

DESIGN AND DEVELOPMENT OF A LOW-COST IOT-BASED SYSTEM FOR REMOTE VACCINE STORAGE MONITORING

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Abstract

This paper addresses the design and development of a low-cost system empowered by the Internet of Things (IoT) and utilized for enabling remote monitoring of vaccine storage conditions. The main objectives of this research are to assess the accuracy and reliability of collected and transmitted environmental parameters by the developed IoT system and provide accessibility remotely. The system employs a low-cost microcontroller, environmental sensors, Wi-Fi modules, cloud storage systems and mobile/web applications for online observation. The NodeMCU ESP8266 microcontroller ensures wireless connectivity and DHT11 sensors consistently record the temperature and humidity inside and outside the vaccine container. A NEO-6M GPS module is also incorporated to enable reliable location tracking. The sensor readings are continuously sent at fixed intervals to the ThingSpeak cloud platform. Our final product is a personal mobile application called QuickVax, which allows user interaction and offers the functionality of uploading participant data and viewing real-time environmental readings. The experimental results showed that the system maintains optimal temperature conditions throughout the supply cold chain, minimizing vaccine spoilage risk and enabling location tracking in the remote environment.

INTRODUCTION

Vaccines are essential public health tools that are employed on a global level for the prevention of the spread of infectious diseases and the reduction of death rates worldwide [1]. Their efficacy is however, extremely responsive to the right storage and transport conditions, particularly temperature control. Most vaccines must be stored in a very narrow temperature range of between 2–8 °C in order to be effective since

changes above or below this range will cause them to become partially or fully ineffective [2]. Maintaining this "cold chain" from production line to administration is therefore one of the trickiest issues of global immunization campaigns, especially in remote or under-developing communities [3].

Traditionally, systems for storing vaccines lack real-time tracking and cannot deliver alarms or tracking

signals while the vaccines are in transport. Cold chain breaks caused by poor infrastructure, breakdowns of equipment, or human errors result in loss of vaccines, higher expenditures and weakened immunization campaigns [4]. There is therefore a critical requirement for scalable and affordable systems that are reliable and capable of offering persistent environmental protection and location tracking to ensure effective storage and transport of vaccines.

New developments in the Internet of Things (IoT) have made it possible to design intelligent low-cost systems that are able to achieve real-time data acquisition, cloud monitoring and remote accessibility [5]. The integration of temperature and humidity sensors with wireless microcontrollers, GPS modules and cloud servers allows the IoT-enabled systems to improve cold chain logistics with increased transparency, traceability, and reliability [6]. This paper outlines the design and development of a Smart Vaccine Storage Box, an IoT system that incorporates a NodeMCU ESP8266 microcontroller [7], internal and external DHT11 environmental sensors [8] for monitoring and a NEO-6M GPS module [9] to track location in real-time. The information is relayed to the ThingSpeak cloud system [10] at a rate of every 15 seconds for remote visualization. Our final product is a customized mobile application called QuickVax, which might be used by healthcare professionals to enter patient information and access environmental conditions.

1. Literature Review

Vaccine cold chain is an important factor in maintaining vaccine efficacy, particularly in rural locations with limited infrastructure support. Poor storage and transport conditions can result in vaccine spoilage and render public health interventions ineffective, if not harmful. Recent studies have focused on optimizing vaccine cold chain management through the application of Internet of Things (IoT) technologies that allow for the monitoring and accessibility of environmental parameters in real time during transportation.

The vaccine cold chain became prominent in the 1960s and the 1970s through the worldwide campaign to eradicate smallpox and served as the foundation of contemporary immunization programs. The *Expanded Programme on Immunisation* (EPI)

highlighted the requirement for a stable cold store in the remotest locations. Initial challenges in monitoring exposure to heat resulted in innovations in the form of temperature-sensitive vaccine vial monitors (VVMs) and better refrigeration. The success of vaccination also relied on the development of human resources in the form of training and the formulation of policies. There are three main lessons from the success of the cold chain in eliminating smallpox: integrating with other health supply chains, re-designing for efficiency, and decreasing dependence on refrigeration [11].

In many developing regions, cold chain management remained a significant challenge. This was primarily due to insufficient infrastructure for temperature-controlled transportation. A real-time monitoring system designed to track the temperature, humidity and location of vaccine carriers was proposed to address this issue. This system allowed for trip management, enhancing transparency and accountability throughout the vaccine distribution process. This system particularly improved vaccine coverage in remote areas by enabling remote monitoring, ensuring vaccine storage safety and effective distribution [12].

Cloud computing further significantly enhanced vaccine storage management by enabling real-time monitoring and data storage, thus reducing reliance on manual checks. Given the sensitivity of vaccines to temperature and humidity, cloud-based solutions ensured that environmental conditions are continuously tracked, which resulted in improved accuracy and efficiency. This technology allowed 24/7 access to vaccine data, facilitated remote monitoring and ensured the integrity of the data, enhancing trust and transparency in vaccine distribution. Cloud platforms also enabled the authentication of IoT devices through reliable tracking and data consistency. The studies showed that integrating cloud computing in the cold chain reduced errors, ensured compliance with storage guidelines and improved vaccine management especially in remote or low-resource areas [13].

2. Methodology

The methodology section is divided into three main subsections. The first subsection discusses the conceptual design and data flow of the Smart Vaccine

Box system. The second subsection details the hardware implementation, including all sensors, controllers, and actuators. The third subsection describes the software implementation, covering the microcontroller firmware and mobile/cloud integration.

4.1. Conceptual Design and Design Flow

Vaccine storage systems are required to maintain a precise temperature range to ensure preservation of their efficacy. According to established health guidelines, vaccines sensitive to temperature fluctuations must be stored within a range of 2–8 °C to remain viable [14]. The Smart Vaccine Box is engineered to continuously monitor the internal environment and external factors.

The essential parameters such as temperature and humidity are monitored via two identical environmental sensors. The primary sensor is installed within the vaccine storage unit to continuously measure internal temperature and humidity levels, while the secondary sensor is positioned externally to record ambient

environmental conditions. Both sensors transmit their acquired data to the central NodeMCU microcontroller (ESP8266-based) through digital communication interfaces. This dual-sensor arrangement permits comparative evaluation between the controlled storage environment and external conditions, thereby enabling comprehensive assessment of thermal stability. The system incorporates an NEO-6M GPS module to additionally capture precise geolocation coordinates during transportation events, ensuring complete spatial tracking capability throughout the cold chain distribution process.

Figure 1 illustrates the conceptual design of the system. During operation, the NodeMCU acquires temperature and humidity readings from both internal and external sensors, while simultaneously logging GPS coordinates to track the vaccine storage unit’s location. The microcontroller processes this data and transmits it to the ThingSpeak cloud platform at regular intervals for remote monitoring. A dedicated mobile application interfaces with the cloud to provide real-time visualization of environmental conditions.

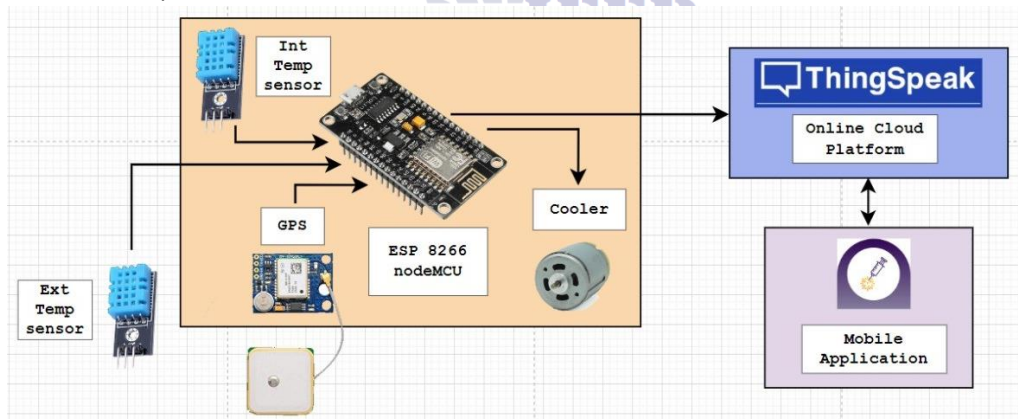


Figure 1: Conceptual design.

The healthcare workers can record patient details including name, age, gender, vaccine type and consent status (whether the individual (or his/her legal guardian) agrees or refuses to receive the vaccine [15]) through the application which are then securely transmitted to ThingSpeak.

4.2. Hardware Implementation

Figure 2 illustrates the hardware connections of the Smart Vaccine Storage Box. The system integrates multiple hardware components, each playing a crucial role in achieving real-time environmental monitoring and location tracking. A detailed explanation of each component is provided below.

4.2.1 NodeMCU (ESP8266) Microcontroller

The central controller utilized in this system is a NodeMCU development board based on the ESP8266 Wi-Fi microchip. The ESP8266 chip has a Wi-Fi module that enables the NodeMCU to establish

direct connections with cloud services [16]. The board is equipped with a micro USB port for power and programming, multiple digital GPIO pins for interfacing with sensors and a 10-bit ADC input and is programmed using an Arduino IDE [17].

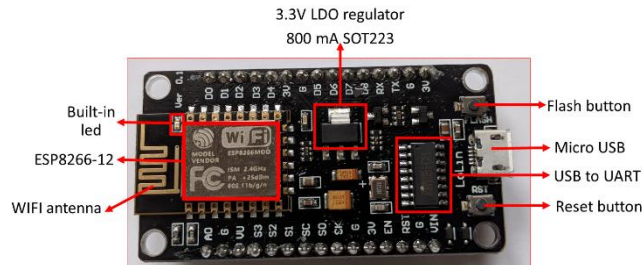


Figure 2: NodeMCU (ESP8266) board.

4.2.2. DHT11 Temperature and Humidity Sensors

Two DHT11 sensors (Fig. 3) are interfaced with the NodeMCU, each of which operates within a voltage range of 3.5–5.5 V and outputs a calibrated digital signal for temperature and humidity measurements.

In practice, both sensors are powered by the NodeMCU's 5 V supply, and their single data lines are connected to separate digital GPIO pins on the NodeMCU.

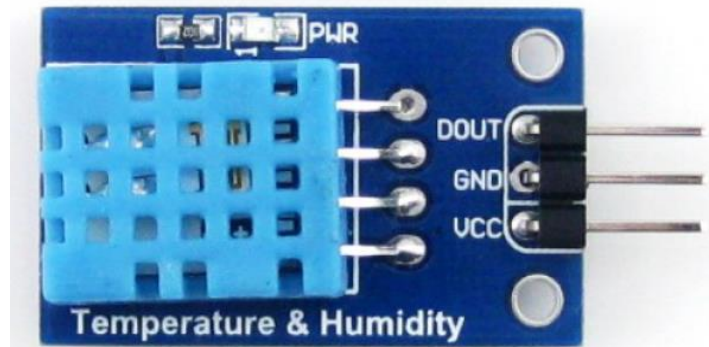


Figure 3: DHT11–Temperature and Humidity Sensors.

4.2.3. NEO-6M GPS Module

A NEO-6M GPS module (Fig. 4) is connected to the NodeMCU via the UART serial interface [18], typically operating at a 9600 baud rate. The GPS module provides NMEA sentences containing

latitude and longitude data [19]. The NodeMCU firmware parses these serial data using a GPS parsing library to extract current geographic coordinates. The GPS module is powered via the same 5V supply.



Figure 4:NEO-6M GPS Module

The passive cooling mechanism using coolant packs regulates the temperature inside the box. This passive method minimizes power requirements and avoids the complexity of motor drivers and transistors. The NodeMCU continues to monitor temperature conditions to ensure that the passive cooling remains effective. All components including the NodeMCU, sensors and GPS share a common 5 V supply.

4.3. Software Implementation

4.3.1. ThingSpeak

ThingSpeak is an IoT analytics cloud platform that facilitates the aggregation and visualization of live data streams [20]. It is used to store and visualize sensor data from the ESP32 in real time. It receives temperature, humidity, and GPS data from the ESP32, along with vaccination verification data submitted via the QuickVax application.

4.3.2. MIT Application Inventor:

MIT App Inventor is an open source, block-based programming platform developed by the Massachusetts Institute of Technology (MIT). It has a

visual, drag-and-drop interface that allows users to develop fully working Android apps without any coding skills [21]. The App Inventor employs a two-stage application development approach. First, developers construct the user interface by visually arranging interactive widgets. Then, rather than writing traditional code, the app's logic is built by snapping together color-coded blocks representing commands [22].

4.3.3. QuickVax Mobile Application:

QuickVax, the mobile application introduced herein, is developed on MIT App Inventor, addresses two key functionalities: public health data collection and IoT-based remote environmental monitoring. This application is organized into two primary modules:

1. Vaccine Registration
2. Environmental Monitoring

A centralized menu interface (Fig. 5) allows users to navigate seamlessly between these modules. Figure 6 demonstrates the operation of the Environmental Monitoring Module.

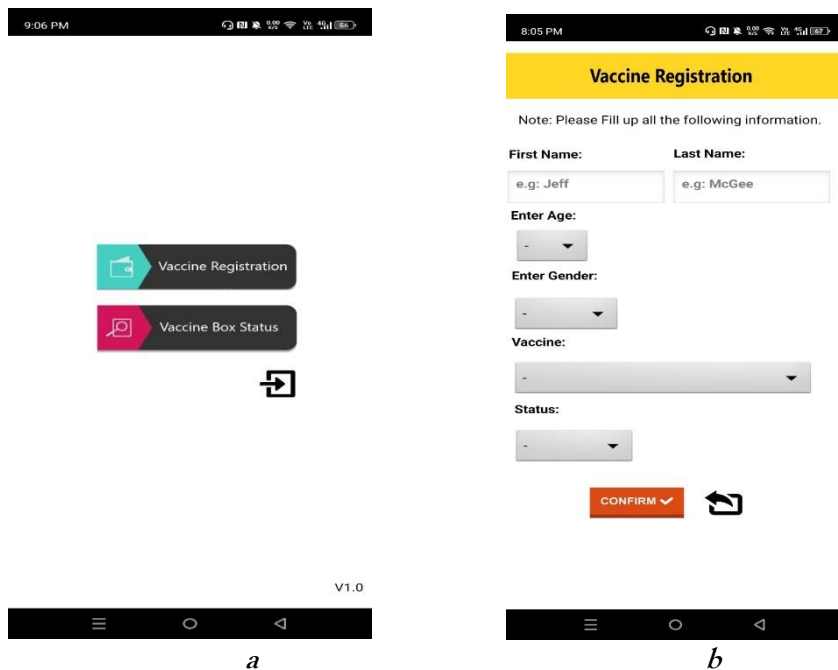


Figure 5:(a)MIT QuickVax App menu (b) Vaccine Registration Window.



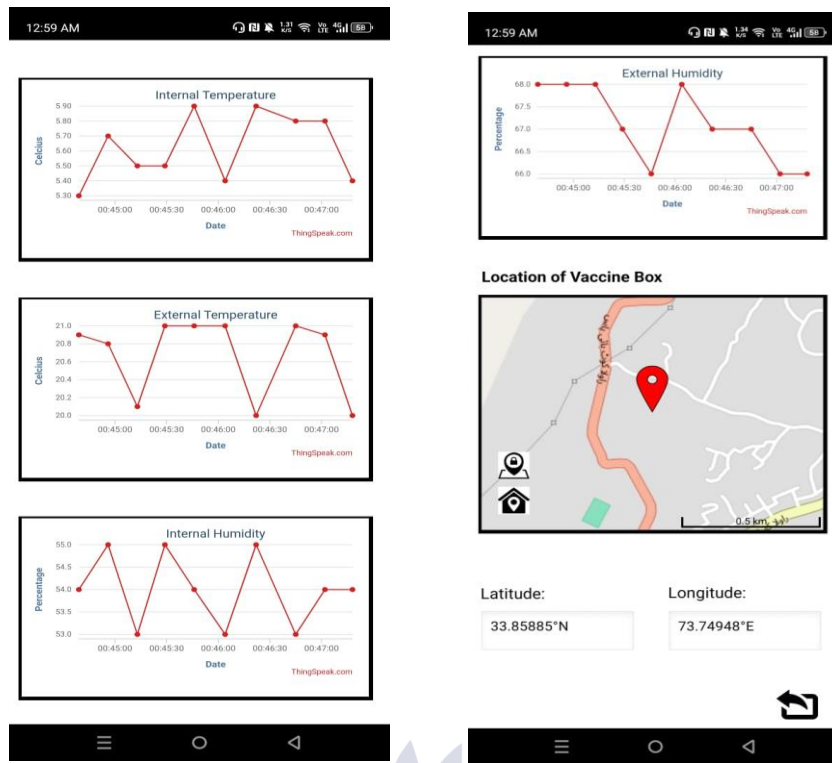


Figure 6: Environmental Monitoring Window.

Figure 7 illustrates a portion of the block-based logic implemented in MIT App Inventor to support the Environmental Monitoring functionality of the QuickVax app. These blocks handle tasks such as sending HTTP requests to ThingSpeak, decoding the received data, and updating the app’s user interface with real-time sensor values including GPS coordinates.

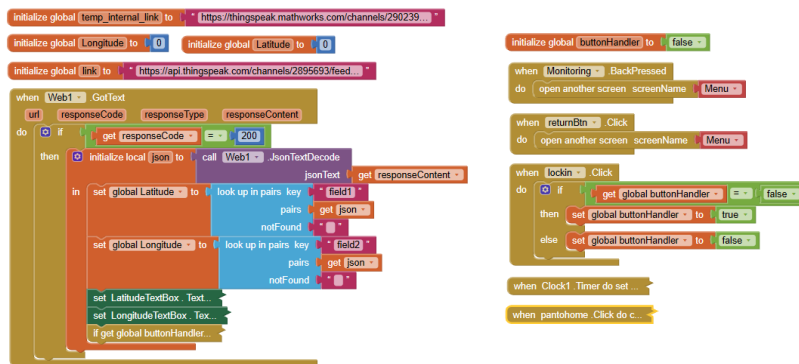


Figure 7: Environmental Monitoring window.

3. Results and discussions

5.1. Thingspeak

Figure 8 (a) presents the real-time plots for internal and external temperature, while Figure 8 (b) displays the corresponding plots for internal and external humidity.

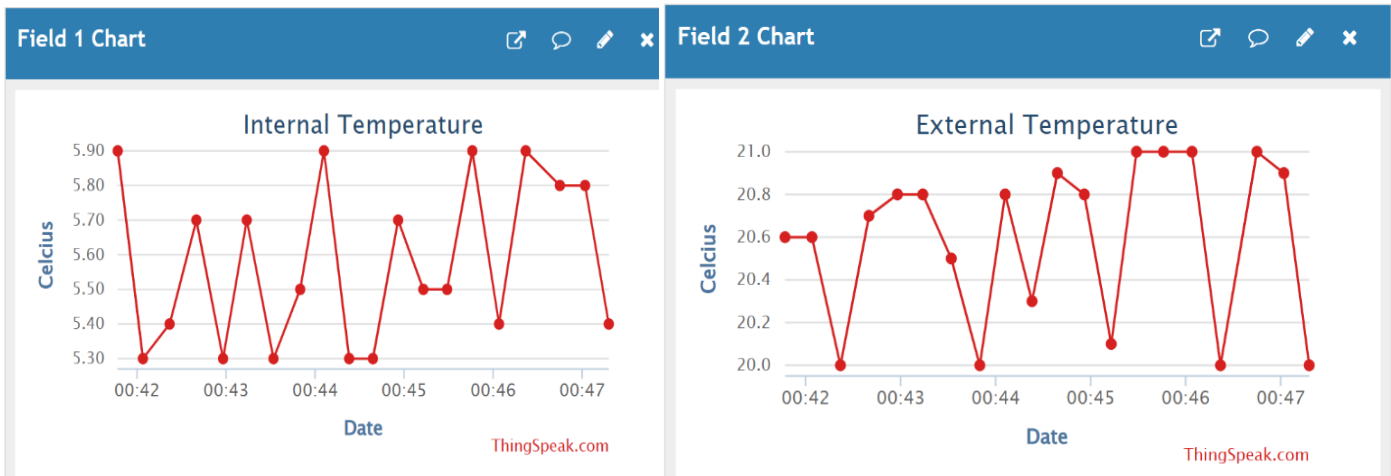


Figure 8(a): Thingspeak Temperature Charts.

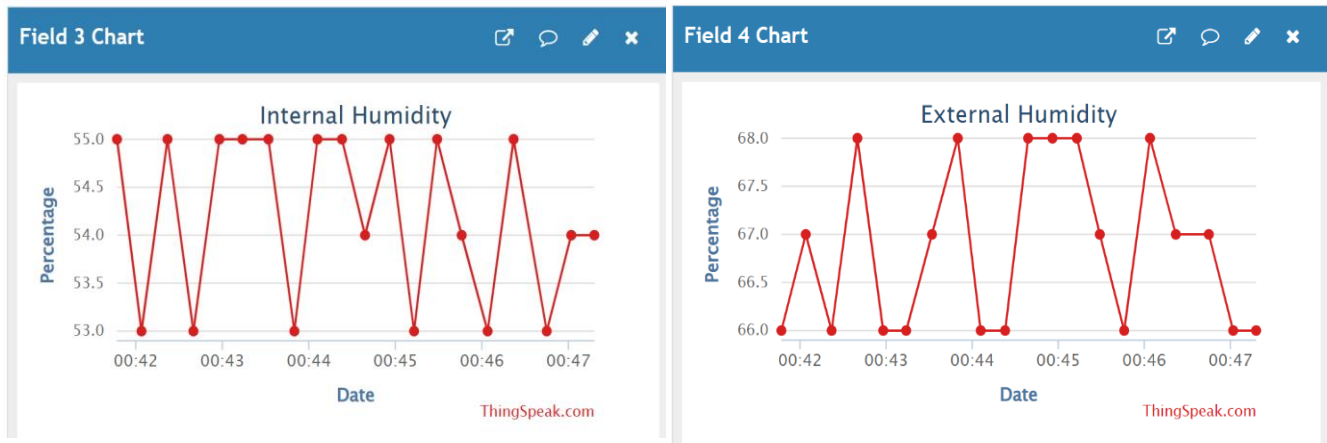


Figure 8(b) : Thingspeak Humidity Charts.

The data gathered from the sensors and GPS module is stored in the ThingSpeak database. Figure 9(a) illustrates an example of the sensors data (internal and external temperature and humidity) and GPS locations (longitude and latitude) logged in ThingSpeak. Figure 10 shows vaccination data such as name, age, gender and status logged in ThingSpeak.

	A	B	C	D	E	F	G	H
1	created_at	entry_id	Internal Temp	External Temp	Internal Humid	External Humid	Latitude	Longitude
2	2025-05-30T19:33:16+00:00	1	5.5	21	54	67	33.85882	73.74949
3	2025-05-30T19:33:33+00:00	2	5.7	20.1	54	66	33.85885	73.74949
4	2025-05-30T19:33:49+00:00	3	5.5	20.9	55	68	33.85885	73.74948
5	2025-05-30T19:34:06+00:00	4	5.6	20.4	55	67	33.85885	73.74949
6	2025-05-30T19:34:22+00:00	5	5.9	20.8	55	66	33.85883	73.74949
7	2025-05-30T19:34:39+00:00	6	5.3	20.6	54	68	33.85884	73.74947
8	2025-05-30T19:34:55+00:00	7	5.9	20.8	54	67	33.85882	73.74949
9	2025-05-30T19:35:11+00:00	8	5.9	20.6	54	66	33.85883	73.74948
10	2025-05-30T19:35:28+00:00	9	5.5	20.1	54	67	33.85883	73.74949
11	2025-05-30T19:35:44+00:00	10	5.5	20.1	54	66	33.85885	73.74947
12	2025-05-30T19:36:01+00:00	11	5.6	20.9	53	67	33.85884	73.74948
13	2025-05-30T19:36:17+00:00	12	5.6	20	53	66	33.85884	73.74949
14	2025-05-30T19:36:34+00:00	13	5.5	20.1	54	67	33.85882	73.74947
15	2025-05-30T19:36:50+00:00	14	5.9	20.2	53	66	33.85885	73.74947
16	2025-05-30T19:37:07+00:00	15	5.5	20.3	53	66	33.85883	73.74948
17	2025-05-30T19:37:23+00:00	16	5.4	20.8	54	68	33.85883	73.74948
18	2025-05-30T19:37:39+00:00	17	5.6	20.7	55	68	33.85883	73.74949

Figure 9(a): Demonstration of Sensor data logged in ThingSpeak

	A	B	C	D	E	F	G
	created_at	entry_id	Name	Age	Gender	Vaccine	Status
2	2025-05-30T21:41:16+00:00	1	James Malding	53	Male	pertussis	Accepted
3	2025-05-30T21:41:32+00:00	2	Alice Johnson	60	Male	Hib	Accepted
4	2025-05-30T21:41:47+00:00	3	Robert Smith	35	Male	diphtheria	Rejected
5	2025-05-30T21:42:03+00:00	4	Emily Davis	45	Male	diphtheria	Accepted
6	2025-05-30T21:42:19+00:00	5	Michael Brown	20	Male	tuberculosis	Rejected
7	2025-05-30T21:42:34+00:00	6	Linda Wilson	40	Female	pertussis	Rejected
8	2025-05-30T21:42:50+00:00	7	William Moore	58	Male	Hib	Rejected
9	2025-05-30T21:43:06+00:00	8	Patricia Taylor	58	Female	hepatitis	Rejected
10	2025-05-30T21:43:22+00:00	9	David Anderson	21	Male	pertussis	Accepted
11	2025-05-30T21:43:37+00:00	10	Barbara Thomas	44	Male	measles	Accepted
12	2025-05-30T21:43:53+00:00	11	Joseph Jackson	46	Female	tuberculosis	Rejected
13	2025-05-30T21:44:10+00:00	12	Susan White	18	Male	meningitis	Accepted
14	2025-05-30T21:44:25+00:00	13	Thomas Harris	32	Male	pertussis	Rejected
15	2025-05-30T21:44:41+00:00	14	Jessica Martin	18	Female	diphtheria	Rejected
16	2025-05-30T21:44:57+00:00	15	Charles Thompson	35	Male	tetanus	Accepted

Figure 10: Demonstration of Vaccination data logged in ThingSpeak.

4. Conclusion

This study presents an IoT-based framework for real-time vaccine cold chain monitoring, focusing on temperature, humidity and location tracking through cloud platforms like ThingSpeak. The system reduces human error and ensures vaccines remain within optimal conditions during transport and storage by automating data collection. The use of cloud computing enhances data accessibility, offering real-time insights and improving transparency. This framework is particularly beneficial for remote areas with limited infrastructure providing a cost-effective and scalable solution for vaccine supply chain management.

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