
DEVELOPMENT OF AN IOT BASED SMART SYSTEM FOR COLD SUPPLY CHAIN STORAGE AND TRANSPORTATION

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ABSTRACT

Cold supply chains have gained increased importance due to the demand pressures which arose from higher consumption levels. However, in order to meet the standards and customer requirements regarding the storage and transportation of cold supply chain products, especially foods and pharmaceutical products, it is important to monitor critical environmental conditions throughout the process. Hence, this article presents the development of an IoT-based smart system aimed at optimizing cold supply-chain operations through real-time environmental monitoring. The system utilizes a NodeMCU ESP8266 microcontroller, DHT11 sensor, and 16×2 LCD to acquire and display environmental data. An application called ColdGuard was developed to facilitate remote monitoring and notification. Experimental evaluation in this study focused primarily on temperature monitoring, temperature excursion detection, and communication latency. The results demonstrated satisfactory performance in real-time temperature monitoring and alert generation, with low communication latency. The developed system provides a foundation for enhanced monitoring of environmental conditions in cold-chain storage and transportation.

Keywords: Storage System; Supply Chain; IoT; NodeMCU ESP8266 microcontroller; DHT11 Sensor

1. INTRODUCTION

The Internet of Things (IoT) has emerged as an important technology for improving visibility, traceability, and operational efficiency across supply-chain systems. IoT enables the use of interconnected sensors, communication networks, and data-processing platforms to collect and transmit real-time information about goods, equipment, and environmental conditions (Al Mahmud *et al.*, 2025). Within supply-chain management, its major applications include tracking product location and monitoring storage and transportation conditions (Archana, 2025).

Cold supply chains are particularly dependent on effective environmental monitoring because they handle temperature-sensitive products such as fresh food, vaccines, pharmaceuticals, and chemicals (Mutambik, 2026). These products must be maintained within specified temperature ranges throughout storage, handling, and transportation in order to preserve their safety, quality, and effectiveness (Protopappas *et al.*, 2025). Failure to maintain these conditions may result in spoilage, reduced product efficacy, economic losses, and potential risks to consumers (Snyder *et al.*, 2024).

Conventional cold-chain management methods often rely on periodic manual inspections and standalone temperature-recording devices. Such approaches may not provide timely notification of temperature excursions, equipment malfunction, or transport delays (David, 2026). Consequently, there is a growing need for systems capable of continuously monitoring cold storage facilities and refrigerated vehicles, transmitting data in real time, and alerting relevant personnel when predefined conditions are violated (Puthukkattu Mansoor Ahamed, 2026).

IoT-based systems provide a suitable solution to these challenges by integrating environmental sensors, wireless communication technologies, cloud-based storage, and data-analysis tools (Ramani *et al.*, 2025). These systems can monitor parameters such as temperature, humidity, location, and refrigeration-unit status remotely and in real time. The information generated supports prompt corrective action, improves product traceability, reduces waste, and enhances compliance with cold-chain quality requirements (Lingeswari *et al.*, 2025). As the demand for the safe distribution of

perishable and temperature-sensitive goods continues to increase, the adoption of IoT in cold supply-chain operations has become increasingly important (Müller *et al.*, 2026).

Therefore, this study focuses on the development of an IoT-based system for cold supply-chain storage and transportation. The proposed system is intended to provide real-time monitoring and notification of critical storage and transport conditions, thereby supporting the preservation of product integrity, improved operational efficiency, and reduced losses across the cold supply chain.

The article is structured as follows; section one gives the introduction while section two some of the literatures as regards the cold storage system. Section three gives the materials and methods used in carving out this article. Section four presents the results and discussion with regards to the article. Also, section five is the conclusion and a list of references is given thereafter.

2. LITERATURE REVIEW

This subsection reviews related studies on IoT-based cold supply-chain storage and transportation systems. Cil *et al.*, (2022) developed an IoT-enabled cold-chain monitoring system for refrigerated containers in a port environment. Their system used wireless sensor networks, RFID, GSM communication, and database storage to monitor temperature and humidity in real time and issue visual, audible, e-mail, and SMS alerts. Also, (Lamberty & Kreyenschmidt, 2022) reviewed IoT-enabled sensing technologies for fresh fruit and vegetable supply chains. They identified temperature, humidity, oxygen, carbon dioxide, vibration, and shock as important parameters for preserving product quality during storage and transport. Gillespie *et al.*, (2023) developed a real-time anomaly-detection system for refrigerated food delivery vehicles. The system collected temperature, humidity, GPS, and accelerometer data and used a cloud dashboard and alert algorithm to identify potentially harmful temperature excursions. Goodarzian *et al.*, (2023) designed an IoT-enabled responsive and green vaccine cold-chain network. Their model incorporated artificial-intelligence methods to support temperature-sensitive vaccine distribution while considering responsiveness, environmental impact, and logistical decisions. Wu *et al.*, (2023) developed an Internet-of-Everything and digital-twin service platform for cold-chain logistics. The platform integrated real-time temperature and humidity monitoring, Bluetooth Low Energy positioning, anomaly detection, warehouse-worker safety monitoring, and paperless shipment processes. Alshdadi *et al.*, (2024) demonstrated a low-cost NodeMCU-based cold chain monitoring prototype, the system proposed in this study introduces several distinct operational and empirical enhancements. Unlike existing baseline architectures, our proposed ColdGuard system incorporates a dual-view multi-tenant workflow tailored for commercial logistics—distinguishing between administrative multi-device management and secure, link-based customer shipment tracking. Furthermore, this study extends previous work by explicitly evaluating transmission latency under dynamic thermal fluctuations and assessing sensor responsiveness during transient tampering/lid-opening excursions. Negueroles *et al.*, (2024) developed a blockchain-based digital twin for IoT logistics and transportation. Their study demonstrated how blockchain and digital-twin technologies can strengthen data integrity, fleet management, scalability, and decision-making in logistics applications relevant to refrigerated transport. Xie *et al.*, (2025) proposed a time-temperature coordination strategy for chilled-meat supply chains using cold-chain IoT data. The study modelled product-quality changes and energy consumption, showing that time and temperature can be jointly adjusted to improve freshness and supply-chain benefit. (Müller *et al.*, 2026) reviewed the integration of IoT and artificial intelligence in food cold chains. They concluded that IoT has progressed from simple temperature logging to multi-sensor real-time monitoring, while AI can support predictive risk assessment, failure detection, and logistics optimisation. Wanitwattanakosol *et al.*, (2026) designed an IoT early-warning and value-stream-mapping intervention for a Thai SME cold warehouse. Using ESP32 and DHT22 sensors, commodity-specific alerts, and workflow redesign, the study showed how monitoring and process improvement can jointly reduce food losses.

3. MATERIALS AND METHODS

This subsection presents the materials used in the actualization of this article.

3.1 Sensors: The DHT11 sensor provides a temperature resolution of 1°C (typical accuracy $\pm 2^\circ\text{C}$). Consequently, all temperature readings and threshold comparisons in this study are reported to the nearest 1°C. The DHT11 sensor is a basic, low-cost digital sensor that can measure both temperature

and humidity. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air, providing digital output readings. The DHT11 has a slow sampling rate of once every second and is ideal for projects that don't require high precision or fast updates. It is widely used in various IoT and weather monitoring systems (Marzuki *et al.*, 2026). The system employs embedded temperature and humidity sensors that continuously monitor the conditions within storage facilities and transportation vehicles. These sensors are critical for ensuring that products are kept within the required temperature ranges.

3.2 Microcontroller: The NodeMCU is an open-source IoT platform based on the ESP8266 Wi-Fi module, which combines a microcontroller with Wi-Fi capabilities. It provides a development environment for building connected devices, using the Lua scripting language or Arduino IDE. NodeMCU simplifies the integration of hardware with cloud services, making it ideal for IoT applications. It features multiple GPIO pins, ADC, and PWM capabilities, allowing it to interface with various sensors and actuators (Marzuki *et al.*, 2026). A compact microcontroller with Wi-Fi connectivity serves as the central processing unit of the system. It collects data from the sensors and transmits it to a cloud-based platform for further analysis and monitoring (Kaliaskarov *et al.*, 2026).

3.3 Cloud Storage and Backend Service: The system uses Firebase (Google's Backend-as-a-Service platform) for real-time data storage, synchronisation, and notification delivery. Sensor readings from the NodeMCU ESP8266 are transmitted over Wi-Fi and stored in the Firebase Realtime Database (Li *et al.*, 2025). This enables instantaneous updates on the ColdGuard mobile application dashboard and supports automated email/SMS alerts when temperature thresholds are violated. Firebase was selected because of its low latency, built-in authentication, and straightforward integration with the ESP8266 and mobile clients (Lawrenson & Johnson, 2026).

3.4 Mobile Network Connectivity: Mobile network connectivity refers to the ability of mobile devices, such as smartphones and tablets, to connect to a cellular network for voice, data, and multimedia communication. This connection is provided through wireless communication standards like 2G, 3G, 4G LTE, and 5G, enabling users to access the internet, make calls, send texts, and use applications while on the move. The infrastructure includes cell towers, base stations, and communication protocols that facilitate seamless connectivity across large geographic areas (Parker & di Pietro, 2026). The system utilizes mobile 4G/5G networks to ensure that data transmission is reliable and timely, allowing for immediate notifications in case of any deviations from the set parameters (Nasreddine *et al.*, 2026).

Based on the above components used, the system was coupled using the block diagram given in Figure 1.

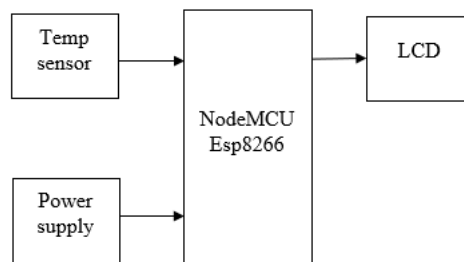
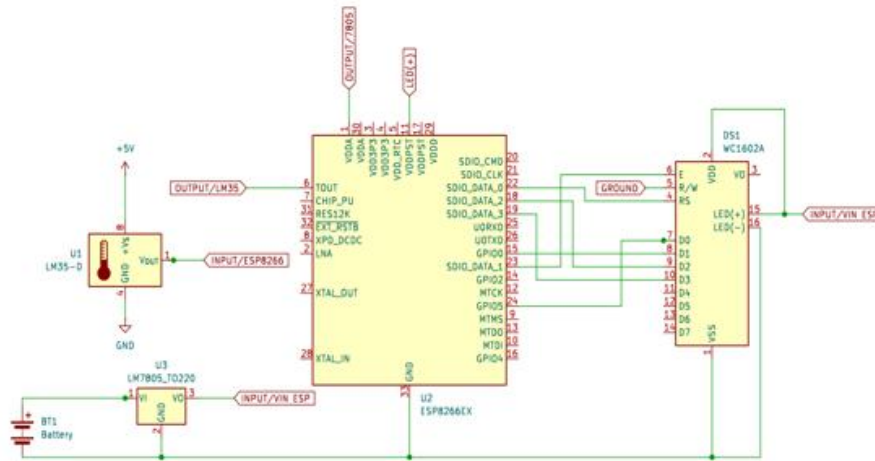


Figure 1: Block Diagram of the System

Based on the block diagram in Figure 1, the system was integrated using the circuit diagram in Figure 2.



3. **Real-Time Temperature Monitoring:** This occurs continuously during shipment. The system continuously monitors the temperature, and the data are transmitted to the application for real-time display on the dashboard. A maximum temperature threshold of 8°C was configured for the monitoring system. When the measured temperature exceeds 8°C, the system automatically flags a temperature excursion and initiates the notification process.
4. **Notification System:** this is automated, based on real-time monitoring. The crossing of a pre-set threshold triggers an alert which is reflected on the dash board (e.g., temperature out of range), the system sends an email and SMS to the user (customer) with the alert details. The notification includes a link to dashboard where the user can monitor the temperature live.
5. **Monitoring Dashboard:** On the logistics company's application point of view, the dashboard shows all ongoing shipments and the status of each monitoring device. It provides a quick overview of which shipments are within the safe temperature range and which have alerts. On the side of the user, the customer can only see visualization of their own individual shipment.

The overall monitoring framework encompasses customer onboarding, shipment initialization, dynamic telemetry visualization, and automated alert delivery. Figure 4 illustrates the primary administrative interface displaying fleet device statuses, while Figure 5 highlights the dynamic gauge interface for real-time temperature tracking. Auxiliary steps including customer record generation, unique link creation, and email/SMS dispatch via Firebase are backend automated processes executed upon starting a shipment

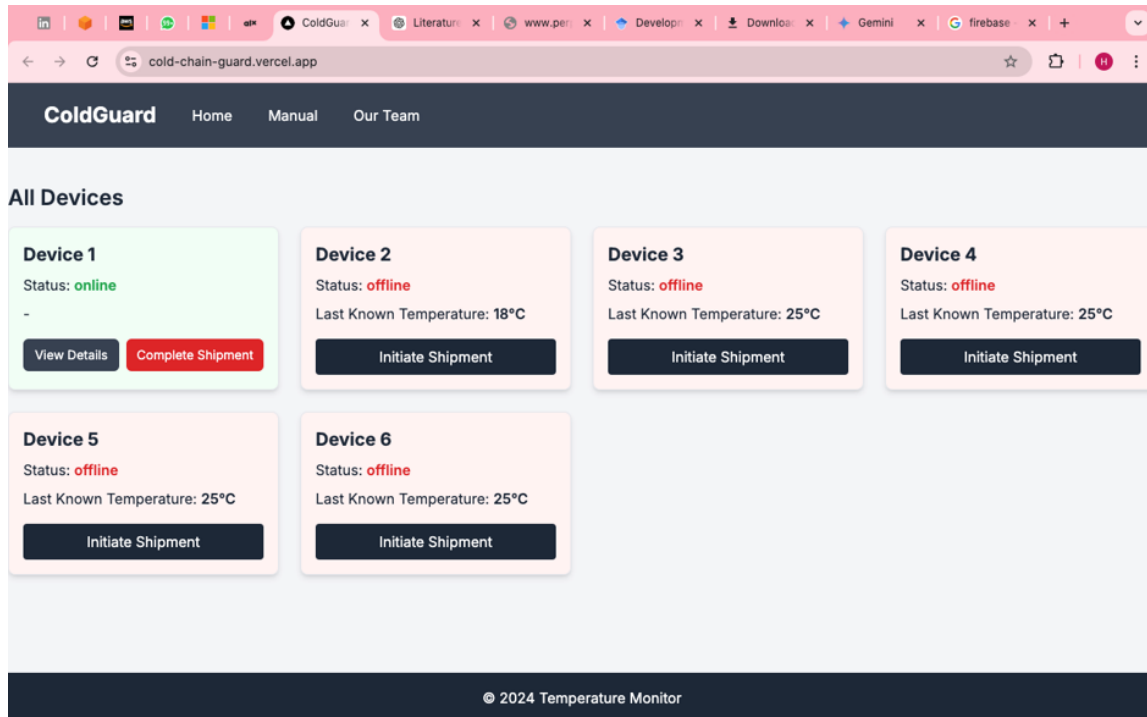


Figure 4: Screenshot of the Application View of the system

Figure 4 illustrates the central logistics management dashboard displaying connected device statuses and shipment initiation controls.

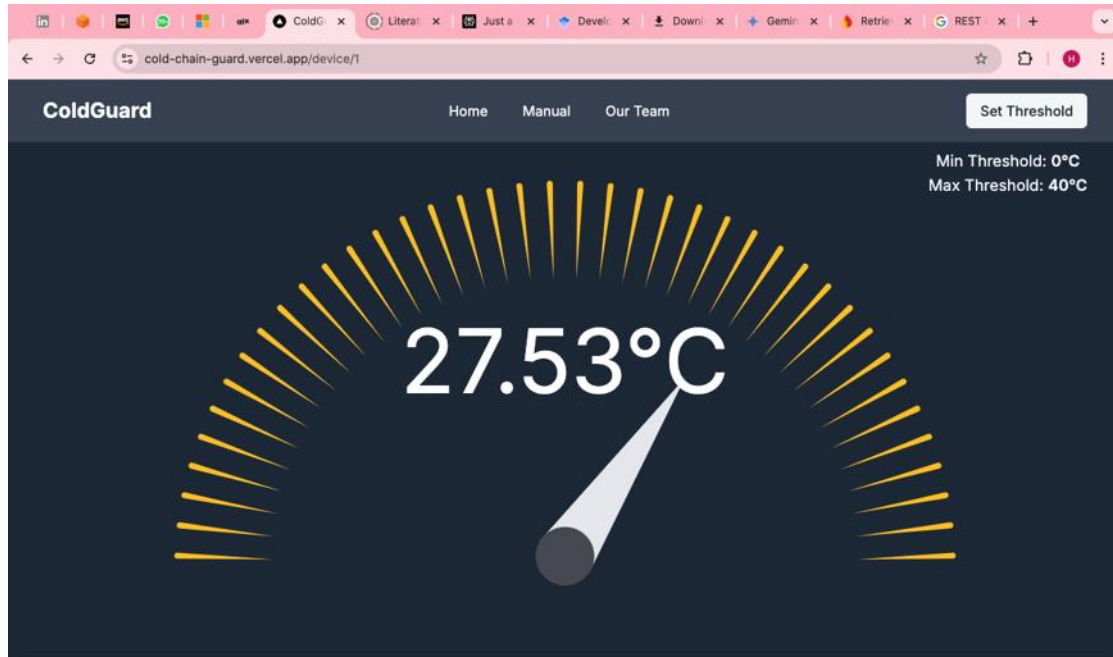


Figure 5: IoT Monitoring Dashboard UI displaying active node data alongside offline nodes showing default placeholder readings (25.0°C).

As shown in Figure 5, when a remote sensor node loses connectivity or goes offline, the dashboard interface defaults to a software fallback placeholder value of 25.0°C pending reconnect, rather than displaying dynamic temperature readings.

4. RESULTS AND DISCUSSION

During the experimental evaluation, five 50-cl units of the frozen test material were placed inside the prototype storage unit to simulate temperature-sensitive products under cold-chain conditions. Temperature readings were continuously monitored and recorded for a period of six hours using the DHT11 sensor connected to the NodeMCU ESP8266. Before data acquisition, the monitoring system required approximately 10 s for initialization, followed by approximately 20 s for the temperature readings to stabilize. The recorded temperature data were transmitted to the ColdGuard application for real-time monitoring. The temperature excursion response was evaluated using the predefined maximum temperature threshold of 8°C throughout the six-hour experimental period.

4.2.1 Temperature Readings: Continuous monitoring of environmental conditions within the prototype storage unit. When the monitoring system was put on, it took about 10 seconds to initialize and another 20 seconds for the temperature readings to stabilize.

When the monitoring system was powered on, the LCD initially displayed a startup message ('Temp Monitoring system') for approximately 10 seconds during component initialization before transitioning to active environmental temperature readouts, as shown in Figure 6.



Figure 6: Physical Prototype LCD Displaying System Initialization Message.

4.2.2 Alert Frequency: Alert frequency refers to the number of alerts generated when the measured temperature exceeded the predefined threshold of 8 °C. During the six-hour experimental period, the temperature crossed the 8 °C threshold on three occasions, generating a total of three alerts. The first alert occurred at approximately 12:30 (corresponding to the sharp spike shown in Figure 7), while the remaining two alerts were recorded after deliberate lid-opening events. No false alerts were observed when the temperature remained below the threshold. These results confirm that the system reliably detects and reports temperature excursions.

4.2.3 Temperature Variation: Following the primary temperature excursion peak at 12:30 PM (10.2°C), closing the enclosure caused a brief temperature recovery down to 7.5°C at 1:00 PM. However, as the prototype relies on passive thermal insulation rather than active mechanical refrigeration, continuous ambient heat exchange—compounded by two deliberate lid-opening events—resulted in a gradual, persistent temperature rise for the remainder of the 6-hour evaluation. This upward trajectory reflects the expected thermal dissipation profile of passive cold containers and underscores the system's ability to maintain real-time monitoring and active alert generation throughout prolonged threshold breaches

. This is shown in Figure 7.

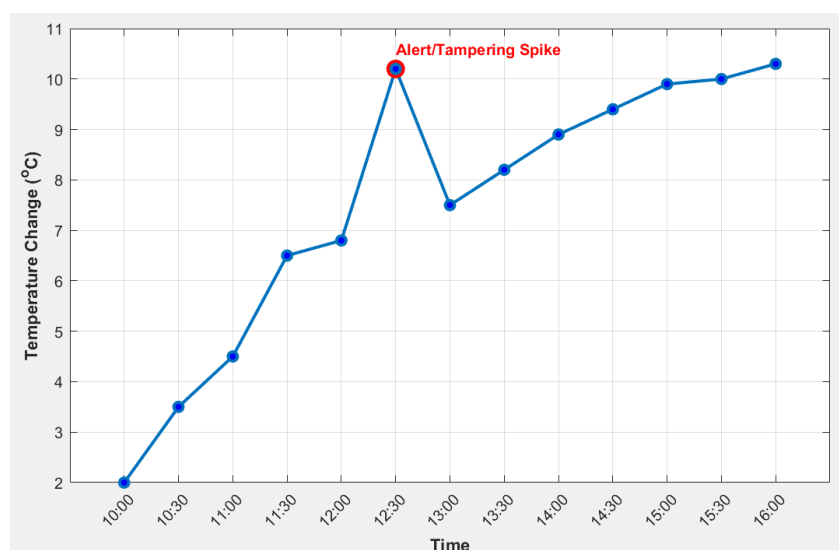


Figure 7: Temperature Variation against Time

From Figure 7, The sharp temperature spike at 12:30 PM indicates a potential abnormal event, such as tampering or a temporary loss of cooling conditions. This demonstrates the system's ability to promptly detect and flag temperature anomalies through alert generation.

4.2.4 Latency Variation: The latency measurements ranged from 0.1 s to 0.5 s, with an average delay of 0.21 s. Figure 8 presents the relationship between temperature change and the corresponding latency delay recorded during data transmission. Most of the recorded transmissions were completed within 0.1–0.2 s, indicating stable communication between the NodeMCU ESP8266 and the ColdGuard application. Although brief increases in latency were observed at some temperature-change conditions, the recorded delays remained below 0.5 s, demonstrating the capability of the system to support near-real-time monitoring and alert delivery. This is shown in Figure 8.

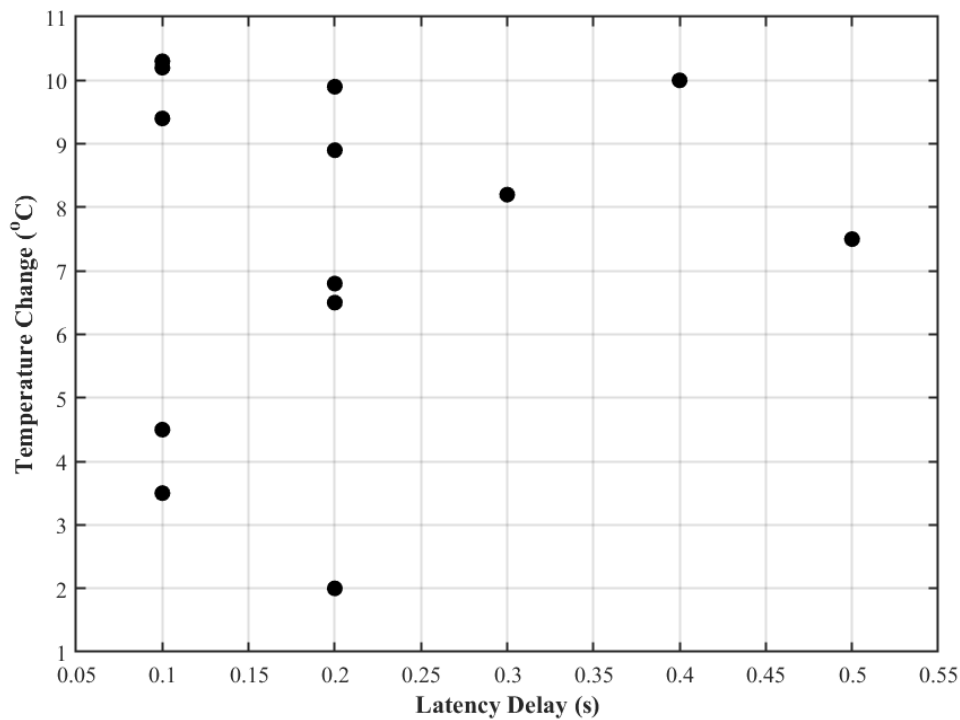


Figure 8: Latency Variation against Temperature Change

5. CONCLUSION

This study presented the development of an Internet of Things (IoT)-based cold chain monitoring system utilizing a NodeMCU ESP8266 microcontroller, DHT11 temperature and humidity sensor, 16×2 LCD module, and the ColdGuard mobile application. The developed system enabled continuous real-time acquisition, visualization, and remote monitoring of environmental parameters critical to cold chain operations. Experimental evaluation demonstrated reliable sensor performance, low end-to-end communication latency, and effective detection of temperature excursions through automated alert generation mechanisms. The results validated the system's capability to maintain continuous visibility of cold chain conditions, thereby facilitating timely intervention during abnormal events. Furthermore, the integration of cloud-enabled monitoring and mobile-based notifications enhances operational efficiency, traceability, and data accessibility across the supply chain. The developed platform provides a functional, low-complexity IoT solution for continuous temperature and humidity monitoring in cold-chain storage and transportation. Experimental results confirmed reliable real-time data acquisition, low communication latency, and effective detection of temperature excursions through automated alerts. These capabilities support improved visibility and timely intervention, which can help reduce product losses and enhance compliance with cold-chain

requirements. Future work will focus on integrating higher-accuracy sensors, power-consumption analysis, multi-node scalability testing, and predictive analytics to further strengthen the system's practical applicability.

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