

COLD CHAIN LOGISTICS FOR PHARMACEUTICALS AND VACCINES

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ABSTRACT

Vaccines and medications are very susceptible to fluctuations in temperature and humidity, which may have far-reaching effects on public health if these elements are not adequately regulated during storage and transportation. Vaccines and drugs are particularly susceptible to these changes. Despite the fact that India is a prominent participant in the pharmaceutical business on a global scale, the country's rural regions and last-mile delivery zones continue to face significant challenges in terms of cold chain logistics. As a result of COVID-19, the infrastructure of the cold chain is now being prioritised for improvement and expansion. The purpose of this research is to investigate the current situation of cold chain logistics in India with regard to immunisations and drugs that are sensitive to fluctuations in temperature. This article highlights the significance of Internet of Things (IoT) technology in enhancing the visibility, traceability, and reliability of supply chain operations. Particular attention is paid to real-time sensors, smart cold storage units, and GPS-enabled reefer trucks. Regulatory compliance, lower spoilage rates, and reduced dependency on manual procedures are all mentioned as consequences of incorporating IoT in the framework that has been presented. In addition, a cost-benefit analysis is used in order to evaluate the financial viability and scalability of investing in cold chain solutions that are made available by the Internet of Things. Not only that, but we also discuss a regional case study that illustrates how the implementation of a smart cold chain system impacted operational performance after it was implemented. For the goal of providing policymakers in India with data-driven insights and proposals for enhancing the pharmaceutical cold chain, the objective of this research is to give them with the information.

Keywords: Cold Chain Logistics, Pharmaceuticals, Vaccines, Temperature-Sensitive Supply Chain, Internet of Things (IoT), Vaccine Storage and Transportation, Reefer Trucks, IoT-Enabled Monitoring, India

INTRODUCTION

Items in the pharmaceutical industry, particularly vaccines, are among the most temperature-sensitive products that are transported across the global supply chain. The efficiency and safety of these compounds are tightly tied to maintaining them within a certain temperature range (often between 2 degrees Celsius and 8 degrees Celsius), regardless of whether they are being stored or transported. According to the World Health Organisation (WHO), even a little amount of distraction may have a significant impact on the economy, the environment, and the health of the general population [1]. The reliability of cold chain systems is of the highest significance in India since the country is responsible for

meeting more than sixty percent of the global demand for vaccinations and is home to the largest immunisation programme among all countries [2].

Post-COVID Context and Emerging Challenges

During the COVID-19 pandemic, it was discovered that India's cold chain logistics were very insufficient, particularly with relation to the distribution of vaccinations in the last mile. Problems such as uneven geographic access, poor power backup, and dependency on human monitoring are still widespread, despite the fact that the electronic vaccine identification network (eVIN) played a significant role in digitising vaccine inventory and temperature tracking at more than 29,000 cold chain locations [3]. In addition, the use of mRNA vaccines that are sensitive to variations in temperature has shown that India's present infrastructure for ultra-cold storage and refrigerated transportation is not suitable [4].

Role of IoT in Transforming Cold Chain Monitoring

There are a number of ways in which the Internet of Things (IoT) is altering the dynamics of cold chain logistics. Some of these variations include intelligent routing, predictive maintenance, and real-time monitoring. According to Ali and Khan (2023), cold storage units that are connected with Internet of Things (IoT) technology and reefer trucks that are equipped with sensors, global positioning systems (GPS), and data analytics platforms make it possible to continuously monitor conditions such as temperature, humidity, and shipping[5]. This helps to reduce the possibility of errors, promote adherence to the Good Distribution Practices (GDP) established by the World Health Organisation, and reduce product losses that are caused by spoiling. According to IMARC Group (2024), pharmaceutical supply chains have lately seen either an increase in the reliability of delivery or a drop in the amount of spoilage by as much as twenty to thirty percent[6].

OBJECTIVES

1. To assess the effectiveness and weaknesses of India's post-COVID cold chain logistics system for medications and vaccines.
2. To evaluate the scalability and cost-benefit of implementing IoT-enabled reefer truck and cold storage systems.

RESEARCH METHODOLOGY

A systems-based approach is used in this research project in order to create and assess an Internet of Things (IoT)-enabled cold chain logistics framework for medicines and vaccines. In the beginning of the process, the Internet of Things devices and the overall system software are described in depth, with the emphasis being placed on the hardware and communication capabilities of the essential components. These include the Low Temperature Alert Terminal (LTAT), which is used for monitoring temperatures in storage units and trucks in real time; the Internet of Things Gateway Device (IGD), which is used for data aggregation and transmission to the cloud; and the Cold Chain Visibility Equipment (CCVE) and Cold Chain Integrated Equipment (CCIE), which are used to ensure end-to-end traceability, device authentication, and system alerts. In order to provide real-time warnings, remote configuration, and

compliance monitoring, the architecture that is enabled by the Internet of Things links these hardware modules with a dashboard and analytics engine that are hosted in the cloud. A proof of concept for the Internet of Things-enabled framework was constructed by taking use of a simulated cold chain network. This proof of concept included temperature sensors, GPS modules, and cloud telemetry in order to imitate real-world operational circumstances. The purpose of this framework was to verify the practical value of the framework. In addition, the research investigates application scenarios and analysis, starting with the creation of system user requirements and determining the unique requirements of stakeholders such as health departments, logistics providers, and vaccine producers. Following that, the design of the system's business functions will map out the main processes, which will include monitoring of cold storage, tracking of shipments, and the creation of alerts. The examination of system equipment needs evaluates the technical parameters (such as sensor accuracy, battery life, and connection standards) as well as the practicality of deployment in both urban and rural environments. In India's pharmaceutical logistics business, the implementation of an Internet of Things-enabled cold chain solution is evaluated in terms of its scalability, cost-effectiveness, and sustainability. These components jointly contribute to the evaluation of these aspects.

RESULT

IOT DEVICES AND OVERALL SYSTEM SOFTWARE

Temperature is the key factor impacting vaccination cold chain stability. Vaccines must be maintained at the right temperature to stay effective and pure. This is why vaccinations must be monitored for temperature changes during transport and storage. Establishing an information system and developing and deploying IoT-focused hardware and software is necessary. This system simplifies data collection and access throughout vaccine manufacture and delivery. Quick choices may ensure quality and spot abnormalities. The vaccination procedure requires a solid cold chain logistics infrastructure since vaccines move through multiple processes before reaching the immunisation facility. This requires regular monitoring and automatic controls. Installing an intelligent, integrated system is difficult. This includes determining what devices are needed, installing them on objects, validating data for accuracy, processing enormous amounts of data, correcting data transmission issues, and more.

Many temperature monitoring systems exist now. They include skilled data recorders and temperature loggers. These loggers require upgrading for real-time and remote data sharing. For cold chain monitoring, RFID and WSN are becoming dominant [7, 8]. These technological advances increase cold chain efficiency and manpower costs. Active RFID tags can verify cold chain integrity at cheap cost. Wireless data transmission simplifies installation and use, and they're more efficient, inexpensive, and user-friendly. Scanning these tags provides real-time temperature and location data synchronised to a central database. RFID and WSN are financially significant. These sensor devices are frequently limited in number. They must be allocated properly according on the application's demands to be cost-effective. Technical help for the system service may include designing gear and software to record ambient temperature during vaccination. Table 1 lists all these units and their capabilities. IoT hardware has four primary categories.

- Cold-chain vehicle equipment (ccve),

- Intelligent gateway devices (igd),
- Low-power temperature acquisition tags (ltat), and
- Cold-chain incubator equipment (ccie).

The following software parts are required for data transmission and management.

- Cloud databases,
- Cloud service platforms, and
- Mobile applications

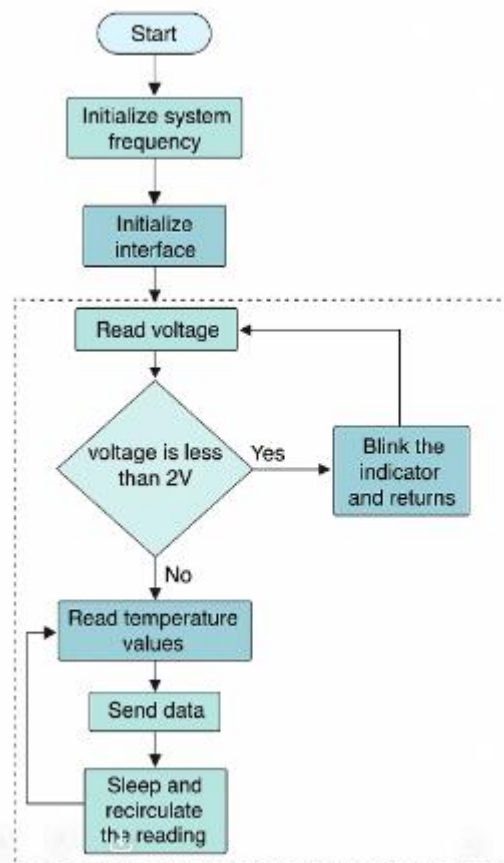


Figure 1. Proposed LTAT workflow.

1. The LTAT's hardware design and process

The LTAT monitors vaccine storage temperature as the system's data source. Due to vaccine storage spaces' tight confines and stringent sealing requirements, the LTAT must be tiny, energy-efficient, and easy to set up. Thus, the LTAT uses the low-power CPU CH583 M [9]. Its tiny size, low power consumption, and built-in wireless transmission circuit make it easy to transfer data wirelessly across the unusual 2.4 GHz range. Digital and analogue temperature sensors are available. Digital sensors provide

precision, improved peripheral circuitry, power economy, and user-friendliness, whereas analogue sensors are often more complex and less exact. The precision of LTAT must be less than 0.3 °C. This investigation will use a TMP112 [10] temperature sensor. This sensor has cutting-edge accuracy and low power consumption at 2.0V. The system may run for almost three years on disposable 1200 mAh lithium batteries. LTAT is shown in Figure 1. Data sampling frequency is set after activation. Since the vaccine storage environment's temperature is stable, the LTAT is generally programmed to take data every minute to conserve electricity. With this setup, the LTAT will sleep most of the time. If the battery voltage decreases below 2.0V, an alarm indicator lights up, indicating that the battery must be replaced. Check the battery voltage before, during, and after each data transmission. The LTAT's components have a minimum functioning voltage of 2.0V. The LTAT is the primary hardware for system implementation and must be incorporated in every vaccine storage device. Practical system deployments need cost management. Table 1 lists LTAT hardware pricing. Table 1 estimates that one LTAT costs \$3.

2. Hardware design and overall functionality of IGD

In addition to linking the LTAT to cloud servers, the IGD maintains and transmits data. The IGD can receive temperature readings from several LTATs over 2.4 GHz. Data is processed, stored, and displayed in real time allowing on-site managers to obtain temperature data. After repackaging, the IGD transmits freshly created data to cloud servers for central management. The IGD uses the T113-S3 core [11] to conduct these tasks while preserving system speed. Historical records, alert logs, and real-time data visualisation are available on the system's 7-inch capacitive touchscreen. In addition, the IGD incorporates a 4G Cat.1 EC200U module for reliable cloud server connectivity [12]. This module makes it simple to transfer all LTAT temperature data to a cloud server for remote access. The IGD's 4800 mA lithium battery ensures long-term performance. This capability keeps the device functioning for over 24 hours even if the power is off. The device software uses QT technology to provide a human-machine interface on Linux 5.4. Local data storage and management employ MySQL database technology. The software's functional structure is presented in Figure 2.

Table 1: Cost Estimate for LTAT

Item (Model)	Quantity	Unit Price (USD)
Microcontroller (CH583 M)	1	1.00
Temperature sensor (TMP112)	1	0.50
LED	1	0.01
PCB board	1	0.50
Resistors and capacitors	20	0.10
Lithium battery (1200 mAh)	1	1.0

3. Hardware design scheme and workflow of the CCVE

Transportation is crucial for vaccines. Transport at optimal ambient temperature is crucial. The CCVE is mostly used for vaccine cold chain transportation. The main goal is to transmit and monitor vaccination temperature in real time and offer location updates. The cargo container has two temperature monitoring units connected to the CCVE via cables. T. The temperature controller is located in the cab for easy visibility by the driver. The low-power CH32V307 [13] is CCVE's main microcontroller. The device's 2.4-inch TFT LCD displays temperature and location. The device uses a 4G Cat-1 module via TTL to upload data to cloud servers continuously. The Beidou L76K location module allows real-time vehicle tracking. Figure 3 depicts the system's architecture. A system process schematic is presented in Fig. 4. After initialisation and device startup, the system recovers its parameter settings. The 4G CAT1 module then configures. The system connects to the cloud server after initialisation. System time must be synced with the server to start temperature data collection. The technology also collects car location data every minute to save electricity and communication. Our suggestion uploads location and temperature data to the server regularly.

4. Hardware design scheme and workflow of the CCIE

CCIEs can transmit little vaccine quantities over short distances. Sometimes just a little amount of vaccine is needed. This technique swiftly transports the vaccine at a safe temperature, meeting these demands. Common equipment includes a collection controller and isolation box. The ideal insulated box is tiny, airtight, and heat-retaining. A 4G module, display unit, MCU, and external temperature sensor are common in the collection controller. The setup collects and sends data to the cloud server. A perfect CCIE and CCVE would have equal hardware and software requirements.

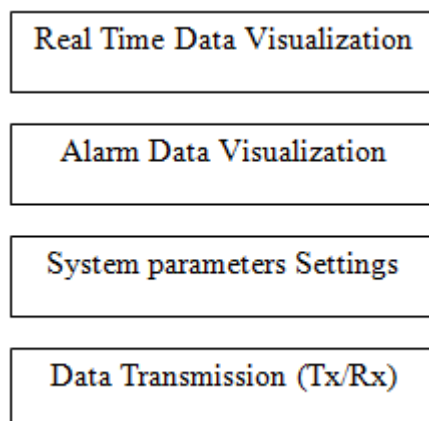


Figure 2. Organisational framework of the IGD software.

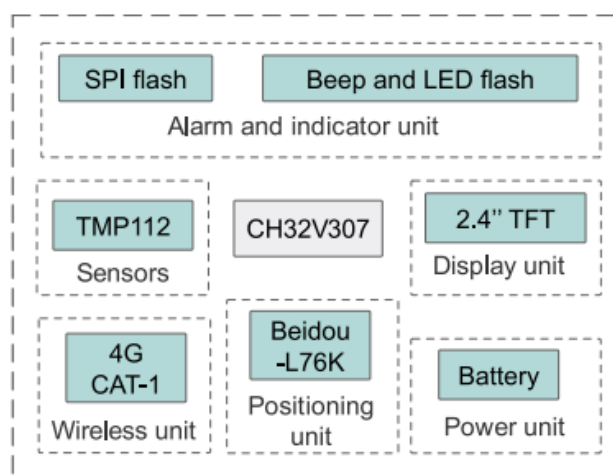


Figure 3. A schematic of the CCVE infrastructure.

IOT-ENABLED FRAMEWORK

The above devices create an Internet of Things (IoT) architecture that automatically monitors real-time vaccination ambient temperature factors to reduce vaccine loss during transportation and storage. This study also aims to demonstrate the viability of IoT-based wireless network systems with sufficient flexibility, signal loss protection, and energy independence. Maximum battery autonomy requires real-time variable measurement and power consumption reduction in the system's architecture. In design and modularisation, system stability, maintainability, and sustainability were prioritised. Figure 5 shows that most IoT systems include four components: These layers cover the vaccine data lifecycle, from temperature data collecting to data processing, storage, and display for the receiver. Vaccine owners may also monitor their immunisations' lifetime via the cloud, including storage temperature.

- **Sensor/perception layer:** Cold storage, refrigerators, or freezers used to keep vaccines mostly comprise this layer's energy-saving temperature detecting sensors. Additionally, recordings are sent to succeeding levels using wireless protocols like ZigBee, Bluetooth, and Wi-Fi.
- **Gateway layer:** Data is transferred to the next layer in its raw form because of the computational and storage constraints of IoT devices. Dedicated access points (APs) and transportable modules are often more robust than sensor nodes. They are able to swiftly evaluate and store data, as well as conduct preliminary investigations based on artificial intelligence, and carry out other fundamental pre-processing operations. In addition, these middleware devices communicate with the cloud layer by means of the Internet, relaying sensor data[14]. This tier also includes IGD, CCVE, and CCIE.
- **Cloud layer:** An essential part of this system, this layer first ensures data integrity and security by completing data receipt and remote access control of different terminal devices, and second, it makes real-time data uploading of terminal devices possible, using protocols like IGD, CCVE, and CCIE. Second, real-time processing and analysis of the received data is possible. Real-time processing and analysis of incoming data aids in the extraction of useful information and provides decision-making assistance.

- Application layer: Vaccinators, managers, and manufacturers are among those who have access to the temperature data and other vaccination details. Managers will be able to keep a closer eye on the avoidance and occurrence of epidemics with the use of the vaccination data. One example is the distribution and current situation of vaccinations.

A framework-specific temperature-sensing layer measures vaccine storage temperatures. A gateway device receives this data for continuous monitoring. To minimise vaccine loss or spoilage, temperature irregularities might alert vaccine administrators for rapid action. These measurements are stored in a cloud database. Due to device resource limits and the requirement to avoid delays during unmonitored night hours, SMS notifications are managed via the cloud. Notifying numerous vaccine managers at once is easier. Medical supervisors may use temperature analysis to make decisions. This setting ensures that your system runs smoothly and uninterrupted independent of the administrator's processing power.

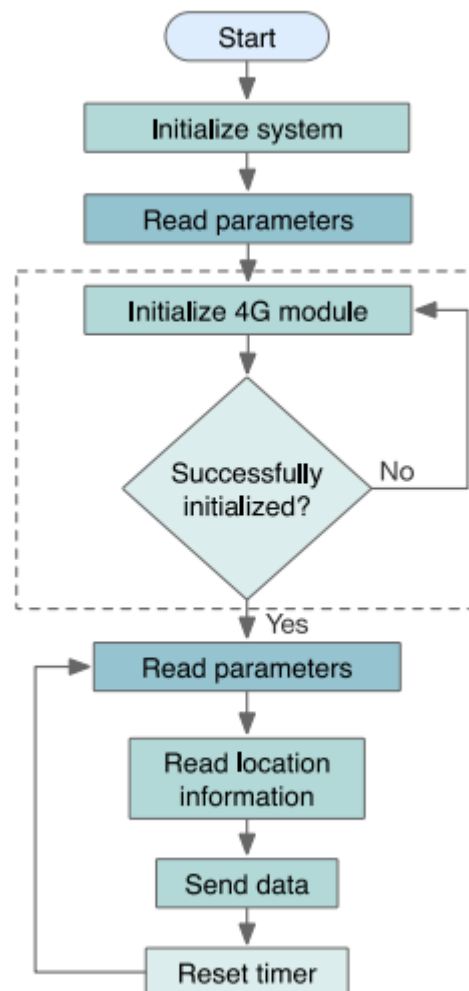


Figure 4. CCVE workflow diagram.

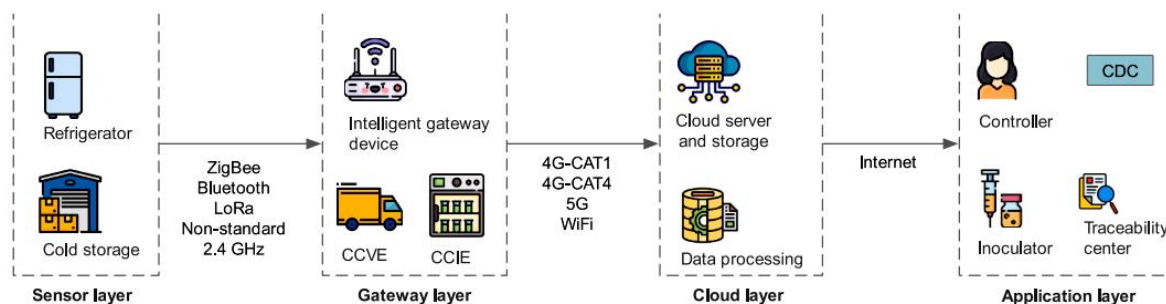


Figure 5. Idea for IoT framework.

PROOF OF CONCEPT FOR IOT-ENABLED FRAMEWORK

The LTAT's acquisition temperature accuracy, power consumption, and low-temperature operation stability; the IGD data reception and transmission stability; the power failure alarm function; the CCVE and CCVE data acquisition accuracy and stability; the positioning function; and the mobile phone APP's functionality, operability, and stability must be verified. This ensures the framework can provide the desired outcomes in practice. Confirmed system stability, performance, and cloud platform alert and warning capabilities. The validation objectives are used to create a unique validation program including test cases, settings, data, etc. Make sure the test cases cover the whole framework, from core functions and boundary conditions to exception handling and more[15]. Test at a community vaccination clinic with two cold chain insulation boxes, five vaccine storage freezers, a city CDC cold chain transport vehicle, and two vaccine managers. Since all equipment must fulfil system accuracy criteria, LTATs will be installed in vaccine storage freezers, IGDs surrounding them, CCIEs in the cold chain insulation box, and CCVEs on the transport vehicle. A competent metrology business calibrates all equipment before installation. Temperature

APPLICATION CASES AND ANALYSIS

In every large province, several immunisations are given annually. Traditional vaccine management systems fragmented information and reduced efficiency. Insufficient immunisation control and supervision caused mishaps. To solve this problem, the provincial disease control agency will create an IoT-based vaccine monitoring system. This system regulates vaccine distribution and storage temperature by integrating and regulating data throughout the province's vaccine circulation process. This is possible by using proven medication administration and control methods. Thus, the province has established a comprehensive vaccine traceability information chain that regulatory authorities may simply see and retrieve. To assist regulatory efforts, vaccination circulation chain data may be generated and examined for abnormalities. The next parts describe the system's user requirements design, business functionality design, and device requirements analysis.

1. System user requirements design

Platform users and platform operation and maintenance users are the two primary types of users for this vaccine regulating platform.

Platform operation and maintenance: The platform is operated and maintained by provincial drug regulatory bureau personnel, provincial and municipal disease control and prevention centres, vaccine unit workers, and vaccination specialists. These users monitor equipment data input and design and install equipment early on. The platform's structural design, operation, maintenance, and administration establish organisational structures, define human roles, manage data, and authorise users. To keep the platform running well, several duties are needed.

Platform users: These users include vaccination unit staff, vaccination workers, provincial/municipal disease control and preventive regulatory personnel, and the provincial drug regulatory bureau. User power varies by role; other roles may utilise appropriate functional modules.

Provincial and municipal disease control and prevention centres oversee vaccine refrigeration, dispatch, inventory management, and intake. They oversee vaccine admission and shipping and record inventory on the platform. Provincial authorities can get this data. The supervisors may monitor the temperature of any vaccinations kept or carried in the province. Individual vaccination unit staff store and utilise immunisations. They must input their unit's storage, inventory, and immunisation data onto the platform. All team-specific vaccination temperature data is available. Supervisors may view provincial vaccine data analytics findings via the site[16]. They now know where and how many individuals are receiving immunisations. By setting warning criteria, they may create a system to notify them of temperature data. In a vaccination emergency, regulatory authorities can immediately locate the affected vaccine, establish its distribution statistics, and notify the proper parties to intervene offline. This speeds vaccination recalls and reallocations.

2. System business function design

Distribution-related temperature storage is crucial to vaccination control throughout the lifetime. To comply with the Vaccine Management Law and serve provincial pharmaceutical regulatory agency officials, this vaccine supervision platform was established. An assessment of the system's commercial performance follows.

- While distributing the vaccine, the platform checks cold chain equipment temperature, humidity, and other environmental conditions in real time. It rapidly warns regulatory authorities to take emergency action if irregularities occur during storage and transportation of the province's immunisations.
- The software tracks vaccine arrival, exit, inventory, distribution, and usage across all provincial institutions. It also tracks the spread of immunisations in the region to track each vaccine batch.
- The platform calculates and analyses provincial vaccine stock and usage. Predetermined warning systems alert to potential threats such a declining immunisation supply. These enable regulatory bodies to make educated decisions, such as resource reallocation, to ensure vaccination supply.
- The platform interacts with vaccine manufacturers to acquire batch numbers and producer information. This ensures the province can trace each immunisation.

3. System equipment requirements analysis

Provincial and local disease control and prevention centres store vaccines in centralised management facilities and cold storage warehouses. They are also delivered in refrigerated vehicles at different distribution levels, kept in insulated boxes for emergency small-batch vaccine allocations, and stored in several temperature-specific refrigerators or freezers in various vaccination centres at all stations[17]. Different IoT-enabled devices are needed for real-time temperature monitoring at each storage site. Fig. 8 shows storage sites and equipment needed. Multiple vaccine storage and distribution sites exist. We calculate the amount of devices needed for each vaccine storage location to decrease cost, improve system maintainability, and optimise equipment setup:

Cold Storage: Vaccine manufacturers offer cold storage to provincial and municipal disease prevention centres. The temperature points to monitor and cold storage space may vary. Thus, several temperature labels exist. Expression 1 illustrates how many cooling storage temperature labels are needed:

$$NLTAT = U\{H, S, \epsilon\},$$

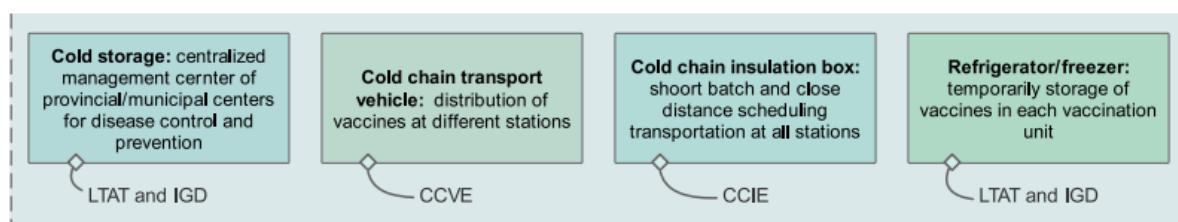


Figure 6. Storage and equipment needs.

Here, H represents the cold storage's height, S its size, and ϵ its interference source coefficient. Certain immunisations are kept at -40°C because to the low temperature of cold storage. The gateway is generally kept outside the cold storage to maintain its performance. The gateway receives temperature information from many LTATS in concentrated cold storage locations. Expression 2 shows gate count.

$$NIGD = U\{NLTAT, D, \epsilon\},$$

ϵ represents the environmental interference source coefficient, and $NLTAT$ is the number of LTAT below 10. Distance between LTAT and IGD is D .

Cold-Chain Transport Vehicles: Vaccines in bulk are usually the intended cargo of this vehicle. Common equipment seen in transportation vehicles typically have two wired temperature sensors. For some cases involving very large box volumes, it is necessary to add extra temperature sensors. Every onboard device has a limit of four temperature sensors.

Cold-chain Insulation Box Equipment: Emergency transfers and the distribution of modest vaccine amounts during periods of low demand are regular uses for this device. The Centres for Disease Control and Prevention (CDC) community centres typically handle its administration and distribution[18].

Refrigerator/Freezer: Due to the range of immunisations and their temperature storage demands, vaccination centres employ refrigerators or freezers. Because of this, vaccines have the greatest storage options. Although normally kept and operated in one place, these storage devices may be relocated as needed. Certain vaccine storage chambers must have temperature monitoring. Thus, LTAT freezers should be temperature-zone-specific. The number of temperature-independent storage sections precisely correlates to the number of LTATs in this design. That for IGDs is equivalent to cold storage in amount. Expression 2's IGD formula remains unaltered[19].

The provincial drug administration counted all vaccine storage facilities. Table 2 shows the total gear required to comply with the rules. Internet of Things Vaccine Monitoring System servers are managed by the Provincial Drug Regulatory Authority's Operation and Maintenance Department. Each vaccine storage facility will have an administrative department to install and configure IoT devices. By adding IoT to the system's integrated design, we improved its performance and made it better than traditional immunisation management. Table 3 examines the two techniques based on efficiency, accuracy, real-time responsiveness, environmental effect, installation processes, and sustainable development.

Table 2: Number of Different Pieces of Equipment

Device Name	Number of Devices
LTAT	24,172
IGD	5,672
CCVE	1,465
CCIE	346

Table 3: Examining Efficiency

Performance	IoT System	Traditional Systems
Consumption	Low	High
Accuracy	High	Low
Real-time	Yes	No
Real-time Alarm	Yes	No
Installation Method	Simple	Complex
Environmental Protection	High	Low
Development Sustainability	Yes	No

DISCUSSION

When compared to more traditional infrastructures, cold chain logistics for pharmaceuticals and vaccines that make use of Internet of Things-enabled technologies provide considerable improvements in terms of both performance and scalability. It is shown in Table 2 that the LTAT makes use of low-cost components, such as the CH583 M microcontroller and the TMP112 temperature sensor, in order to achieve a unit cost of around \$3.11. Because of its cost-efficiency, this system would be of tremendous advantage to developing nations like India, whose budgetary constraints frequently block technological advancements in healthcare logistics[20]. This system would allow for large-scale deployment without imposing a considerable financial load on the country.

The degree to which devices are being implemented throughout the cold chain is highlighted in Table 3, which can be seen here. In addition to continuously transferring data and monitoring temperature conditions in real time, the system is made up of 24,172 LTATs and 5,672 Integrated Gateway Devices (IGDs). A total of 1,465 CCVE units are available, each of which enables centralised control and data integration. Additionally, there are 346 CCIE units that provide assistance for cold chain integration. Through the use of this distribution model, a multi-tiered technique for monitoring cold chain infrastructure in real time is implemented.

As an additional point of interest, a comparison of the two sets of data shown in Table 3 demonstrates that Internet of Things (IoT) systems perform better than traditional setups across all parameters[21]. All of the features that are supplied by Internet of Things systems are not present in traditional models. These capabilities include low power consumption, high accuracy, real-time data tracking, and alerts. Installation is simplified by the Internet of Things (IoT), which reduces the amount of time spent on deployment and the amount of technical labour required. These solutions are highly sustainable from an environmental point of view, which is fantastic news for logistics projects that are environmentally conscious[22]. It is difficult for current systems to properly manage temperature-sensitive vaccines because they lack scalability, accuracy, and flexibility. This presents a difficulty for pharmaceutical companies. When taken as a whole, the data demonstrates that cold chain logistics that are driven by the Internet of Things (IoT) contribute to the achievement of sustainable development goals while simultaneously boosting operational reliability and product safety. They allow real-time visibility, traceability, and low-cost scalability, making them an essential investment for improving India's pharmaceutical supply chain after the COVID outbreak.

CONCLUSION

With the implementation of cold chain logistics for medicines and vaccines, which is made possible by the Internet of Things, there is a revolutionary potential to enhance the sustainability, efficiency, and reliability of healthcare delivery in India. This potential may be realised via the deployment of cold chain logistics. In order for the country to further solidify its position as a global leader in the production of pharmaceuticals, it is of the utmost importance to safeguard perishable goods from exceptionally high temperatures. According to the findings of the research, Internet of Things-based solutions provide a number of advantages over traditional methods. These advantages include enhanced environmental performance, ease of deployment, cost-effectiveness, and real-time monitoring. Components such as LTATs, IGDs, CCVEs, and CCIEs provide for supply chain visibility from the beginning to the end. This visibility is made possible by the strategic deployment of these components. Incorporating such

intelligent solutions not only enhances operational efficiency but also aligns with national health goals and global sustainability objectives. This is of utmost significance in light of the growing emphasis placed on vaccine safety and data-driven logistics. Therefore, in order to strengthen the pharmaceutical logistics ecosystem in India, it is necessary to make rapid investments in cold chain infrastructure that is enabled by the Internet of Things.

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