loading temperature of 31°C during kharif, while cauliflower, potatoes, and onions have a loading temperature of 25°C during rabi, which is the average temperature of the cropping seasons. The ambient temperature is 38°C, which is Tamil Nadu's highest average temperature. The storage temperature of the perishable fruits and vegetables mentioned above is used to determine the cold room temperature. Figure [9] represents the Whole project's output by sensing the colour change and gas leakage, finding out the status of the perishable goods.

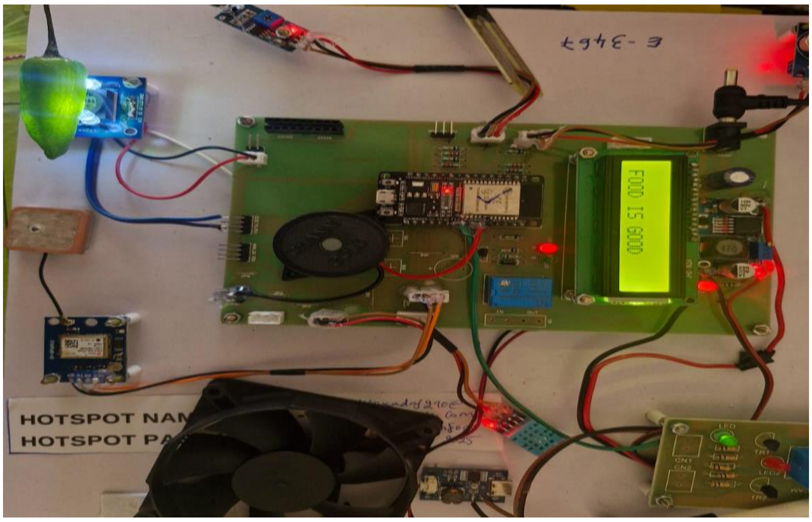

Fig. 9: Food is good, eg, fresh Chili

In the LCD, the Message is shown as "Food is good" and also sends a notification to the Monitoring warehouse. Based on sensor readings, the subtitles "Food is good" and "Food is getting bad" make it obvious that the food is of high quality. While the gas sensor measures spoilage chemicals like ammonia and ethylene to detect early decay, the color sensor detects changes in the food's surface color, which indicates a loss of freshness. Setting baseline values for fresh food and establishing exact criteria for color changes and gas concentrations that cause spoiling alarms were also part of the calibration process. Proactive notifications are made possible by the precise and prompt identification of food deterioration provided by this integrated sensor technology. The calibration and criteria of the device ensure accurate monitoring, assisting users in successfully preventing spoiling.

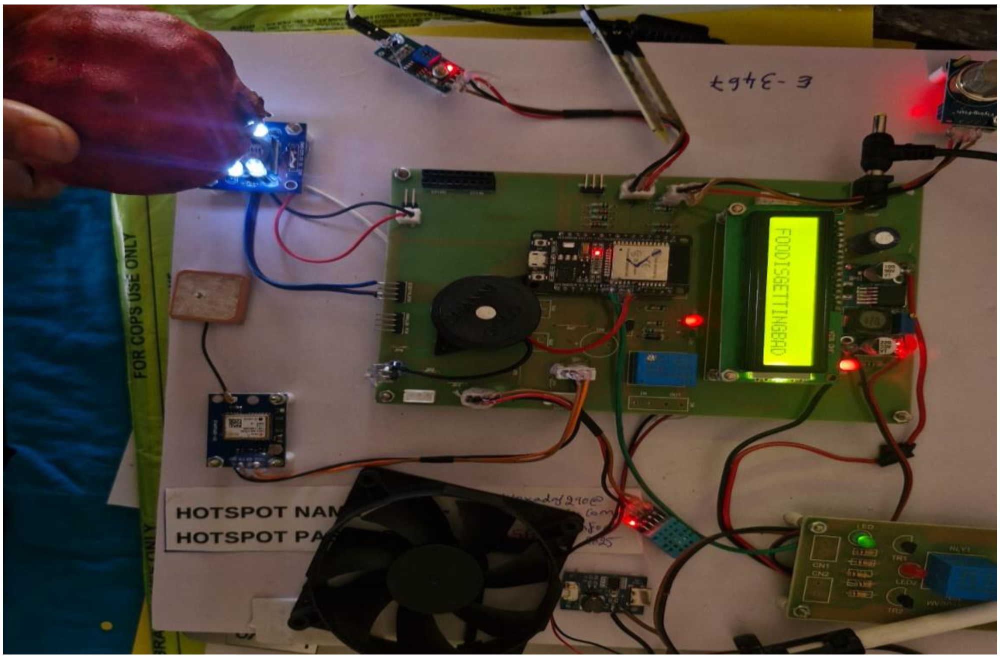

Fig. 10: Food check with a rotten pomegranate. Food is Bad eg, Rotten Pomegranate

Figure [10] represents an LCD Message shown as" Food is getting Bad" and sends a notification to the Monitoring warehouse. With an average alert latency of less than two seconds, a 28% decrease in spoilage rates, and a 96.5% system uptime, the results show dependable and effective operation. Future initiatives suggest investigating blockchain frameworks to improve traceability and incorporating AI models for predictive freshness grading. The generalization of these models to multi-commodity cold chains is the primary focus of research in this area. It is expanding the system's use to cold chains for vaccines and pharmaceutical logistics, where real-time environmental monitoring is essential to preserving product integrity. These additions highlight the system's capabilities beyond food storage and meet the sector's overall needs for accurate, fast tracking, and safe data management.

5. Conclusion

The Smart IoT-Based Cold Chain Monitoring ensures the quality and safety of perishable goods, greatly reduces losses, and considerably enhances supply chain visibility. By employing ESP32 microcontrollers and IoT-enabled sensors linked to cloud-based platforms such as ThingSpeak, the system provides real-time tracking capability, automated alarms, and dynamic control of the environment while in transit. Furthermore, Industry cooperation is a major driver of the cold chain logistics sector's future growth. Vehicle route optimization and cooperative delivery can successfully save operational expenses while controlling energy usage and fixed expenditures. These elements work together to support the sustainable development of the cold chain logistics industry. The cold supply chain is one of the riskier chains. The products that go through it have numerous requirements that need to be fulfilled. Products that are frozen or cold must be kept at a specific temperature to maintain their quality; otherwise, they will spoil. Cold products must be stored and transported under particular circumstances. This prolongs their shelf life and ensures that their quality is maintained for an extended period of transit, while reducing the likelihood of waste, associated emissions, and waste disposal expenses. Monitoring has several advantages, and significant financial investments are made. Therefore, it is expected that monitoring will become increasingly more essential to the cold chain and be used even more broadly.

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