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Research Article

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Climate-Resilient Vaccine Logistics: Evaluating the Role of Portable Cold Chain Solutions in Remote Healthcare

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Abstract

Introduction: *Efficient vaccine storage and transportation are critical for the success of immunization programs, particularly in remote and resource-limited areas. This study analyzes the efficiency and impact of battery-powered active vaccine carriers within global vaccine distribution systems.*

Objectives: *To evaluate the performance, efficiency, and user acceptability of the battery-powered Emvólio vaccine carrier in rural and remote areas of Northeast India.*

Study design: *This study is a cross-sectional, observational study conducted across multiple rural health centers in Meghalaya and Manipur, Northeast India.*

Methods: *Emvólio, a portable, batterypowered medical-grade refrigerator developed by Blackfrog Technologies, was evaluated through rigorous field trials in diverse environmental conditions. Key performance indicators such as temperature stability, battery longevity, and user feedback were analyzed. The carriers' ability to harness solar energy for sustained operation in off-grid areas was also assessed.*

Results: *The results demonstrated significant improvements in maintaining optimal vaccine storage temperatures and enhancing vaccine reach to underserved populations. Emvólio outperformed traditional solutions like Ice Lined Refrigerators (ILR) and Solar Direct Drive refrigerators (SDD) in terms of energy efficiency and cost-effectiveness.*

Conclusion: *DRE-compatible, batterypowered active vaccine carriers offer a robust, sustainable, and scalable solution for strengthening immunization infrastructure in remote and climate-affected areas, ensuring vaccine effectiveness and improved health outcomes.*

Keywords: Emvólio, Portable, Vaccine Carrier, Solar, Climate Resilient and Primary Health Care

Abbreviations

- **BFT:** Blackfrog Technologies
- **CAPEX:** Capital expenses
- **CHCs:** Community Health Centres
- **DFs:** Deep Freezers
- **ILRs:** Ice-lined Refrigerators
- **SDD:** Solar Direct Drive
- **IPHS:** Indian Public Health Standards
- **MPPT:** Maximum Power Point Tracking
- **OPEX:** Operating expenses
- **PHCs:** Primary Health Centres
- **SCs:** Sub-centers
- **PV:** Photovoltaic
- **SDG:** Sustainable Development Goal
- **VVM:** Vaccine Vial Monitor
- **CFC:** ChloroFluroCarbon
- **WHO:** World Health Organization

1. Introduction

A successful immunization system involves numerous socioeconomic, cultural, technical, and environmental factors. It encompasses the implementation of a comprehensive immunization schedule, organizing routine immunizations, ensuring proper storage, transportation, and distribution of vaccines to healthcare facilities, identifying areas with low coverage, monitoring and surveillance, and fostering collaborations. The timely completion of the vaccination schedule is of utmost importance in maintaining immunity against diseases and ensuring cost-effectiveness in healthcare. However, the transportation of vaccines across the vast expanse of India and many countries presents significant challenges that need to be overcome. WHO has emphasized that poor cold chain logistics and the lack of reliable cold chain storage are major contributors to vaccine wastage, particularly in developing countries [1]. This is particularly concerning in rural or hard to reach areas with limited health infrastructure, and vaccines may need to be administered outdoors, under direct sunlight, or in extreme hot/cold weather. This task is further complicated by the diverse climatic conditions, making transportation a critical aspect of vaccine distribution.

In the context of rising climatic events and natural disasters, vaccination programs confronts challenges including accessibility and transportation issues, particularly for last mile delivery in low-income settings [2, 3]. For example, inaccessibility to vaccine may result from population migration and health facility isolation due to floods, hurricanes, etc. Heat waves and rise in the ambient temperature causes the icepacks used in passive vaccine carriers to melt faster, limiting the immunization coverage. Natural calamities might also cause frequent power outages at rural health centers, affecting the continuous operation of cold chain equipment.

A review spanning 7 years (2007–2014) revealed that in low- and middle-income countries, vaccines were exposed to freezing temperatures during transportation in 28.1% of the cases. In India, a specific study found vaccines exposed to sub-zero temperatures for 18.1% of the time during transportation [4]. The research gap identified for this study has been showcased from the limited empirical evidence on real-time temperature monitoring and its effectiveness in preventing temperature deviations during the transportation of vaccines, particularly in the context of the varied climatic conditions across India [5]. Over the last two years, India has experienced extreme weather events such as droughts, extreme heat, excessive precipitation, cyclones, and cold waves [6].

According to the Global Climate Risk Index 2021, India was the seventh most affected country by the devastating impact of climate change. In recent years, the climate in North-East India has been changing. The region receives heavy rainfall during the monsoon months of June to September. However, the situation has worsened, and the rain comes in quick bursts, causing floods, followed by long dry periods that lead to drought and frequent power outages. Consequently, alternative cold chain solutions, such as solar-powered and battery-operated vaccine carriers, are urgently needed to ensure reliable and effective vaccine delivery in these regions (UNICEF, 2022) [7].

Although the components of cold chain logistics have been the subject of previous studies, there is a noteworthy lack of comprehensive study that combines data-logging technologies with a strategy framework to improve temperature control across the cold chain, from storage to last-mile delivery. The scope of this article includes highlighting the usage of active refrigeration devices (Emvólio, developed by Blackfrog Technologies Pvt. Ltd) for last mile vaccine delivery applications, discussing the technology status, comparing their performance if already available, and underscoring the remaining technological challenges to be addressed.

1.1. Healthcare System and the Challenges with Immunization in Rural India

Providing comprehensive quality healthcare services and reducing health inequalities are key priorities and goals of sustainable development. Despite this, in developing countries especially in India, many regions face serious challenges in achieving comprehensive health care delivery in rural areas. Figure.1 illustrates the challenges of inadequate rural healthcarefacilities and their impact on vaccine delivery [8].

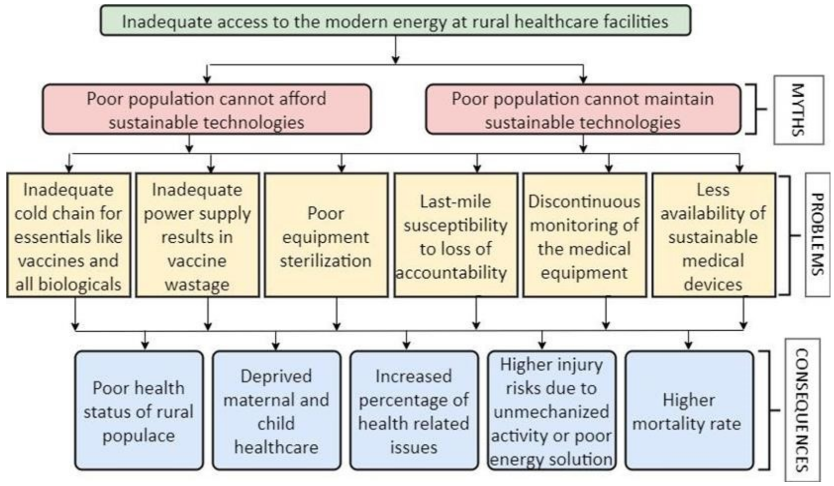

Figure 1: Challenges of Rural Health Facilities

Inadequate access to alternate energy in rural healthcare facilities leads to significant challenges and negative consequences. A common misconception is that socioeconomically vulnerable population populations cannot afford or maintain sustainable technologies, which further limits their implementation. This energy inadequacy results in several problems, including insufficient cold chain systems for vaccines and biologics, leading to wastage, poor sterilization of medical equipment, loss of accountability in last-mile delivery, discontinuous monitoring of medical equipment, and limited availability of sustainable medical devices. These issues contribute to severe consequences such as poor health among rural populations, inadequate maternal and child healthcare, an increased prevalence of health-related problems, higher risks of injuries due to unmechanized or inefficient energy solutions, and ultimately, elevated mortality rates. Addressing these energy challenges is essential to improving rural healthcare outcomes.

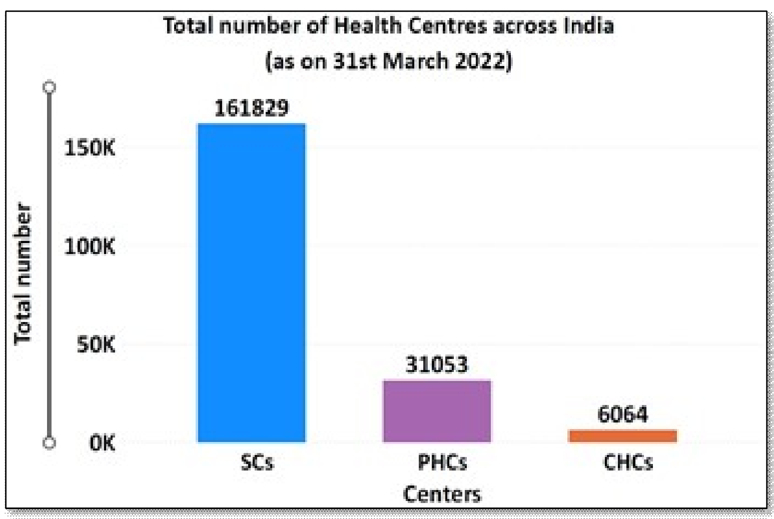

Figure 2: Total Number of CHCs, PHCs, and SCs Across India

Figure 2 provides quantitative data on the total number of Community Health Centers (CHCs), Primary Health Centers (PHCs), and Sub-Centers (SCs) across India. According to the Rural Health Statistics 2021-22, the total number of Community Health Centers (CHCs), Primary Health Centers (PHCs), and Sub-Centers (SCs) across India are 5,480, 24,935, and 1, 57,935, respectively [9]. The average population covered by SCs, PHCs, and CHCs are 5691, 36049, and 164027, respectively, as of 31 March 2022. This information highlights the scale and distribution of healthcare infrastructure, particularly in rural and remote areas. The large number of SCs, which serve smaller populations but are often located in remote locations, underscores the logistical challenges in maintaining a reliable vaccine cold chain.

These facilities are frequently underequipped with static cold chain equipment such as Ice Lined Refrigerators (ILRs), primarily due to constraints in power availability, inadequate infrastructure, and high installation and maintenance costs. Furthermore, even where such equipment exists, the lack of timely maintenance support and limited availability of trained technicians often results in prolonged equipment downtime, further jeopardizing vaccine storage reliability. A study by found that lack of preventive maintenance and delayed repairs often render cold chain equipment nonfunctional, especially in rural and resource-limited settings. This highlights the urgent need for climate-resilient and low-maintenance alternatives, such as portable, battery-operated, or solar-powered refrigeration systems, to ensure uninterrupted vaccine delivery in such vulnerable regions.

Based on the amount of vaccines to be carried, each stage of the cold chain (national, regional, villages) requires specific transport and storage equipment. While the choice of transport mode is mainly influenced by road conditions, the choice of storage equipment depends on the availability of energy resources (mainly electricity), the duration of transportation or storage as well as the volume of vaccines [10].

To help procurement agencies make decisions, the PQS catalogue lists prequalified cold chain equipment. The refrigeration equipment falls into two main categories: passive and active. Passive refrigeration devices do not require any external source of energy during use and are thus considered as off-grid solutions. Such equipment consists of (i) long-term passive containers, which are used to store vaccines at health facilities where electricity is unreliable, (ii) cold boxes, typically used for distribution of vaccines between facilities and (iii) vaccine carriers, used to transport vaccines from the facilities to the beneficiaries, for outreach and immunization sessions.

The required number of cold chain equipment as per the IPHS guidelines at various levels of Primary Health Care institutions in India are outlined below [11,12,13].

CHC	PHC	SC
Ice Lined Refrigerator (L) - 1	Ice Lined Refrigerator (S) - 1	Vaccine Carrier – 2
Deep Freezer (L)- 1	Deep Freezer (S)- 1	Ice packs
Cold Box (L) - 1	Cold Box (L) - 1	
Cold Box (S) -1	Cold Box (S) -1	
Vaccine Carrier - 3	Vaccine Carrier - 3	
Ice packs	Ice packs	

Table 1: Existing Cold Chain Equipment at Health Centers as Per IPHS Guidelines

An ideal vaccine carrier, as defined by the WHO, should maintain temperatures between 0°C and 10°C for a minimum of 15 hours while maximizing vaccine storage volume [14]. But the current systems are insufficient for operation under extremely high or low temperatures; for example, icebased carriers often face challenges such as freezing in cold climates or thawing in hot conditions, which can lead to vaccine wastage. The WHO recommends storing vaccines between 2°C and 8°C throughout the cold chain process. Exposure to temperatures outside this range can negatively affect the vaccine's immunological properties and reduce its effectiveness. According to the WHO, an adverse heat event occurs when vaccines are exposed to temperatures above 8°C for 10 hours or more. On the contrary, an adverse freezing event occurs when vaccines are exposed to temperatures below -0.5°C for 1 hour or more. It's worth noting that vaccines are generally more sensitive to freezing than to heat events [15]. Multiple studies have demonstrated that exposure to extreme temperatures within vaccine supply chains is prevalent in developed and developing countries. In lower-income countries, as much as 37% of vaccines are exposed to temperatures below the recommended range, making it a crucial matter that needs to be addressed.

1.2. Exploring the Potential of Stand-Alone, Solar-Powered Systems for Last-mile Vaccine Cold Chain Management in India

The WHO/PQS/E003 category pertains to refrigerators and freezers used for storing vaccines, requiring superior temperature control to prevent accidental freezing of the vaccines. One way to achieve this is by using electric compression cycle appliances that eliminate the need for thermostat adjustments. The WHO/PQS/E003 category covers refrigerators and freezers that can operate using electricity or heat produced by burning liquid fuel or gas. The refrigeration cycle devices can be powered by various energy sources such as compression cycle with reliable electricity, compression cycle Ice-lined refrigerator (ILR) with intermittent electricity, solar electricity/direct drive compression cycle, solar electricity/battery-powered compression cycle, and absorption cycle. Among these, solar-powered vaccine refrigeration systems (WHO/PQS/E003.2.2) are becoming increasingly popular as they benefit areas without reliable conventional energy supply.

Solar energy is also one of the prominent renewable energy sources due to its inexhaustible nature and eco-friendliness. The potential of solar energy is substantial, with its amount exceeding the current global energy demands. Solar energy has witnessed more rapid development in the last few decades than other renewable sources. The annual global radiation ranges from 1600 to 2200 kWh/m^2, indicating the high potential of harnessing solar energy to meet energy demands [16,17,18]. India is located between the Tropic of Cancer and the equator, providing a tropical climate with extended hours of sunshine each day. The country enjoys an annual average temperature ranging from 25°C to 27.5°C [19], and its average daily solar radiation incident is between 4 kWh/day and 7 kWh/day. With such a high availability of solar energy, India is an ideal prospect for solar energy applications.

Photovoltaic (PV) technology is the most effective method for harnessing the sun's power. Recent studies have made significant strides in developing intelligent solar-powered storage systems in vaccine cold chain management [20]. However, there is still untapped potential in stand-alone solarpowered systems that can provide an innovative solution to this problem.

1.3. Emvólio as a Climate-Resilient Solution: A 4E Perspective

- **Efficiency** - Emvólio, a portable battery and DRE-powered medical-grade refrigerator, plays a pivotal role in enhancing the last-mile vaccine cold chain — especially in regions vulnerable to climate disruptions. Unlike traditional ice-based carriers that suffer from inconsistent temperature control and require frequent ice replenishment, Emvólio delivers stable, precise temperatures (2– 8°C) for over 15 hours without ice. Integrated IoT-enabled features enable real-time monitoring of temperature, battery status, and location, ensuring operational transparency and reducing the burden on health workers.
- **Economics (Return on Investment)** - Despite higher initial capital expenditure compared to icebased solutions, Emvólio proves cost-effective over its 10-year lifecycle. Its low energy consumption (~0.84 kWh/24h) and compatibility with solar power significantly reduce ongoing operating expenses. Moreover, the reduction in vaccine spoilage and the ability to support longer outreach sessions lead to a higher return on investment by maximizing dose utilization and minimizing logistical overhead.
- **Environmental needs** - Emvólio's climate-resilient design enables operation in areas with frequent power outages, extreme temperatures, and infrastructure challenges — conditions increasingly common due to climate change. Powered by decentralized renewable energy, such as a 100W solar panel, it eliminates reliance on fossil fuels and conventional refrigerants, minimizing the risk of environmental contamination. Its clean, sustainable energy profile directly contributes to reduced carbon emissions, aligning with global climate action goals.
- **Equity** - By extending the cold chain to underserved and off-grid areas, Emvólio addresses a critical equity gap in immunization efforts. Its portability and ease of use empower frontline health workers in remote sub-centers, where access to conventional cold chain equipment is limited or absent. This ensures timely vaccine access for hard-to-reach populations, enhancing immunization coverage and health equity.

Figure 3 emphasizes the positioning of the above-mentioned vaccine carrier (Emvólio) for the vaccine cold chain network.

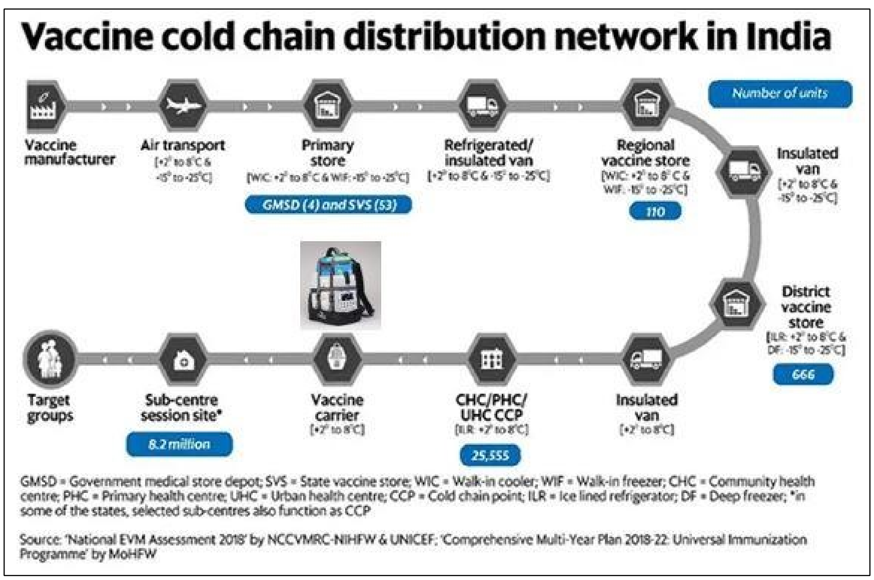

Figure 3: Proposed Positioning of Solar-Powered and Stand-Alone Vaccine Carrier (Emvólio) In the Vaccine Cold Chain Network

2. Study Methods, Discussion and Findings

To better understand how a DRE-compatible, battery-powered portable vaccine carrier can help improve the last-mile vaccine supply chain, a cross-sectional study was conducted among rural health centers in Meghalaya and Manipur (States in Northeast India, Figure 4). The study aimed at collecting data from the field on the performance, user acceptability, and impact of Emvólio from January to June 2023. The data was collected from healthcare workers in Primary Health Centers (PHC) and Sub Centers (SC) of Meghalaya and Manipur, where Emvólio is used for institutional and outreach immunization sessions. Other vital parameters of the device including device temperature, battery performance, location, etc., were also continuously monitored through the online dashboard.

Recent data shows that there are approximately 100 healthcare centers in remote regions of Manipur, out of which 41 are solar-powered. There are 609 healthcare centers in Meghalaya, out of which 475 are solar-powered. Each health center in Meghalaya has a maximum load capacity of 1 kW and a photovoltaic capacity of 1 kV. In comparison, Manipur's health centers have a maximum load capacity of 3 kW and a photovoltaic capacity of 3 kV. These numbers demonstrate the current status of solar-powered health centers in these two states and provide insight into the possibility of adoption of solar-powered health equipment in remote healthcare facilities.

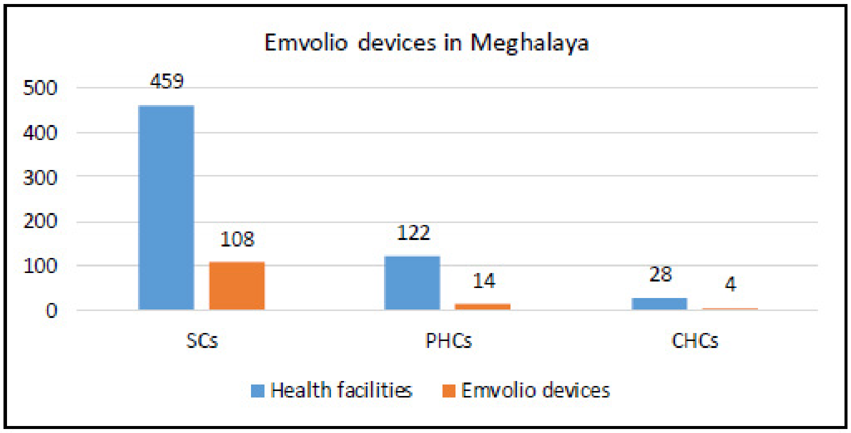

Figure 4: Total Number of Health Centers and the Number of Emvólio Units Deployed in Meghalaya

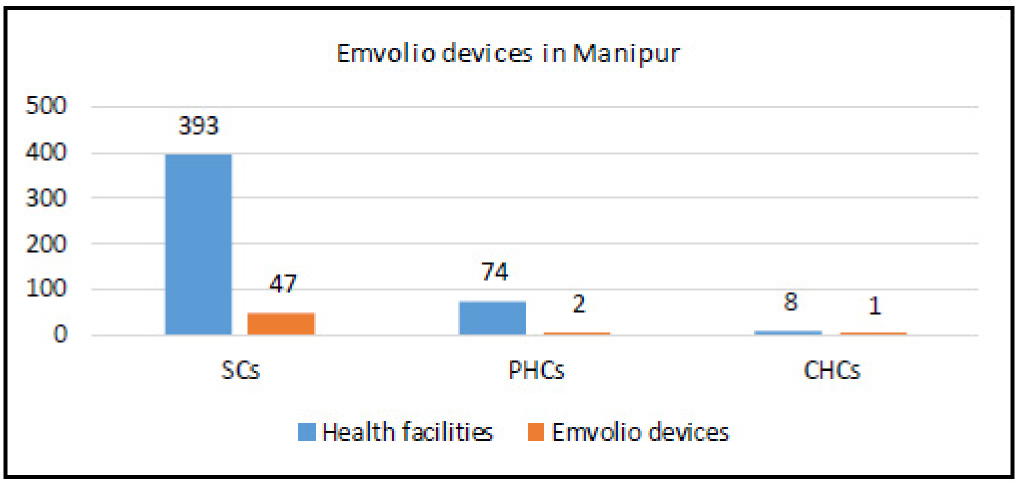

Figure 5: Total Number of Health Centers and The Number of Emvólio Units Deployed in Manipur

To evaluate the operational performance and effectiveness of Emvólio, quantitative data on the usage of devices in the field were systematically collected. Data points were gathered on several key variables, including the average duration of device usage per session, the average distance traveled during each session, etc. Feedback from end users (ANMs) were also collected from the field (Figure 6). These metrics were tracked across multiple field locations, ensuring a comprehensive understanding of the device's functionality under varying conditions. The data collection process was facilitated by the IoT dashboard integrated into each device, which provided real-time updates on parameters such as battery level, temperature control, and device location.

Category	Value
Total number of devices deployed (As of Nov 2023)	178
Total cooling hours (Jan to June 2023)	14,552.77 hours
Average battery life per charge of a device	12.5 hours
Average number of vaccine vials carried in a device	14
Average utilization of device per session	5.5 hours
Average distance traveled per session	4.8 km

Table 2: Emvólio Usage Data in Meghalaya And Manipur (Data Retrieved from Dashboard)

Each data point highlights the extensive use of the device at the field level, even in the most hard-to-reach areas served by peripheral health centers (Sub-Centers). The device's average battery life of 12.5 hours is sufficient to support a full day of vaccination activities. During outreach sessions, health workers typically carry 10 to 15 vials, equating to approximately 70 to 140 doses. These sessions usually begin around 9 a.m. and conclude by 1 p.m., with an additional 1–2 hours spent traveling to and from the site The findings from this study underscore the potential of Emvólio in addressing some of the most pressing challenges faced by the vaccine cold chain, especially in remote and resource-limited areas.

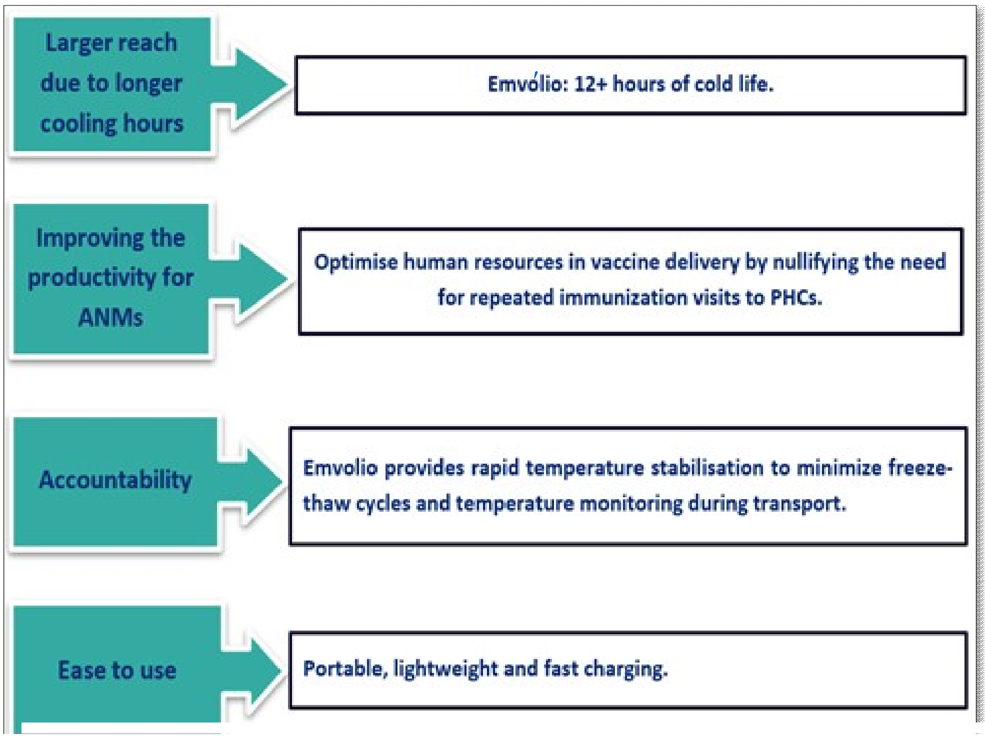

Figure 6: Summary of Feedback Collected from the End Users in the Field

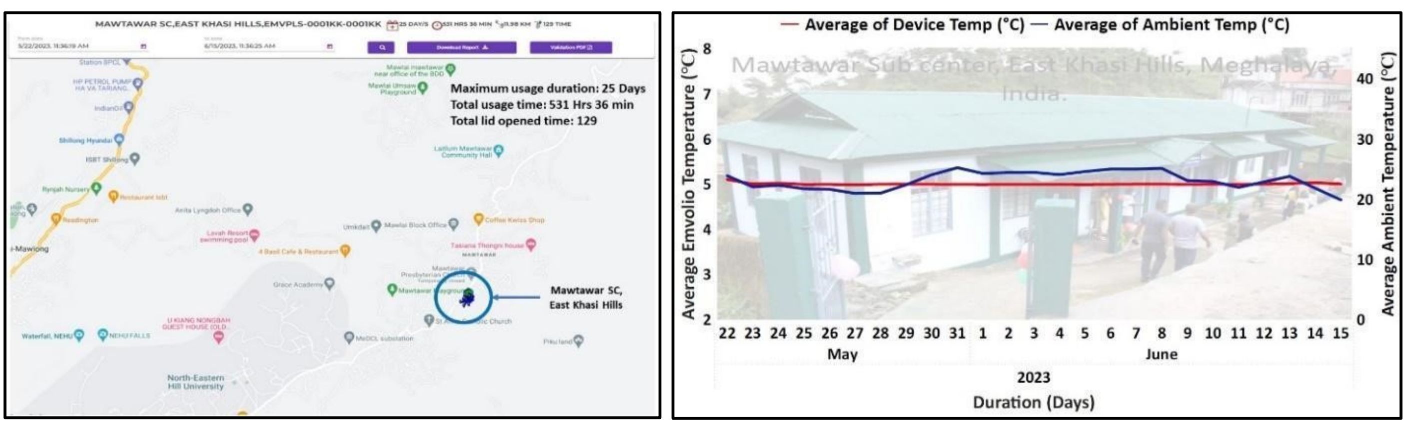

Figure 7: Mawtawar SC, East Khasi Hills, Meghalaya, India (a) Location (b) Device and Ambient Temperature

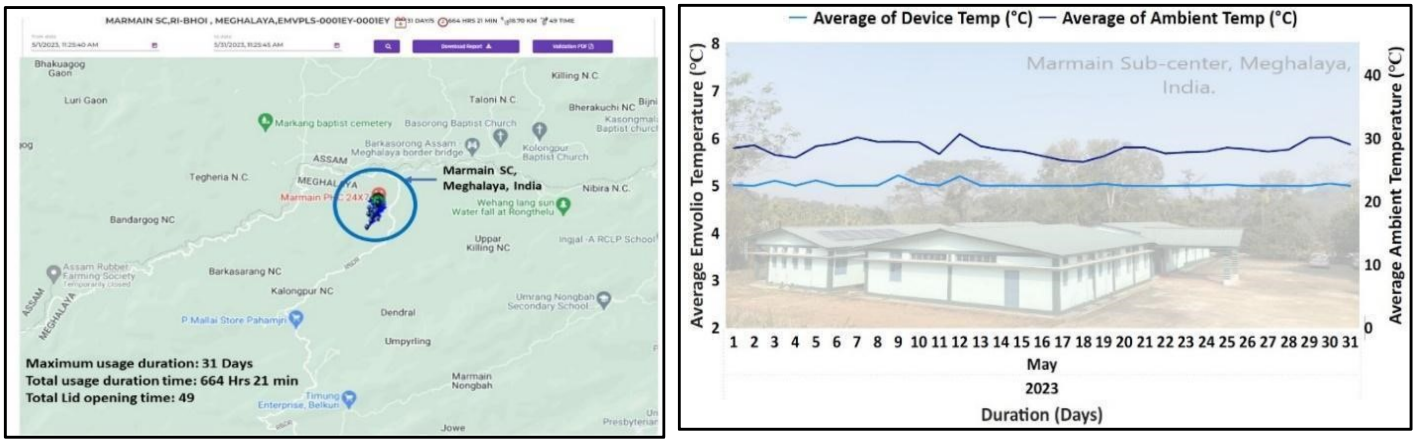

Figure 8: Marmain SC, Meghalaya, India (a) Location (b) Device and Ambient Temperature

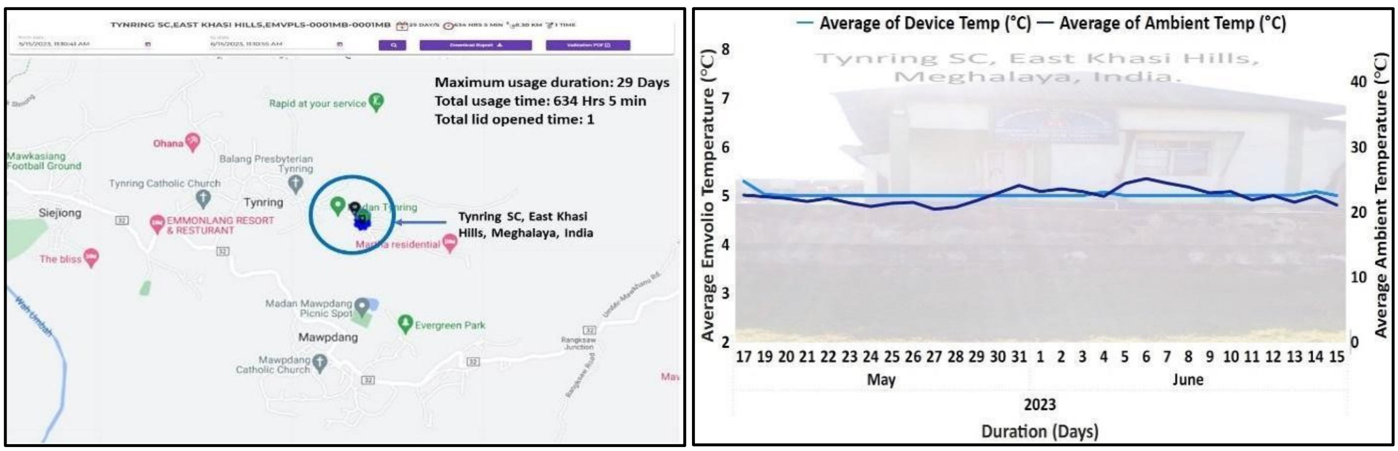

Figure 9: Tynring SC, East Khasi Hills, Meghalaya, India (a) Location (b) Device and Ambient Temperature

The findings from this study underscore the potential of Emvólio in addressing some of the most pressing challenges faced by the vaccine cold chain, especially in remote and resource-limited areas. By demonstrating that Emvólio can maintain optimal vaccine storage temperatures under varying environmental conditions, the study highlights the feasibility of portable, solar-powered vaccine carriers as a critical solution to improve immunization coverage in underserved regions.

In India, many sub-centers lack reliable cold chain equipment other than passive vaccine carriers, which significantly impedes the efficiency and effectiveness of vaccination programs. [21] Passive vaccine carriers, while useful for short-term transport, rely on ice packs that melt over time, leading to limited operational durations. As a result, health workers are often forced to travel long distances to the nearest cold chain point, such as Primary Health Centers (PHCs) or Community Health Centers (CHCs), to collect vaccines for immunization sessions. After the session, any leftover vaccines must be returned to these central facilities for storage, a process that is not only timeconsuming but also burdensome for health workers, who frequently have to manage these logistics amidst already heavy workloads.

Moreover, the duration of immunization sessions is often constrained by the melting of ice packs, which requires health workers to carry additional ice packs for longer campaigns or when vaccines are transported to more distant or remote areas of reliable cold chain infrastructure at sub-centers has long been a challenge in the Indian healthcare system, contributing to inefficiencies and the risk of vaccine wastage.

The absence of static cold chain equipment such as Ice Lined Refrigerators (ILRs) at these centers compounds the problem, as such equipment is costly and requires stable electricity supply, which is often not available in rural or remote locations. The cost structure requirements of ILRs make them impractical for use in smaller, decentralized healthcare settings.

Given these challenges, the need for a dependable and economical vaccine storage system at subcenters is more urgent than ever.[22] The findings of this study suggest that these difficulties can be addressed with the introduction of an affordable, portable, and energy-efficient solution like Emvólio (Figure 10). This device offers a promising alternative to traditional cold chain equipment by providing a portable refrigeration system that can operate as both a stationary and mobile refrigerator. Its compatibility with decentralized renewable energy (DRE) sources ensures its continuous operation even in areas with unreliable or intermittent electricity supply. This feature makes Emvólio especially suitable for remote regions where electricity instability is a significant barrier to maintaining a constant cold chain. Furthermore, the devices could simplify the logistics of vaccine storage and transportation. After immunization sessions, unused vaccines can be stored directly at the sub-center, eliminating the need for ILRs or large refrigerators. This system not only reduces the burden on health workers but also enhances the sustainability and reliability of vaccine storage, allowing for more flexible and extended vaccination campaigns.

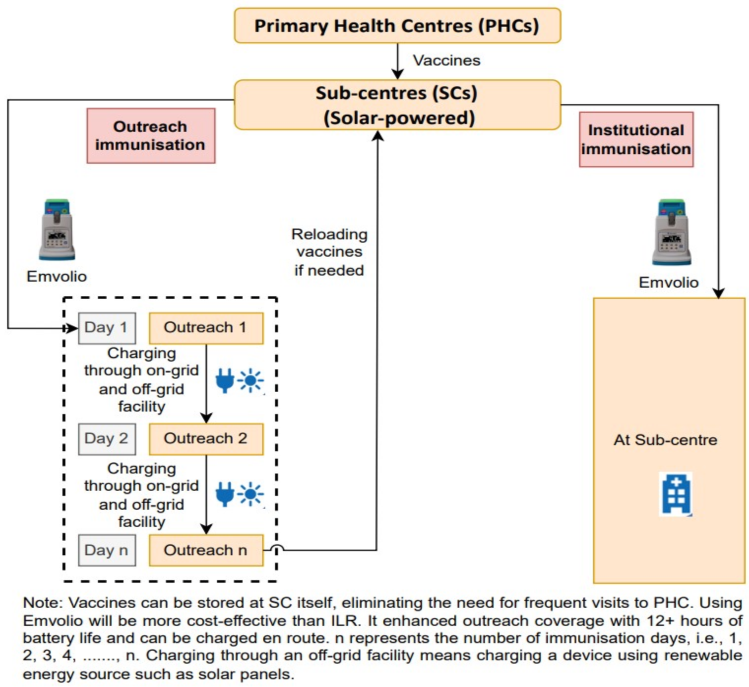

Figure 10: Reimagining Immunization Outreach Sessions with Emvólio

The energy efficiency and portability of Emvólio could help improve vaccine availability in remote areas, where access to traditional cold chain infrastructure is often limited, thereby increasing vaccination coverage and reducing wastage [23].

In order to assess the practical applicability and cost-effectiveness of Emvólio in vaccine cold chain management, it is essential to compare its performance against traditional cold chain solutions like Ice-Lined Refrigerators (ILRs) and Solar Direct Drive (SDD) refrigerators. A comparison of the three devices was done based on key factors such as capacity, cost-efficiency, and suitability for different use cases, providing a clearer understanding of when and where each solution is most effective. Emvólio, being a portable vaccine carrier, is designed with flexibility and mobility in mind, making it particularly suitable for outreach immunization sessions in rural and remote areas. In contrast, ILRs and SDDs are larger systems designed to store substantial quantities of vaccines over extended periods, making them ideal for centralized vaccine storage in centralized healthcare settings. However, the smaller capacity of Emvólio is an advantage in scenarios where mobility and access to underserved populations are critical, and the healthcare infrastructure is questionable such as remote SCs.

The cost estimation for all three systems is based on a useful life of 10 years. Although the energy consumption and operating expenses of Emvólio is approximately equal to that of SDD, the device will prove cost-effective over the years. The comparison with ILRs and SDDs underscores the importance of tailoring cold chain solutions to the unique demands of healthcare systems. While centralized storage units excel in high-volume vaccine storage, portable devices like Emvólio address critical gaps in last-mile delivery, offering flexibility, mobility, and reliability in off-grid and hard-to-reach areas.

Details	**Emvólio**	**ILR**	
Company/Capacity	BFT 1.5 L	WHO/PQS-E003/080	WHO/PQS-003/079
Capital expenses (CAPEX) (A+B)	**~ $ 2600**	**~ $ 1975**	**~ $ 2694**
● **Cost of Equipment (A)**	~ $ 2395	~ $ 1197	~$ 1317

● Other expenses (B)	~ $ 210	~ $ 778	~ $ 1376
Total energy consumption expenses (Average electricity tariff rate in North-East India = $ 0.043 per kWh)			
Energy consumption during stable running for 24 hours (Total energy expenses during stable running for 24 hours)	~ 0.84 kWh/24h (~ $ 0.036/24h)	~ 1.63 kWh/24h (~ $ 0.07/24h)	~ 0.54 kWh/24h (~ $ 0.023/24h)
Energy consumption during cooldown test for 24 hours (Total energy expenses during cooldown test for 24 hours)	~ 0.90 kWh/24h (from battery) (~ $ 0.04/24h)	~ 2.04 kWh/24h (~ $ 0.087/24h)	~ 0.77 kWh/24h (~ $ 0.033/24h)
● Power consumption for 10 years (C)	$ 120	$ 272	$ 103
● Maintenance and repair expenses (D)	~ $ 1053	~ $ 1892	~ $ 1365
Operating expenses (OPEX) (C+D)	**~ $ 1222**	**~ $ 2225**	**~ $ 1528**
Floor area	~ 0.65 sq. ft.	~ 8.67 sq. ft.	~ 7.37 sq. ft.
Weight	6.7 kg	145 kg	46.6 kg
TOTAL COST OF OWNERSHIP (TCO)	**~ $ 3826**	**~ $ 4191**	**~ ₹ 4215**

Table 3: Comparison of Emvólio with ILR

PQS code: *E003/080, **PQS code: E003/079, Note: The device's performance tested at 43°C; CAPEX = cost of equipment (A) + other expenses (B); other expenses = recommended spare parts + in-country transportation + installation kit + installation labor; OPEX = operating expenses (electricity + gas + kerosene) (C) + maintenance expenses + repair expenses (D). The CAPEX and OPEX calculations are done by considering the product's useful life (~ 10 years). (1 USD = 83.51 INR)

Details	**Emvólio**	**SDD**	
Company/Capacity	BFT 1.5 L	WHO/PQS- E003/090	WHO/PQS-E003/068
Capital expenses (CAPEX) (A+B+C)	**~ $ 2850**	**~ $ 7424**	**~ $ 7783**
• Cost of Equipment (A)	~ $ 2395	~ $ 5687	~ $ 6047
• Solar panel requirement (B)	200 W (~ $ 245)	400 W (~ $ 496)	500 W (~ $ 496)
• Other expenses (C)	~ $ 210	~ $ 1257	~ $ 1257
Total energy consumption expenses (Average electricity tariff rate in North East India = $ 0.043 per kWh)			
Energy consumption during stable running for 24 hours (Total energy expenses during stable running for 24 hours)	0.84 kWh/24h (~ $ 0.036)	0.34 kWh/24h (~ $ 0.014)	0.80 kWh/24h (~ $ 0.034)
Energy consumption during cooldown test for 24 hours (Total energy expenses during cooldown test for 24 hours)	0.90 kWh/24h (from battery) (~ $ 0.039)	0.97 kWh/24h (~ $ 0.042)	1.60 kWh/24h (~ $ 0.067)
• Power consumption for 10 years (D)	~ $ 120	~ $ 130	~ $ 209
• Maintenance expenses + repair expenses (E)	~ $ 1053	~ $ 263	~ $ 263
Operating expenses (OPEX) (D+E)	**$ 1222**	**$ 429**	**$ 508**
Floor area	0.65 sq. ft.	7.05 sq. ft.	8.67 sq. ft.
Weight	6.7 kg	145 kg	46.6 kg
TOTAL COST OF OWNERSHIP (TCO)	**~ $ 4071**	**~ $ 7873**	**~ $ 8304**

Table 4: Comparison of Emvólio with SDD

PQS code: *E003/090, **PQS code: E003/042, Note: The device's performance tested at 43°C. CAPEX = equipment cost (A) + Solar panel requirement (B) other expenses (C); other expenses = recommended spare parts (solar panel) + in-country transportation + installation kit + installation labor; OPEX = operating expenses (electricity + gas + kerosene) (D) + maintenance expenses + repair expenses (E). The CAPEX and OPEX calculations are done by considering the product's useful life (10 years). (1 USD = 83.51 INR)

4. Conclusion

The findings from this study underscore the transformative impact of Emvólio in improving lastmile vaccine cold chain efficiency and climate resilience in remote and challenging environments. Traditional vaccine storage methods, while effective in controlled settings, often fall short in maintaining temperature stability and reliability during the last-mile delivery in rural and off-grid areas. Emvólio's battery-powered and solar-compatible design addresses these limitations by ensuring consistent temperature control and operational flexibility even in regions with limited infrastructure and harsh climatic conditions.

The deployment of Emvólio in Northeast India demonstrated significant opportunities in vaccine delivery and enhancing immunization coverage, especially in geographically isolated and underserved communities. The ability of Emvólio to maintain optimal storage conditions despite fluctuating ambient temperatures and power availability showcases its robustness and adaptability in diverse environmental contexts. Additionally, the positive feedback from healthcare workers regarding its ease of use, portability, and reliability further validates its practical benefits and suitability for outreach immunization sessions.

While Emvólio's portability and innovative design offer unique advantages, this study also highlights the importance of context-specific solutions. Its smaller capacity, compared to larger cold chain equipment like ILRs and SDDs, positions it as a complementary solution for mobile and last-mile delivery rather than a substitute for centralized storage. Overall, Emvólio represents a critical advancement in enhancing the resilience and efficiency of vaccine cold chain logistics, particularly in the face of climate change and the growing demand for equitable healthcare access. By bridging the gap in last-mile delivery, Emvólio not only contributes to more effective immunization campaigns but also strengthens global health systems' capacity to respond to future challenges.

However, while Emvólio's performance in terms of temperature stability and battery longevity is promising, real-world implementation brings several challenges. First, the scaling of such technology to a national or regional level requires addressing infrastructure gaps, such as the availability of reliable solar power and the cost of procurement for remote health centers. While Emvólio proves to be cost-effective over its lifetime, the upfront investment might deter adoption without external funding or incentives. A clearer understanding of cost per vaccine dose and potential for cost savings at scale could help mitigate this concern and highlight the device's financial viability. Also, introducing any new technology into an established healthcare system often encounters resistance. Healthcare workers might prefer traditional systems they are familiar with, especially if they perceive the new device as complex or unnecessary.

Furthermore, governments and implementing agencies must factor in long-term supply guarantees and a robust maintenance support system to ensure continuity of operations. Without these, even the most advanced technologies risk becoming ineffective in the field. Continued investment in and research on portable, sustainable cold chain technologies like Emvólio is essential for building inclusive, climate-resilient health systems. By bridging the gap in last-mile delivery, Emvólio not only contributes to more effective immunization campaigns but also strengthens the capacity of global health systems to respond to current and future challenges. Emvólio serves as a valuable alternative to an ILR, as shared by an ANM from Senapati district, Manipur. She uses Emvólio to store vaccines collected from the cold chain point, which enables her to go the extra mile in reaching remote communities.

Author statements

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