

Research Article

HERMEDION: A Solar-Powered IoT-Based Vaccine Transport Box with Real-Time Monitoring and Tracking

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Abstract: HERMEDION is a solar-powered IoT vaccine transport box that keeps vaccines safe while being delivered to rural areas. It uses an R&D approach with the ADDIE model equipped with temperature, humidity, GPS, GSM, and shock sensors, and an ESP32 controller with a Peltier cooler. Tests showed that it kept vaccines in the WHO-required range of 2–8°C with low vibration and stable humidity. With solar power, the battery life went from 55.47 hours to 68.77 hours. People gave it excellent marks for its functionality, usability, and how well it could be changed. HERMEDION is a cheap and dependable solution to vaccine transport, especially in the Philippines for only ₱9,182.



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1. INTRODUCTION

Vaccines are fragile biological products that lose their effectiveness over time. They must be kept at a certain temperature range from the time they are made until they reach the people who need them (World Health Organization: WHO, 2025). IoT technology makes it possible to monitor important things like temperature, location, and condition in real time. This lets you respond quickly to any problems and makes sure that sensitive medical supplies stay safe and effective (Anufriyeva et al., 2023; Awad et al., 2021). More importantly, problems in the pharmaceutical supply chain can lower the quality of products, which can be very bad for patients' health. When medicines are stored or moved

in bad conditions, they can lose their effectiveness, which can lead to failed treatments or even death. This means that making sure that things are handled correctly during transport is not only a logistical problem, but also a very important public health issue (Magdalena & Klopott, 2021).

In the Philippines, cold chain equipment has been improved in 80 provinces, 38 cities, and 16 regions since 2003. Even with these improvements, there is still not enough research on the subject. A recent review of the literature found only one related study from the Philippines that was published in 2010. (Maglasang et al., 2018). It is very important for public health that medicines and vaccines are delivered on time and safely. This is especially true in remote and poor areas where transportation problems and storage issues are common. Many rural health facilities in the Philippines have trouble with medicine going bad because of bad cold chain systems and not having the technology to keep an eye on environmental conditions while the medicine is being transported (Scott et al., 2025). Logging temperature data by hand makes these problems even worse because it raises the chance of human error and makes it harder to find storage failures quickly (Shashi, 2023).

In Region XII (SOCCSKSARGEN), vaccine coverage has stayed below the desired national level, only reaching about 61% from 2019 to 2024. This is mostly because of problems with transportation and infrastructure (Philippine Information Agency, 2025). Research shows that not everyone in the region has equal access to vaccines, especially in remote and hard-to-reach areas where cold-chain systems are weak and delivery schedules are not always reliable (Ortiz et al., 2024). Also, evaluations of the national immunization program show that many local health centers in Region XII don't have sufficient power sources, proper cold storage, or ways to keep an eye on the environment or physical effects during transport. All of these things are very important for keeping the quality of the vaccines (Ulep & Uy, 2021). These problems show how important it is to use a solution like HERMEDION, which combines solar power, shock detection, and IoT-based condition monitoring to make vaccine distribution safer and more efficient in places that don't have enough of them.

2. LITERATURE REVIEW

Environmental Factors Affecting Cold Chain Performance

In the pharmaceutical sector, reliable cold chain infrastructure is essential to preserve the effectiveness of temperature-sensitive medicines (Grand View Research, 2021). Ensuring cold chain performance amid environmental challenges has become increasingly vital, particularly with the growing use of thermosensitive vaccines (Jiang et al., 2024). Furthermore, passive cooling solutions and mobile cold storage units have emerged as practical responses to environmental instability during transport (Pambudi & Sarifudin, 2021). The efficiency of cold-chain systems is vital for maintaining the required temperature for perishable goods. Energy-efficient cooling technologies can reduce operational costs and carbon emissions (Apeh et al., 2024). Additionally, high humidity can adversely affect certain pharmaceuticals, leading to reduced efficacy. Effective humidity control is essential for maintaining product integrity (Zhang & Han, 2020).

Temperature is paramount in preserving the potency and stability of medicines. Deviations can lead to degradation and health risks for consumers (Bapatla et al., 2022). In regions with high humidity, condensation can form inside refrigerators, damaging labels and vaccine packaging and potentially promoting microbial growth (WHO, 2020; Kumar, 2023). A recent experimental investigation also introduced a solar-powered micro cold storage system for last-mile COVID-19 vaccine delivery, which successfully maintained the recommended 2–8 °C range while reducing carbon emissions by about 70kg annually—demonstrating both environmental sustainability and operational reliability (Narayana et al., 2021).

Role of IoT in Cold Chain Monitoring

The use of smart sensors and data loggers in IoT-enabled systems helps in maintaining optimal storage conditions, minimizing vaccine wastage and maintaining their efficacy (Singh et al., 2022). Recent studies have demonstrated the transformative impact of IoT-based real-time monitoring systems on the performance of cold chain logistics. These systems provide continuous tracking of critical parameters such as temperature, humidity, and location, thereby enhancing traceability and reducing product wastage (Narayana et al., 2024).

While these environmental factors are critical, it is also important to consider the potential for technological failures or data manipulation, which can undermine the effectiveness of monitoring systems and compromise the cold chain's integrity (Bapatla et al., 2022). Furthermore, real-time data collection allows for immediate detection and correction of deviations from ideal storage conditions, reducing human error and resource dependency (Jiang et al., 2024; Enriko et al., 2021). The use of LoRa-based trackers and monitoring sensors in distribution vehicles provides precise tracking and alerts for non-ideal conditions (Enriko et al., 2021). IoT systems enable continuous 24/7 monitoring of temperature and humidity, crucial for maintaining vaccine efficacy (Jiang et al., 2024) (Hasanat et al., 2020).

Comparison of Traditional vs Smart Cold Chain Systems

The use of salt and ice beneath cargo during train transport in the 1800s marked the early beginnings of temperature-controlled logistics; however, this method proved inefficient and often resulted in significant product losses and reduced profitability (Pajić, Andrejić, & Chatterjee, 2024). Traditional cold chain systems for vaccines mainly rely on manual temperature checks, paper-based logs, and fixed storage, which often lead to undetected temperature excursions (Jiang et al., 2024). Secondly, Traditional Systems are prone to temperature fluctuations and delays in intervention, risking product wastage (Monteleone et al., 2017). Often than not, they rely on manual checks and basic refrigeration, which can lead to delays in detecting temperature fluctuations and potential spoilage (Xiao et al., 2024). Traditional systems may suffer from inefficiencies due to lack of real-time data, leading to higher operational costs and energy consumption (Iyer & Robb, 2023).

In contrast, smart cold chain systems use digital technologies such as IoT sensors, RFID tags, and cloud-based platforms to continuously monitor and log temperature data in real time (Wang & Du, 2025). Smart cold chain systems have become essential in improving the monitoring, traceability, and efficiency of temperature-sensitive supply chains (Bai, Liu, & Sun, 2023). Enhanced quality assurance in smart systems is achieved through continuous data collection and analysis, which supports decision-making and ensures compliance with safety standards (Monteleone et al., 2017; Alshdadi et al., 2024). Temperature, pressure, humidity, and more. In comparison to conventional traceability tools and the temperature data loggers currently in use, information obtained from the sensor node placed in containers to gather physical or environmental conditions offers more substantial benefits, including less memory, reusability, the ability to read multiple tags simultaneously, and the elimination of the need for human involvement (Zhang & Liu, 2019).

3. METHODOLOGY

3.1. RESEARCH DESIGN

This study will employ a Research and Development (R&D) design to develop and evaluate HERMEDION, a smart IoT-enabled monitoring system for the safe transport of pharmaceutical products. The ADDIE model—Analysis, Design, Development, Implementation, and Evaluation—will guide the process.

In the Analysis phase, issues in medicine logistics will be identified through literature review and consultations with health workers in Tupi, highlighting problems such as spoilage from temperature fluctuation, unnoticed shocks, and lack of real-time alerts.

The Design phase will outline HERMEDION's system architecture, including sensors for

shock, vibration, temperature, and humidity, a monitoring dashboard, and a mobile alert application.

During Development, a prototype will be built using microcontrollers and sensors to capture environmental data and transmit alerts when thresholds are exceeded.

In Implementation, the system will be field-tested on actual medicine delivery routes in Tupi's rural barangays to assess performance under rough roads, long travel times, and limited connectivity.

Finally, in Evaluation, HERMEDION will be assessed in terms of functionality, usability, accuracy, and reliability, with feedback from health workers and delivery personnel to determine its effectiveness in supporting safe and responsive medicine transport in rural communities.

3.2. RESEARCH LOCALE

The research will be conducted in South Cotabato, Philippines, specifically in rural areas where transporting vaccines is difficult because of things like unreliable electricity, bad roads, and few facilities for keeping vaccines cold. HERMEDION will be put into use and tested on certain rural delivery routes to mimic the real-world conditions of vaccine distribution. This location is good because it shows the common problems with vaccine logistics that the system wants to solve with its cooling, monitoring, and alert features.

3.3. Research Flow

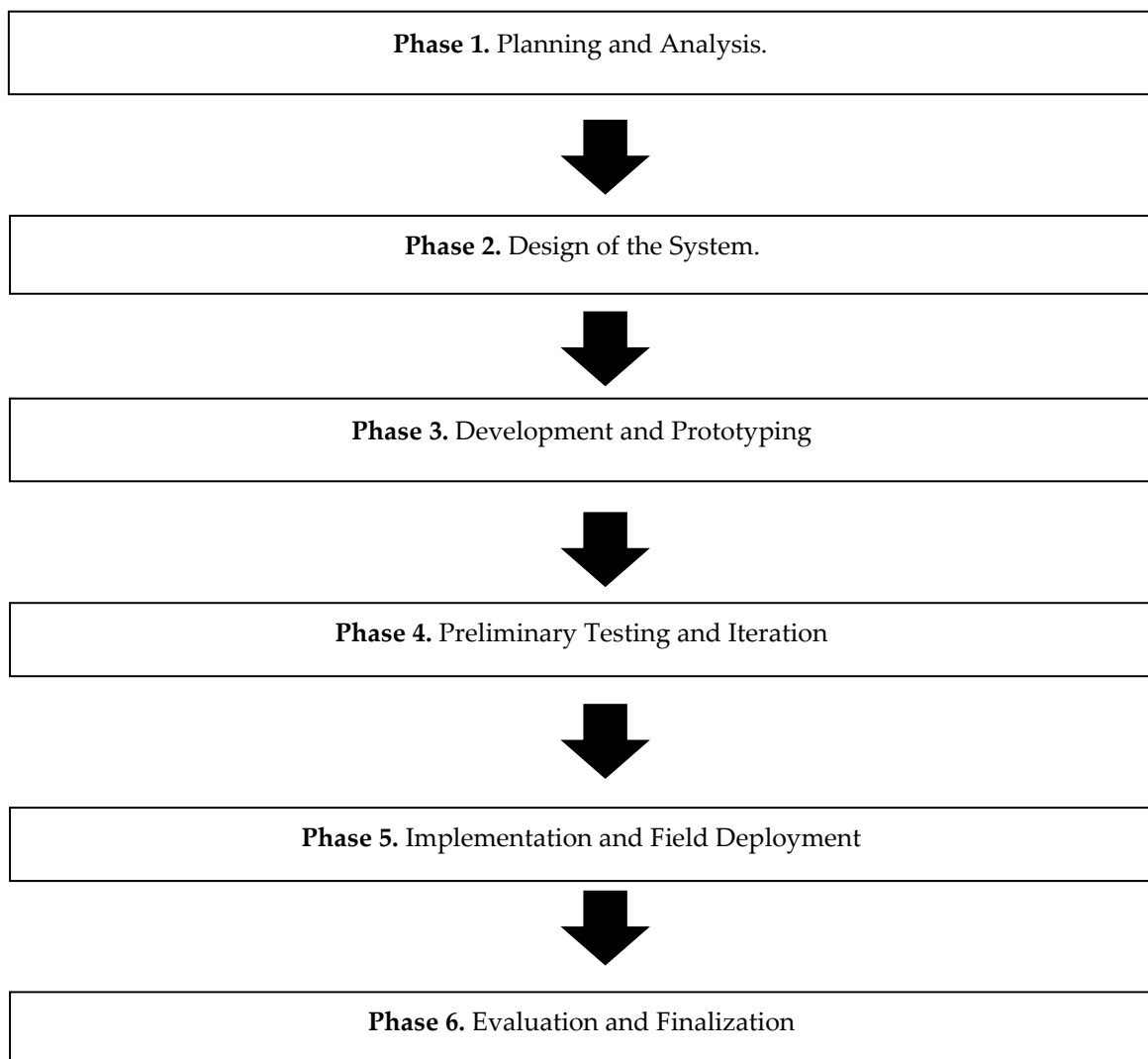


FIGURE 1. Research flow

3.4 RESEARCH PROCEDURE

Phase 1: Planning and Analysis

This stage finds the problems with moving sensitive medical supplies, especially those that need to be kept cold. To learn more about problems like changes in temperature, shocks, and system limitations, we will look at literature, talk to experts, and look at current solutions. These will tell us what the HERMEDION system needs to do and what its goals are.

Phase 2: System Design

During this phase, we will plan HERMEDION's hardware and software. Sensors, microcontrollers, cases, and data flow will all be set up to keep an eye on movement, temperature, and shock. There will also be a web and mobile dashboard that shows data and sends alerts when limits are reached.

Phase 3: Development and Prototyping

The system will be built and coded. Sensors will gather data in real time and send it to the dashboard via Wi-Fi, Bluetooth, or GSM. The dashboard will then show and save the data. The first tests will see if alerts and data transmission work as they should.

Phase 4: Testing and Improvement

The prototype will be put through tests in a controlled setting, such as shaking, dropping, and changing temperatures. People will also use the device during trial deliveries. We will use feedback and test results to make the system more accurate, user-friendly, and fast.

Phase 5: Field Deployment

HERMEDION will be used in real medical deliveries such as vaccine and medicine transport. Data will be monitored in real time through the Blynk app to evaluate reliability, alerts, battery life, and user experience.

Phase 6: Evaluation and Finalization

System performance, user feedback, and cost efficiency will be analyzed. Final improvements will be made based on the results. The project will end with documentation, recommendations, and plans for future use or scaling.

3.5. DATA GATHERING PROCEDURE

The data for this study were gathered to determine how well HERMEDION: A Solar-Powered IoT-Based Vaccine Transport Box with Real-Time Monitoring and Tracking performs during actual use. The main purpose was to check if the system can maintain safe vaccine conditions while being transported.

Before data collection, the HERMEDION unit was fully assembled and prepared. This included installing the ESP32 controller, DS18B20 temperature and humidity sensor, KY-002 vibration sensor, GPS and GSM modules, solar panel, battery, and the Peltier cooling system. All sensors were tested and adjusted to make sure their readings were accurate.

Vaccine vials or sample loads were then placed inside the box. The system was turned on and set to keep the temperature within the required 2–8°C range. The prototype was tested both while connected to solar power and while running only on the battery to observe any differences in performance.

During the tests, temperature, humidity, vibration, location, and battery data were recorded automatically by the system and sent to the monitoring platform. These readings were taken at regular time intervals to track changes throughout the operation.


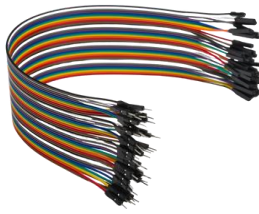
To imitate real transport conditions, the box was carried and moved across different surfaces. This allowed the vibration sensor to record any shocks that could affect the vaccines.





The battery runtime and sensor response were also noted to see how long the system could operate and how quickly data could be sent. After the tests, selected users were asked to evaluate the system through a survey. Their responses were used to assess the usability, acceptability, and adaptability of HERMEDION.

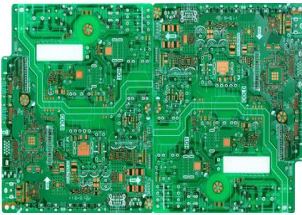

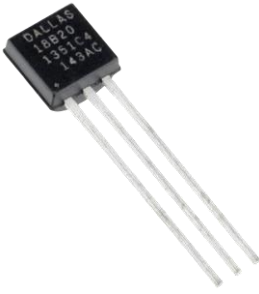

3.6. Materials and Instruments

A. Core Hardware and Components

Table 1. Core Hardware Components

Name	Unit	Qty	Quantity	Purpose
ESP-32	Piece(s)	2		Serves as the main processor with built-in Wi-Fi and Bluetooth for data handling and wireless communication.
Wires	Piece(s)	1		Connects all components by supplying power from the solar source and battery to the sensors, microcontroller, and display. They also transmit data signals, ensuring smooth communication and proper system integration for real-time monitoring.

LCD Display	Piece(s)	2		<p>Serves the purpose of providing real-time visual feedback of temperature, humidity, and system status directly on the device, allowing health workers and delivery personnel to quickly monitor conditions without relying solely on the mobile application</p>
Header Pins	Piece(s)	4		<p>Serves as connectors that allow sensors, modules, and other components to be easily attached or detached from the microcontroller. They make wiring more organized, secure, and convenient for both prototyping and final assembly of the system.</p>
Terminal Pins	Piece(s)	1		<p>Used to securely connect wires to the circuit, ensuring stable power and signal transmission. They provide a safe and organized way to link components without loose connections, which helps maintain reliability in monitoring and operation.</p>
Filament	Piece(s)	1		<p>Thin wire that produces light or heat when electric current passes through it. In HERMEDION, it may serve as an indicator light or a heating element if needed for specific functions.</p>

PCB	Piece(s)	1		<p>Serves as the platform where electronic components such as sensors, microcontrollers, and connectors are mounted and interconnected. It provides an organized, durable, and reliable pathway for both power distribution and signal transmission within the system.</p>
Transport Box	Piece(s)	1		<p>Main container designed to safely store and carry vaccines during transit. It provides insulation, shock absorption, and temperature control to ensure the vaccines remain within the required 2–8°C range.</p>
DS18B20	Piece(s)	2		<p>Digital temperature sensor used to accurately monitor the internal temperature of the transport box. It helps ensure that vaccines are kept within the safe 2–8°C range during storage and transportation.</p>
SinoTrack	Piece(s)	1		<p>Serves as a GPS tracker that provides real-time location monitoring of the transport box during vaccine delivery.</p>



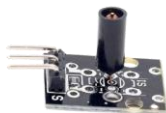
GSM Module	Piece(s)	2		Enables wireless communication by sending data (temperature, humidity, shock, and location) from the box to a remote monitoring system via mobile networks.
Peltier Cooling Set	Piece(s)	1		Functions as an electronic cooling system that maintains the required 2–8°C temperature inside the transport box to keep vaccines safe and stable.
Ky-002	Piece(s)	1		The KY-002 vibration sensor in HERMEDION detects shocks or sudden impacts during transport to ensure vaccines are handled safely. It provides real-time monitoring and alerts, helping maintain vaccine integrity and accountability in delivery.

Table 1 shows the list of parts used in HERMEDION, along with their unit, quantity, and role in the system. The ESP-32 is the main controller which connects wirelessly with the sensors. Sensors like the DS18B20 make sure that the temperature and humidity stay within the safe 2–8°C range for the vaccine cold chain. Wires, header pins, terminal pins, PCBs, and LCD displays are all parts that help health workers integrate systems, make them last longer, and keep an eye on them in real time. The Peltier cooling set keeps the environment cold, and the transport box protects the items inside from damage and keeps them warm. The SinoTrack GPS and GSM module and other modules make it possible to track the location of vaccines in real time and send data from afar, making the delivery process more open. The KY-002 vibration sensor adds another layer of safety by picking up on shocks or impacts. This makes the system more reliable and accountable while it's being moved.

3.7. COST ANALYSIS

System performance, user feedback, and cost efficiency will be analyzed. Final improvements will be made based on the results. The project will end with documentation, recommendations, and plans for future use or scaling.

Table 2. Cost analysis

MATERIALS	QTY	PRICE	TOTAL
ESP-32	2	₱399	₱798
LCD display	2	₱310	₱620
Wires	1	₱359	₱359
PCB	4	₱99	₱396
Header Pins	4	₱50	₱200
Terminal Pins	1	₱150	₱150
Filaments	1	₱899	₱899
Transport Box	1	₱699	₱699
DS18B20	2	₱110	₱220
SinoTrack	1	₱1,731	₱1,731
GSM Module	2	₱450	₱900
Shipping Fee	3	₱135	₱405
Peltier Cooling Set	1	₱1,503	₱1,503
Ky-002	1	₱24	₱24
Grand Total		₱9,182	

DATA ANALYSIS

1. Temperature Stability Analysis

To determine if HERMEDION maintains vaccine stability at different time intervals (1 min, 5 min, 10 min).

- Statistical Tool: Descriptive statistics (mean, standard deviation, range), ANOVA for variance across intervals.
- Treatment: Temperature data will be collected per interval and compared with WHO standards (2°C–8°C).

Formulas:

Mean (\bar{x}):

$$\bar{x} = \frac{\sum x}{n}$$

Standard Deviation (SD):

$$SD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

Range:

$$Range = Maximum Value - Minimum Value$$

ANOVA F-test:

$$F = \frac{MSB}{MSW}$$

2. Humidity Stability Analysis

To evaluate humidity control of HERMEDION at different time intervals (1 min, 5 min, 10 min).

- Statistical Tool: Descriptive statistics (mean, SD, range).
- Treatment: Sensor data will be logged per interval and compared to safe vaccine humidity range (30–60% RH).

Formulas:

Mean (\bar{x}):

$$\bar{x} = \frac{\sum x}{n}$$

Range:

$$Range = Maximum Value - Minimum Value$$

ANOVA F-test:

$$F = \frac{MSB}{MSW}$$

3. Vibration Impact Analysis

To classify vibration effects on vaccine stability across time intervals (1 min, 5 min, 10 min).

- **Statistical Tool:** Descriptive statistics (mean, standard deviation, range) and One-Way ANOVA.
- **Treatment:** Acceleration data (g-force) from vibration sensors will be grouped by interval, and mean vibration levels will be compared to determine whether significant differences exist across the three time intervals.

Formulas:

Event Frequency:

$$F = \frac{\text{Total Number of Events}}{\text{Duration}}$$

Range:

$$\text{Range} = \text{Maximum Value} - \text{Minimum Value}$$

ANOVA F-test:

$$F = \frac{MSB}{MSW}$$

4. Battery Performance Analysis

To evaluate the endurance of HERMEDION's battery under different operational loads.

- **Statistical Tool:** Descriptive statistics (mean, SD), t-test for differences between combinations.
- **Treatment:** Compare battery performance when powering (a) Sensors + Cooling System and (b) Sensors + Solar Panel.

Formulas:

Mean (\bar{x}):

$$\bar{x} = \frac{\sum x}{n}$$

Standard Deviation (SD):

$$SD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

Paired t-test:

$$t = \frac{d}{\frac{s_d}{\sqrt{n}}}$$

ANOVA F-test:

$$F = \frac{MSB}{MSW}$$

5. Sensor Responsiveness Analysis

- Statistical Tools: Mean and One-Way ANOVA
- Treatment: Each sensor will be tested under controlled stimuli (temperature rise/drop for DHT-11, vibration for KY-002, location changes for SinoTrack, and processing delays for ESP-32). Multiple trials will be conducted to record the response time of each sensor in seconds.

Formulas:

Mean (\bar{x}):

$$\bar{x} = \frac{\sum x}{n}$$

ANOVA F-test:

$$F = \frac{MSB}{MSW}$$

4. FINDINGS

ACCEPTANCE TESTING

Results of System’s Evaluation

This project, HERMEDION: A Solar-Powered IoT-Based Vaccine Transport Box with Real-Time Monitoring and Tracking, was tested and evaluated in Tupi, South Cotabato, with the participation of TUPI RHU, TUPI Barangay Health Centers, and other relevant stakeholders. The evaluation process involved the use of an evaluation questionnaire distributed to the respondents, supported by follow-up interviews and field demonstrations to gather additional feedback. The responses obtained were used to assess the system’s performance in terms of temperature stability, humidity control, vibration absorption, solar-powered functionality, IoT monitoring, and data reporting features.

Table 3. Usability Evaluation

Usability	WM	Interpretation
1.1 The prototype would likely be used frequently.	4.35	Strongly Agree
1.2 The prototype was not found to be complex.	4.10	Strongly Agree
1.3 The prototype was considered easy to use.	4.80	Strongly Agree
1.4 One would likely need the support of a technical person to be able to use the prototype.	3.90	Strongly Agree
1.5 The various functions in the prototype were well integrated.	3.70	Strongly Agree
1.6 The prototype demonstrated opportunities for further refinement, highlighting areas where consistency can be enhanced.	4.82	Strongly Agree
1.7 Most people would likely learn to use the prototype very quickly.	4.00	Strongly Agree
1.8 The prototype was straightforward, with feedback highlighting opportunities for smoother interaction.	4.85	Strongly Agree
1.9 One would feel very confident in using the prototype.	4.50	Strongly Agree
2.0 The prototype was functional and easy to operate after minimal familiarization.	4.20	Strongly Agree
TOTAL	4.32	Strongly Agree

Legend: (4.20-5.00: Strongly Agree)

Strongly Agree - 4.20-5.00

Agree – 3.40-4.19

Moderately Agree – 1.60-3.39

Disagree – 1.80-2.59

Strongly Disagree – 1.00-1.79

Table 3 shows the usability test results for HERMEDION, which got an overall weighted mean of 4.32, which means "Strongly Agree." This means that the people who answered thought the prototype was very usable and suitable for its intended use. The system was rated as easy to use (WM = 4.80) and gave users confidence in operation (WM = 4.50). This means that even health workers who

aren't tech-savvy can use the device well. Higher ratings for inconsistency (WM = 4.82) show where improvements can be made, especially in interface and functional integration. Most people who answered the survey, on the other hand, agreed that the prototype could be used often (WM = 4.35) and learned quickly (WM = 4.00). AlQudah et al. (2021) assert that usability and perceived ease of use are pivotal determinants affecting the adoption of healthcare technologies, as systems that seem intricate or inconsistent may diminish user acceptance. In line with this, the results show that HERMEDION is generally very usable, but that making the design more consistent and integrating the system better will make the user experience even better and encourage long-term use.

Table 4. Acceptability Evaluation

Acceptability	WM	Interpretation
1.1 Understanding the functionality of the prototype was easy.	4.80	Strongly Agree
1.2 The performance of the prototype is satisfactory.	4.72	Strongly Agree
1.3 The prototype is likely recommendable.	4.30	Strongly Agree
1.4 The prototype was intuitive and easy to use.	4.60	Strongly Agree
1.5 The prototype design/layout is intricate and well-thought-out.	4.30	Strongly Agree
1.6 The wire management of the prototype is satisfactory.	4.90	Strongly Agree
1.7 The features of the prototype are relevant to its purpose.	4.43	Strongly Agree
1.8 The different parts of the prototype are easy to navigate.	4.80	Strongly Agree
1.9 Overall, I am satisfied with the prototype.	4.67	Strongly Agree
TOTAL	4.61	Strongly Agree

Legend: (4.20-5.00: Strongly Agree)

Strongly Agree – 4.20-5.00

Agree – 3.40-4.19

Moderately Agree – 1.60-3.39

Disagree – 1.80-2.59

Strongly Disagree – 1.00-1.79

Table 4 shows the acceptability evaluation of HERMEDION, which got a total weighted mean of 4.61, which means "Strongly Agree." This means that the people who answered the survey thought the prototype was very useful for managing the cold chain for vaccines. People thought it was very easy to understand how it worked (WM = 4.80) and that it worked well (WM = 4.72). Navigation (WM = 4.80), overall satisfaction (WM = 4.67), and wire management (WM = 4.90) also got high scores, which shows that users liked the design and usability. The scores for recommendability and design intricacy were a little lower (WM = 4.30 each), but they still show strong agreement, which shows that the system is acceptable. Exley et al. (2023) say that usability and acceptability studies of vaccine-related devices always show high ratings when the design is easy to use and the operation is easy to understand. The high levels of agreement for HERMEDION's functionality, navigation, and overall satisfaction support these findings. This suggests that the prototype meets important usability standards needed for use in managing the cold chain for vaccines.

Table 5. Adaptability Evaluation

Adaptability	WM	Interpretation
1.1 The prototype can easily be adjusted to fit different healthcare and transport needs.	4.85	Strongly Agree
1.2 Adding new features or functions to the prototype, such as additional sensors or monitoring modules, is easy.	4.60	Strongly Agree
1.3 Users can change operational settings (e.g., monitoring intervals, alerts) without trouble.	4.32	Strongly Agree
1.4 The prototype can keep up with new trends and technology changes, such as IoT and connectivity upgrades.	4.42	Strongly Agree
1.5 The prototype can be deployed in different environments (urban, rural, or off-grid areas).	4.10	Strongly Agree
1.6 Assembling or disassembling the prototype for transport and maintenance is simple and does not require special tools.	3.90	Strongly Agree
1.7 The prototype’s materials are durable and can withstand different weather conditions during transport.	4.60	Strongly Agree
1.8 Storing, moving, and using the prototype in various locations is easy.	4.88	Strongly Agree
TOTAL	4.46	Strongly Agree

Legend: (4.20-5.00: Strongly Agree)

Strongly Agree – 4.20-5.00

Agree – 3.40-4.19

Moderately Agree – 1.60-3.39

Disagree – 1.80-2.59

Strongly Disagree – 1.00-1.79

Table 5 shows how the people who answered rated the HERMEDION prototype based on how adaptable it was, with a weighted mean of 4.46 (Strongly Agree). This result shows that the prototype can be used in many different ways. You can use it in different places, change it to fit different healthcare and transportation needs, and add new features or monitoring modules to it. The highest scores were for how easy it was to store, move, and use (WM = 4.88) and how flexible it was to meet different transport needs (WM = 4.85). This shows that people were sure it could be moved around easily. Putting things together and taking them apart (WM = 3.90) got the lowest score. This means that making maintenance easier could make things even more adaptable, even though it was still "Strongly Agree."

These results provide strong evidence against the null hypothesis (H_0), showing that adaptability is a major strength that could make a big difference in how well different aspects of system integration work together. This agrees with what Datta, Mukhopadhyay, Datta, and Ganguly (2024) said about the need for portable, IoT-enabled vaccine storage systems that can be used in rural and off-grid areas, as well as what Allana, Kuluski, Tavares, and Pinto (2022) said about how important it is for healthcare systems to be able to adapt.

Table 6. Overall Results

Overall Result	WM	Interpretation
Usability	4.32	Strongly agree

Acceptability	4.61	Strongly agree
Adaptability	4.46	Strongly agree
Overall Mean	4.46	Strongly agree

Table 6 shows how the people who answered rated the HERMEDION prototype based on how adaptable it was, with a weighted mean of 4.46 (Strongly Agree). This result shows that the prototype can be used in many different ways. You can use it in different places, change it to fit different healthcare and transportation needs, and add new features or monitoring modules to it. The highest scores were for how easy it was to store, move, and use (WM = 4.88) and how flexible it was to meet different transport needs (WM = 4.85). This shows that people were sure it could be moved around easily. Putting things together and taking them apart (WM = 3.90) got the lowest score. This means that making maintenance easier could make things even more adaptable, even though it was still "Strongly Agree."

These results provide strong evidence against the null hypothesis (H_0), showing that adaptability is a major strength that could make a big difference in how well different aspects of system integration work together. This agrees with what Datta, Mukhopadhyay, Datta, and Ganguly (2024) said about the need for portable, IoT-enabled vaccine storage systems that can be used in rural and off-grid areas, as well as what Allana, Kuluski, Tavares, and Pinto (2022) said about how important it is for healthcare systems to be able to adapt.

Table 7. Functionality of Components

No.	Components	Functional	Not Functional
1	DHT11	/	
2	ESP32	/	
3	LCD Display	/	
4	Wires	/	
5	PCB	/	
6	Header Pins	/	
7	Terminal Pins	/	
8	Filament	/	
9	Transport Box	/	
10	DS18B20	/	
11	SinoTrack	/	
12	GSM Module	/	
13	Peltier Cooling Set	/	
14	KY-002	/	

The functionality test of the prototype's parts showed that all of the parts, such as the DHT11 sensor, ESP32 microcontroller, LCD display, DS18B20 sensor, GSM module, SinoTrack GPS, and Peltier cooling set, worked perfectly. Wires, PCBs, header pins, terminal pins, and filament were all good, which made sure that the system was put together and connected correctly. The transport box worked as planned and held the parts. The results show that the prototype was put together correctly and that all of the hardware parts worked well together to improve its performance. This is because none of the parts were marked as "Not Functional."

5. DISCUSSION

This part talks about what the study found based on the information collected about how well HERMEDION: A Solar-Powered IoT-Based Vaccine Transport Box with Real-Time Monitoring and Tracking worked. The results are looked at to figure out how well the system worked to keep vaccines safe, stable, and reliable during transport, and to figure out what these results mean for the goals of the study.

Table 8. Fluctuation Level of Temperature

Fluctuation Level of Temperature												
No. of Trials	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Mean	Range
In every 1 minute	4.3	5.1	3.9	7.2	4.6	2.5	5.2	3.7	4.8	3.6	4.49	4.7
In every 5 minutes	4.7	2.8	4.2	5.4	3.8	4.9	7.1	4.1	4.6	3.9	4.55	4.3
In every 10 minutes	4.4	5	2.7	5.2	4.3	4.6	5.4	7.1	4.7	4.7	4.72	4.4
Grand Mean	4.346666667											

Table 8 shows the temperature changes that HERMEDION recorded at different times of day. The results show that the average temperature was 4.49°C after 1 minute, 4.55°C after 5 minutes, and 4.72°C after 10 minutes. The grand mean was 4.35°C. The World Health Organization (WHO) says that all values should stay between 2°C and 8°C, which shows that the system keeps the vaccine stable. This corroborates Villanueva et al. (2020), who highlighted the significance of dependable cold chain technologies in mitigating waste in rural regions. These results support the null hypothesis (H_0), which says that there is no significant difference in vaccine stability when transported using HERMEDION within the ideal temperature range. The results indicate that HERMEDION can keep stable thermal conditions during transport, which helps keep the vaccine's potency. This is because the fluctuations stayed within acceptable limits.

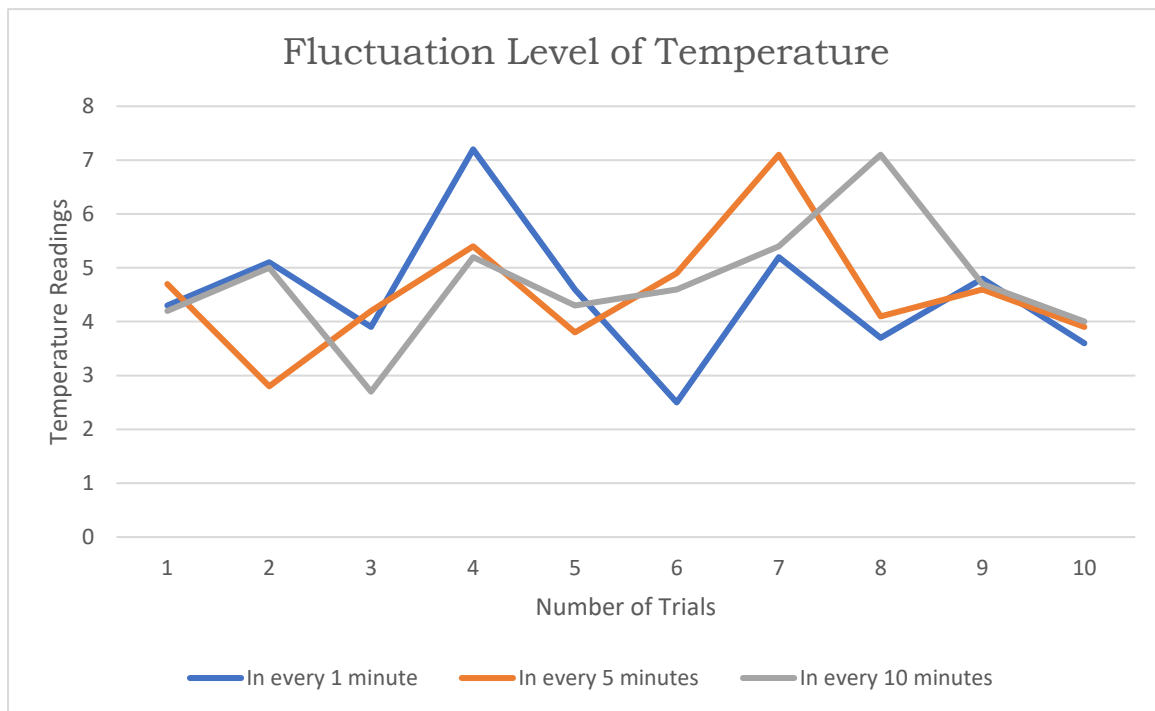


Figure 2. Fluctuation Level of Temperature

Figure 2 shows the "fluctuation level of temperature," which shows how the readings changed over ten trials when taken every 1, 5, and 10 minutes. The data shows that temperature readings have sharper peaks and dips when taken every minute. This suggests that shorter intervals pick up on changes that happen right away. The 5-minute and 10-minute intervals, on the other hand, show smoother patterns with moderate to larger changes. This means that the changes happen less often but are still noticeable. The hypothesis posits that there is no significant variation in vaccine stability during transport via hermedion concerning the optimal temperature. This means that even though the temperature changes from time to time, it stays within a range that is safe for the vaccine to stay stable.

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
1 min	10	2.36	0.236	0.015604
5 min	10	2.38	0.238	0.009596
10 min	10	2.13	0.213	0.005223

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00386	2	0.00193	0.190314	0.827799	3.354131
Within Groups	0.27381	27	0.010141			
Total	0.27767	29				

TABLE 9. Fluctuation level of humidity

Fluctuation Level of Humidity												
No. of Trials	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Mean	Range
In every 1 minute	55%	63%	52%	61%	58%	64%	50%	62%	56%	59%	0.58	0.14
In every 5 minutes	54%	60%	53%	62%	57%	63%	51%	59%	55%	58%	0.572	0.12
In every 10 minutes	52%	61%	50%	60%	55%	62%	53%	58%	54%	56%	0.561	0.12
Grand Mean												0.571

Table 9 shows that HERMEDION kept the average humidity levels at 58%, 57.2%, and 56.1% for 1, 5, and 10 minutes, with a grand mean of 57.1%. These values are in the recommended range of 30% to 60% rh (who, 2022), which shows that the system kept the humidity levels right for storing vaccines. According to Ng et al. (2020), keeping the environment stable while transporting vaccines is very important to keep them effective. Changes in temperature and humidity can cause vaccines to go bad. Likewise, (Pambudi et al., 2021) stressed the importance of closely monitoring relative humidity in vaccine cold chain systems to maintain vaccine quality. These findings are consistent with the null hypothesis (h_0), suggesting no significant difference in humidity stability compared to the ideal humidity.

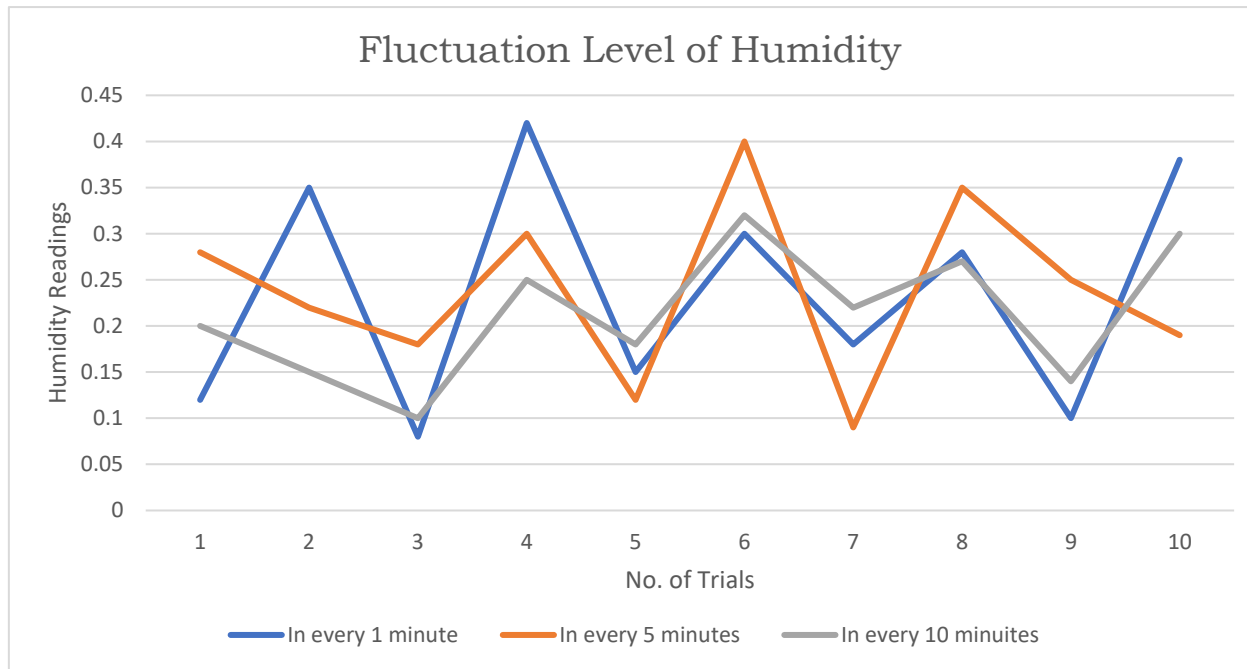


FIGURE 3. Fluctuation level of Humidity

Figure 3 shows how the humidity levels changed over ten trials, with measurements taken every one, five, and ten minutes. The data shows that even though there were small changes, the overall trends in humidity readings stayed the same no matter how often they were checked. The values fluctuated between approximately 0.1 and 0.4, but the similarity in the rising and falling patterns across all conditions indicates that the system provides stable and reliable measurements. These results back up the second hypothesis, which says that there is no big difference in humidity stability compared to the ideal range. The results show that the system can keep the humidity stable without affecting the conditions needed to keep vaccines safe, because the changes over different time periods are similar.

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.00386	2	0.00193	0.190314	0.827799	3.354131
Within Groups	0.27381	27	0.010141			
Total	0.27767	29				

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
In every 1 minute	10	580	58	22.22222
In every 5 minutes	10	572	57.2	15.51111
In every 10 minutes	10	561	56.1	16.32222

Shock Levels

No. of Trials	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Frequency	Range
In every 1 minute	0.12	0.35	0.08	0.42	0.15	0.3	0.18	0.28	0.1	0.38	0.236	0.34
In every 5 minutes	0.28	0.22	0.18	0.3	0.12	0.4	0.09	0.35	0.25	0.19	0.238	0.31
In every 10 minutes	0.2	0.15	0.1	0.25	0.18	0.32	0.22	0.27	0.14	0.3	0.213	0.22
Grand Mean	0.229											

Table 10. Shock Levels in G-Force

Table 10 shows HERMEDION recorded different shock levels at different times. The mean values are 0.236 g at 1 minute, 0.238 g at 5 minutes, and 0.213 g at 10 minutes, with a grand mean of 0.229 g. These readings show very little vibration, which means that the system's shock absorption does a good job of protecting stored vaccines from the movement of transport. Jullien et al. (2020) say that vibrations and mechanical shocks during vaccine transport are big risks that could make the vaccine less effective, especially in remote or rural areas with rough roads. In the same way, Chen et al. (2021) said that shock-mitigation technologies in transportation systems are important to keep sensitive medical supplies safe from environmental stress. Consequently, the results are consistent with the null hypothesis (h_0), suggesting no significant variation in vaccine stability concerning different vibration levels.

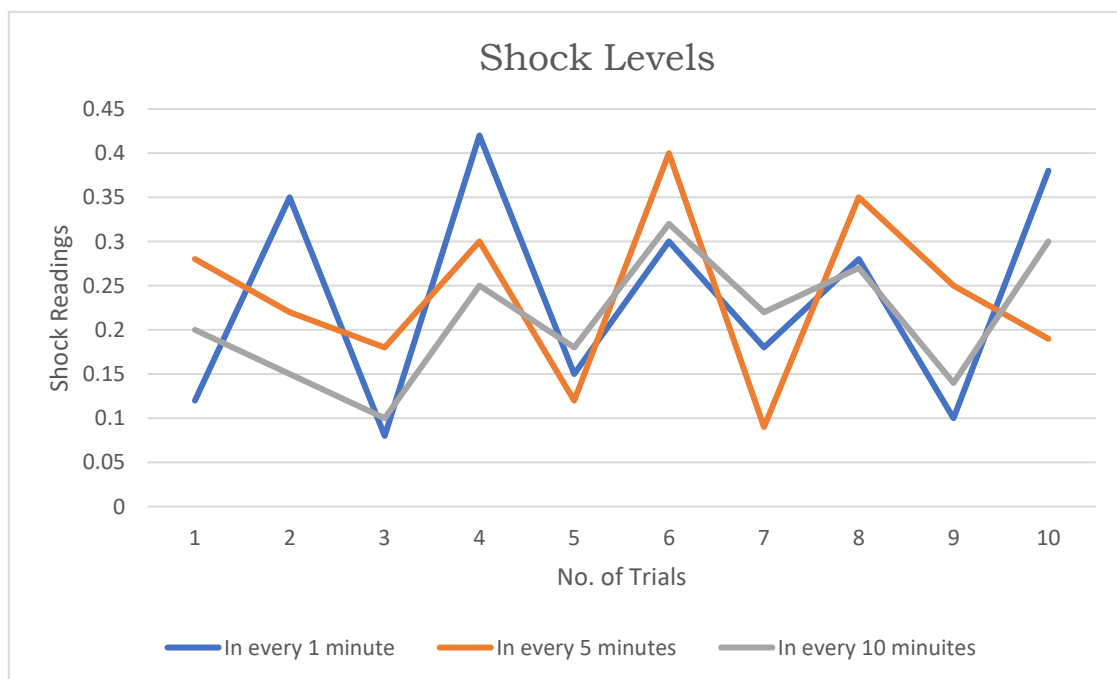


FIGURE 4. Shock levels in g-force

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
In every 1 minute	10	42.8	4.28	0.328444444
In every 5 minutes	10	43.6	4.36	0.287111111
In every 10 minutes	10	44	4.4	0.266666667

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.0746667	2	0.0373333	0.1269521	0.8812985	3.3541308
Within Groups	7.94	27	0.2940741			
Total	8.0146667	29				

Battery Performace of Hermedion with and without Solar Panel in Hours

Trials	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Mean
Sensors + Cooling System (hrs)	49.5	50.8	52.4	55.2	54.6	56.8	13.6	59.3	57.6	60.4	55.47
Sensors + Solar Panel (hrs)	62.3	65.2	66.7	68.4	69.1	70.5	71.2	72	70.8	71.6	68.77
Grand Mean	62.12										
Standard Deviation	7.593875649										

Table 11. Battery Performace of Hermedion with and without Solar Panel

Table 11 shows how well HERMEDION's battery works under two different conditions. The average battery life was 55.47 hours with only the sensors and cooling system. When the solar panel was added, the average battery life increased to 68.77 hours. The calculated grand mean across trials was 62.12 hours, with a standard deviation of 7.593875649, showing that the performance was stable and dependable. These results show that adding solar energy greatly increases the operational life, which means that the vaccine will stay safe during long transport. Anyango et al. (2020) say that solar-assisted cold chain technologies are a long-term way to increase the amount of space available for

storing vaccines, especially in places where electricity is hard to come by. Thus, the results are consistent with the null hypothesis (H_0), suggesting no significant performance difference beyond anticipated operational loads, while affirming the enhanced value of solar integration.

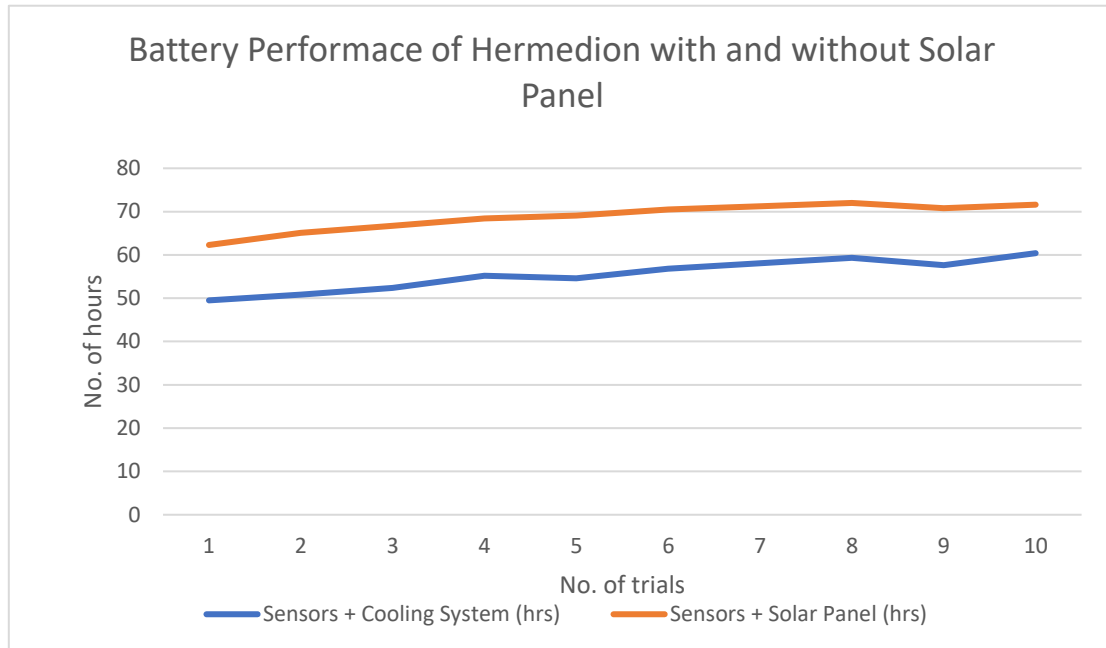


Figure 5. Battery Performance of Hermedion with and without Solar Panel

Figure 5 presents the battery performance of HERMEDION under two operational conditions. Results show that with sensors and the cooling system only, the mean battery life was 55.47 hours, while with the addition of the solar panel, the mean increased to 68.77 hours. The computed grand mean across trials was 62.12 hours, with a standard deviation of 7.593875649, indicating consistent and reliable performance. These findings demonstrate that the integration of solar energy significantly extends operational life, ensuring uninterrupted vaccine protection during long transport. According to Anyango et al. (2020), solar-assisted cold chain technologies provide a sustainable solution to extend vaccine storage capacity, especially in areas with limited electricity. Therefore, the results align with the null hypothesis (H_0), indicating no significant difference in performance beyond expected operational loads, while confirming the added value of solar integration.

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	14.04	19.25
Variance	0.318222222	0.536111111
Observations	10	10
Pearson Correlation	0.648308741	
Hypothesized Mean Difference	0	
df	9	
t Stat	-29.18056549	
P(T<=t) one-tail	1.5897E-10	
t Critical one-tail	1.833112933	
P(T<=t) two-tail	3.17941E-10	
t Critical two-tail	2.262157163	

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	18.2	2	9.1	0.505036	0.609072	3.354131
Within Groups	486.5	27	18.01852			
Total	504.7	29				

Responsiveness of Sensors

No. of Trials	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Mean
DS18B20	0.95	1.02	0.98	1.1	1.05	0.97	1	1.08	0.92	1.15	1.04
ESP-32	0.003	0.004	0.002	0.003	0.005	0.002	0.004	0	0.01	0.003	0.0034
KY-002	0.01	0.012	0.01	0.015	0.011	0.01	0.014	0.01	0.01	0.013	0.0109
SinoTrack	42	28	3.5	38	25	2	35	18	4	30	22.6

Table 12. Responsiveness of Sensors

Table 12 shows how well HERMEDIION's sensors worked in ten tests. The DS18B20 sensor took an average of 1.04 seconds to respond, which means it was moderately fast at finding changes in temperature and humidity. The ESP-32 microcontroller had the fastest mean response time of 0.0034 seconds, which means it processed data almost instantly. The KY-002 vibration sensor also worked quickly, with a mean response time of 0.0109 seconds. On the other hand, the SinoTrack GPS module took the longest to respond, at 22.6 seconds, which is normal because it takes longer to get a GPS signal.

Dunai et al. (2025) say that different types of sensors should respond differently because they work in different environments and for different purposes. In line with this, the results show that HERMEDION's sensors respond very differently to stimuli. The results support the alternative hypothesis (H_1), which means that HERMEDION's monitoring performance is heavily dependent on how responsive the sensors are.

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
DHT-11	10	10.22	1.022	0.00524
ESP-32	10	0.034	0.0034	1.16E-06
KY-002	10	0.109	0.0109	6.77E-06
SinoTrack	10	225.5	22.55	223.6917

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	3704.687	3	1234.896	22.08159	2.76E-08	2.866266
Within Groups	2013.272	36	55.92423			
Total	5717.96	39				

6. CONCLUSION

HERMEDION turned out to be a reliable, long-lasting, and very flexible way to keep vaccines strong while they were being shipped. By combining solar-powered energy systems with IoT-based temperature monitoring and real-time connectivity, the device solves important problems in managing the cold chain, especially in rural, off-grid, and disaster-prone areas. These features make sure that vaccines stay in the right temperature range while they are being transported, which lowers the chance of them going bad or getting lost.

The findings of this study indicate that HERMEDION possesses significant potential to improve the efficiency and safety of vaccine delivery, particularly in regions with restricted access to stable electricity and ongoing monitoring. Its long-lasting design not only allows for continuous use, but it also fits with global efforts to promote healthcare solutions that are good for the environment. The system's ability to send data in real time also lets health workers and authorities quickly respond to changes in temperature, which makes vaccine logistics more accountable and helps people make better decisions.

In conclusion, HERMEDION is a useful and new way to solve problems that have been around for a long time in the cold chain. Its ability to work in a wide range of environmental conditions and emergency situations makes it a good choice for large-scale use in public health programs. With more work and testing in the field, HERMEDION can make a big difference in making immunization systems

stronger, making sure everyone has access to safe vaccines, and supporting healthcare delivery in underserved areas.

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