Challenges and Innovations of Vaccine Cold Chain Distribution in Developing Countries: A Narrative Review

Ifezulike Adaobi Maureen[1*], Darlington Chukwuma Ugwu[2,3], Abiodun Egwuenu[3], Fahad Shehu Muhammad[3], Ishaleku David[1]

[1]Global Health and Infectious Disease Control Institute, Nasarawa State University, Keffi, Nasarawa, Nigeria.

[2]African Leadership in Vaccinology Expertise, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa.

[3]Department of Health Emergency Preparedness and Response, Nigeria Centre for Disease Control and Prevention, Abuja, Nigeria.

[*]Corresponding Author

DOI: https://doi.org/10.51244/IJRSI.2025.12120121

Received: 25 December 2025; Accepted: 01 January 2026; Published: 16 January 2026

ABSTRACT

Vaccines are among the most effective public health interventions for reducing morbidity and mortality from infectious diseases, yet their effectiveness depends on maintaining vaccine potency throughout the cold chain from manufacture to administration. In many low- and middle-income countries, where disease burden is very high, weaknesses in cold chain systems continue to compromise immunisation programme performance and equitable access. Despite decades of investment, evidence indicates that cold chain failures remain common, yet the factors driving persistent gaps and the real-world impact of emerging innovations are not consistently synthesised. The objective of the review was to assess the major challenges affecting vaccine cold chain distribution in developing countries and to synthesise current evidence on technological and operational innovations aimed at addressing these constraints.

A narrative review methodology was employed, drawing on peer-reviewed literature and relevant grey literature published between 2008 and 2025. Searches were conducted in PubMed, Scopus and Google Scholar. Data were extracted and analysed thematically, focusing on logistical, infrastructural, workforce, geographic, economic, and policy-related dimensions of cold chain performance.

The review revealed persistent challenges, including unreliable electricity supply, inadequate storage and transport capacity, long distribution routes, limited funding for maintenance, fragmented governance and shortages of trained personnel. These factors contribute to temperature excursions, vaccine wastage and stock-outs, particularly in remote and underserved settings. Meanwhile, several innovations have demonstrated potential to strengthen cold chain systems. Solar direct-drive refrigeration, real-time temperature monitoring, electronic logistics management information systems, and drone-enabled last-mile delivery have improved reliability, visibility and access in selected contexts. However, many innovations remain pilot-based, donor dependent and insufficiently integrated into national systems.

These findings highlight that strengthening vaccine cold chain systems in developing countries requires a systems-based approach. Sustainable improvement depends not only on technological innovation but also on coordinated investments in governance, financing, workforce capacity, maintenance and data integration.

Keywords: Vaccines, Cold-chain, Immunisation, Innovation

INTRODUCTION

Over the past several decades, global immunization programs have saved millions of lives and prevented countless episodes of vaccine-preventable diseases. The global eradication of smallpox and regional elimination of poliomyelitis, neonatal tetanus, rubella, and congenital rubella, revealed the transformative potential of vaccines (38,52) . The success of vaccination programs, however, depends largely on effectiveness of the vaccine cold chain. This system of temperature-controlled storage and transportation is critical for ensuring that vaccines retain their potency from manufacturing sites to the point of use (7,29,33) . Yet, despite its importance, the cold chain continues to face persistent and complex challenges, particularly in developing countries where disease burden is highest and resources are limited (1,21,59).

Historically, vaccine distribution systems in low- and middle-income countries have evolved alongside the expansion of the World Health Organization's Expanded Programme on Immunization (EPI) launched in 1974. Early cold chain systems relied on kerosene refrigerators and ice-lined boxes, while they enabled initial gains in immunization coverage, they were often insufficient to maintain optimal conditions in tropical climates or remote rural settings (20,33) . Since then, population growth, rapid urbanization, conflict, and the need to deliver new vaccines, some of which require ultra-cold storage have stressed existing systems and exposed major gaps (15,20).

The importance of effective cold chain infrastructure has been repeatedly demonstrated during public health crises. Outbreak responses for diseases such as Ebola in West Africa, cholera in Yemen and yellow fever in Angola highlighted that timely vaccine availability can result in effective containment of widespread epidemic (13,61) . Most recently, the COID-19 pandemic magnified these issues. The unprecedented deployment of mRNA vaccines, some requiring storage at −70°C, forced countries to upgrade or innovate their cold chain systems (47). While high-income countries rapidly adopted ultra-cold freezers and digital monitoring, many developing countries struggled with procurement, electricity access, and workforce training (3). These disparities revealed that without resilient distribution networks, even groundbreaking scientific advances cannot achieve their intended impact.

Studies have shown that several factors make vaccine cold chain management uniquely difficult in developing countries. Geography plays a significant role. Islands, mountainous regions, and areas affected by insecurity often face long transit times and unreliable infrastructure. Economically, many countries depend on donor funding for equipment and maintenance, leading to fragmented systems and limited sustainability (1,35). Policy and governance challenges such as inadequate planning, weak data systems, and overlapping mandates compound these problems (56). Human resource constraints, including shortages of trained logisticians and biomedical technicians, further undermine efficiency (3,16).

Despite these challenges, innovation is reshaping what is possible. Solar direct-drive refrigerators have reduced dependence on grid power, remote temperature-monitoring devices and IoT sensors provide real-time data, and drone technology is being piloted to reach hard-to-access communities(23,37,43,55). Digital dashboards and stock-visibility platforms are improving forecasting and reducing wastage (14). However, many of these innovations remain small-scale or donor-driven, raising questions about scalability, cost-effectiveness, and integration into national systems.

The aim of this review is to synthesize the current evidence on innovations and challenges in vaccine cold chain distribution in developing countries. It builds on lessons from past epidemics and routine immunization programs to identify gaps and opportunities for strengthening systems.

Main objective

The objective of this narrative review is to assess the major challenges affecting vaccine cold chain distribution in developing countries and to synthesise current evidence on technological and operational innovations aimed at addressing these constraints.

The specific objectives

1. To describe the current structure and components of vaccine cold chain systems.
2. To analyse logistical, infrastructural and human resource challenges.
3. To explore geographic, economic, and policy-related constraints affecting distribution.
4. To review recent technological and operational innovations and assess their impact.

METHODOLOGY

Study Design

This work was conducted as a narrative review to synthesize evidence on the challenges and innovations of vaccine cold chain distribution in developing countries. This narrative review design was chosen to allow a broad exploration of literature from diverse sources, including peer-reviewed journals, international health agency reports and grey literature, in order to capturing both technical and operational perspectives.

Search Strategy

A structured search was undertaken to ensure that the review captured a broad and representative body of evidence on vaccine cold chain systems in developing countries. Multiple databases were explored, including PubMed, Scopus and Google Scholar. These platforms were selected because they provide extensive coverage of biomedical, public health and policy-related literature. Search terms were developed in line with the objectives of the review and focused on vaccine cold chain systems, distribution challenges, and technological innovations. Core terms included "vaccine cold chain," "cold chain management," "vaccine storage," "vaccine distribution," and "immunisation supply chain." These were combined with terms related to system challenges and context, such as "logistical challenges," "infrastructure," "health workforce," "governance," "policy," "geographic barriers," "low- and middle-income countries," and "resource-limited settings." Innovation-related terms included "solar refrigeration," "temperature monitoring," "logistics management information systems," "digital health," and "drone delivery." Search terms and synonyms were adapted across databases to maximise retrieval.

Inclusion Criteria

Studies and reports that met the following criteria were included:

1. Studies and reports that focused on vaccine cold chain systems and distribution in developing countries or LMICs.
2. Studies that discussed challenges (logistical, infrastructural, human resource, policy) or innovations (technology, tools, approaches).
3. Studies that included any vaccine type, whether routine immunization, campaign vaccines, or emergency response (Ebola, COVID-19).
4. Studies published in English between 2008 and 2025

Exclusion Criteria

The following were excluded:

- Articles that focused exclusively on high-income countries.
- Studies on non-immunization cold chains (e.g., food or pharmaceuticals unrelated to vaccines).
- Editorials, commentaries or opinion pieces without substantive data or analysis.
- Publications not available in full text.

Data Extraction and Synthesis

Relevant data were extracted from eligible articles, including study context, cold chain components discussed, types of challenges, innovation described, outcomes reported and recommendations. Findings were organized thematically into four categories:

1. Structure and components of cold chain systems
2. Logistical, infrastructural and workforce challenges
3. Geographic, economic, and policy-related barriers
4. Technological and operational innovations

The analysis emphasized comparisons across regions, identification of gaps, and emerging themes.

Information Extraction and Synthesis

Full texts of all included studies and reports were reviewed, and relevant information was extracted using a structured approach. Key details were recorded, including publication year, study location, type of vaccine program and the specific cold chain components described (such as storage, transportation, monitoring, and workforce). Each source was assessed for evidence of challenges in logistical, infrastructural, policy-related and innovative practices, including technological solutions like solar refrigeration, real-time temperature monitoring, and drone delivery. Contextual factors, such as geography, governance and health system capacity, were also noted where available.

Extracted information was organized into thematic categories reflecting the objectives of the review.

1. Structure and components of cold chain systems
2. Logistical, infrastructural and workforce challenges
3. Geographic, economic, and policy constraints
4. Technological and operational innovations

Furthermore, within each category, findings were compared and synthesized to highlight patterns, unique contributions, and gaps. Quantitative information (for example, cold chain failure rates or equipment performance data) was summarized descriptively, while qualitative findings and operational insights were described narratively to preserve their meaning. Sources from international agencies and national programs were included alongside peer-reviewed studies to provide a comprehensive overview.

RESULT & DISCUSSION

Table 1: Summary of key studies on vaccine cold chain systems in low- and middle-income countries, highlighting major challenges and technological innovations (2008–2025)

Author(s)	Year	Country / Region	Focus/ Theme	Innovation / Challenge	Key Findings / Contributions
Adeyemo et al.	2021	Sub-Saharan Africa	Cold chain logistics and access equity	Challenge	Reported regional inequities due to weak infrastructure and fragmented coordination.
Arogundade et al.	2019	Nigeria	Training and capacity assessment	Challenge	Found gaps in workforce competence and supervision across immunization programmes.
Atiga et al.	2024	Ghana	Zipline drone impact study	Innovation	Demonstrated measurable improvement in supply reliability and delivery time.
Bogale et al.	2019	Ethiopia	Cold chain management in public facilities	Challenge	Only 58% of facilities had adequate cold chain practice; training predicted better performance.
Federspiel & Ali	2018	Yemen	Cholera outbreak response	Operational / Challenge	Underscored importance of timely cold chain in outbreak response logistics.
Fritz et al.	2021	Ethiopia, Tanzania, Mozambique	eLMIS and digital LMIS	Innovation	Digitization reduced stockouts and improved vaccine tracking.
Frost et al.	2021	LMICs	Innovative health system strengthening	Innovation	Reviewed new delivery models (drones, IoT, solar) for LMIC supply systems.
Geneti et al.	2024	Ethiopia	Knowledge and practices	Challenge	Linked staff experience, training, and supervision to improved vaccine handling.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue XII December 2025

			among health workers		
Gilbert et al.	2017	India	Digitally enabled supply chain	Innovation	eLMIS improved vaccine stability, data visibility, and workflow efficiency.
Guignard et al.	2019	LMICs	New vaccine introduction	Challenge	Identified policy and infrastructural constraints in adopting new vaccines.
Hagedorn et al.	2025	Nigeria	Decentralized financing and supply chains	Innovation	Demonstrated that decentralized financing improved stock availability and facility performance.
Hasanat et al.	2020	Bangladesh	IoT-based vaccine cold chain monitoring	Innovation	Proposed real-time monitoring system integrating IoT for vaccine safety.
Kanja et al.	2021	Kenya	Factors affecting vaccine availability	Challenge	Power interruptions and limited storage capacity caused vaccine shortages.
Lloyd & Cheyne	2017	Global	Origins and evolution of cold chain	Structural	Provided historical overview and outlined modern cold chain challenges in LMICs.
Lydon et al.	2015	Multi-country	Global cold chain performance	Challenge	Found performance indicators below WHO's 80% benchmark for effective cold chain.
Makinen et al.	2012	LMICs	Vaccine adoption frameworks	Policy	Highlighted donor dependency and sustainability gaps in vaccine logistics.
McCarney et al.	2013	Multi-country (LMICs)	Solar-powered vaccine refrigeration	Innovation	Solar systems improved cold chain reliability in off-grid rural settings.
Munshi et al.	2022	Bangladesh	COVID-19 mass vaccination logistics	Challenge	Described transport and storage bottlenecks during COVID-19 roll-out.
Namuhaywa	2013	Uganda	Cold chain management for EPI	Challenge	Revealed that many facilities lacked functional equipment and continuous power supply.
Numbi & Kupa	2017	DRC	Next-generation vaccine supply chains	Innovation	Argued for integration of modern supply tools to ease logistical bottlenecks.
Ospina-Fadul et al.	2025	Ghana	Drone delivery cost-effectiveness	Innovation	Drone delivery improved last-mile access and reduced stockouts in remote areas.
Pambudi et al.	2022	Indonesia	Cold storage technologies for vaccination	Innovation	Described sustainable cold storage options and renewable energy solutions.
Rusnack	2021	Global	COVID-19 vaccine cold chain	Challenge	Highlighted ultra-cold chain logistics limitations in LMICs.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue XII December 2025

Saraswati et al.	2018	Indonesia	Vaccine cold chain monitoring	Challenge	Documented inconsistent temperature monitoring and lack of standardized supervision.
Shen et al.	2014	Developing countries	Routine immunization future	Policy / Challenge	Emphasized governance and system bottlenecks limiting effective cold chain implementation.
Sinnei et al.	2023	Kenya	Vaccine storage and distribution practices	Challenge	Found rural cold storage facilities lacking maintenance and adequate monitoring.
To et al.	2019	Nigeria	Cold chain logistics in Osun State	Challenge	Identified outdated logistics and poor coordination in cold chain operations.
Tsega et al.	n.d.	Malawi	Training needs in immunization	Challenge	Highlighted workforce gaps and lack of refresher courses for cold chain personnel.
Walldorf et al.	2017	Multi-country	Lessons from emergency vaccine responses	Operational	Highlighted rapid-response cold chain gaps during Ebola and yellow fever outbreaks.
Woldemichael et al.	2018	Ethiopia	Cold chain knowledge among providers	Challenge	Identified gaps in knowledge and monitoring practices affecting potency.
Yakum et al.	2015	Cameroon	Vaccine storage and cold chain monitoring	Challenge	Reported unreliable electricity and temperature excursions leading to potency loss.
Zarekar et al.	2025	LMICs	ICT and immunisation impact	Innovation	Systematic review showing ICT improves stock visibility and service coverage.

Structure and Components of Cold Chain Systems

Vaccine cold chains in developing countries commonly follow a tiered structure, spanning national, regional/provincial, district, and facility or outreach levels (21,48,64). At the top tier, national stores operate walk-in cold rooms and freezer rooms, dispatching vaccines via refrigerated trucks or insulated vehicles to sub-national depots (27). District stores then act as buffer points, supplying facilities with purpose-built refrigerators (increasingly solar direct-drive in off-grid settings), cold boxes, and vaccine carriers for outreach sessions (54,57).

For instance, Ghana employs solar-powered refrigerators in rural health posts, enabling reliable cold storage where grid power is unavailable. In India, the National Centre for Cold-chain Development (NCCD) guides infrastructure planning and standards, driving advancements in equipment and protocols across tiers. Additionally, pilot studies in Niger using drone delivery models have demonstrated significant improvements in vaccine availability at remote health facilities, underscoring logistics innovation within the tiered system.

Quality and potency of vaccines rely on standardized temperature controls typically 2–8 °C for most antigens (41,57) and ≤–20 °C for some, with ultra-cold storage reserved for special campaigns (12,51) . Systems commonly use Vaccine Vial Monitors (VVMs), freeze indicators, calibrated thermometers or data loggers, and documented SOPs for packing, handling, transport, and contingencies (29,30). Tanzania's adoption of an electronic logistics management information system (eLMIS) has recently enhanced visibility across the chain, helping reduce stock-out frequency significantly (14).

Staffing typically includes logisticians, storekeepers, vaccinators, and a smaller team of cold chain technicians who oversee installation, preventive maintenance, and repairs. However, heterogeneity in equipment brands and models often due to donor-driven procurements can complicate upkeep and strong service contracts are rare, especially at lower levels (53,63).

Information management, traditionally paper-based (e.g., stock cards), is gradually shifting toward digitization with eLMIS platforms, though integration remains uneven (14)

In Ghana and Kenya, drone-delivered cold bags coordinated through SMS systems are augmenting last-mile delivery in remote areas, suggesting advanced operational adaptations layered onto existing structures (45).

Logistical, Infrastructural, and Workforce Challenges

Cold chain systems in developing countries are frequently undermined by multiple operational and infrastructural hurdles.

In many low- and middle-income countries, standard cold chain capacity (2-8 °C) remains unreliable, leading to stockouts, increased equipment costs, and limited vaccine availability in remote areas (65*)*. The challenge is particularly acute during outreach campaigns, where uneven carrier performance and ice-pack practices can inadvertently freeze vaccines, compromising potency.

Analyses from multiple African and Asian countries report that insufficient cold chain infrastructure, irregular power supplies, and poor maintenance are major contributors to vaccine wastage and potency loss. For example, the Clinton Health Access Initiative identified systemic drivers of these failures, including limited capacity and underinvestment in countries like Ethiopia, Kenya, and India (4).

In Ethiopia, Bogale (7) revealed that only about 58% of public health facilities demonstrated good cold chain management practices. Significant predictors of reliable performance included over two years of experience, formal training, and supportive supervision. This aligns with findings from Nigeria and elsewhere, where gaps in training and oversight are directly linked to decreased cold chain reliability.

A global review of vaccine supply in 89 countries revealed that for most cold chain indicators, performance fell below the recommended 80% threshold. These shortcomings can ultimately impact vaccine safety and public trust, especially when failures lead to stockouts or compromised doses (62) .

The pandemic exposed and amplified cold chain fragilities. The ultra-cold requirements for mRNA vaccines like Pfizer–BioNTech exposed the scarcity of necessary infrastructure in developing regions (2,25). Failure to maintain cold chain integrity emerged as a leading cause of vaccine discard, with up to 25% wastage linked to distribution system failures (9,67).

Geographic, economic, and policy constraints

Remoteness, difficult terrain, climate extremes, and weak transport links lengthen transit times and narrow delivery “windows,” increasing the risk of temperature excursions and stock-outs at the periphery (28,39,60).

Guidance for site selection during campaigns and COVID-19 roll-outs emphasized geography, energy availability, and alternative modes (e.g., drones) to reach hard-to-access areas, underscoring how location drives cold-chain risk profiles (20,24) .

Many LMIC programmes operate with tight recurrent budgets, so capital equipment purchases outpace funding for energy, preventive maintenance, supervision, and spare parts, the true total cost of ownership (TCO) (37,40). Evidence shows delivery costs per dose vary widely across LMICs and that cold chain/TCO is often underestimated in planning, leading to equipment downtime and vaccine loss (4). Benchmarking tools (e.g., EVM/EVMA) were created to create such gaps and guide cost improvements.

Fragmented accountability between central medical stores, immunisation programmes, and sub-national authorities, plus heterogeneous device portfolios from donor-driven procurement, complicate standards, service contracts, and data integration (25). UNICEF/WHO guidance highlights that weak SOPs, poor asset management, and limited supervision contribute to excursions and wastage; targeted iSC interventions (training, equipment standards, better carriers) can mitigate these failures when embedded in policy and budgets (42,60).

Paper stock cards and siloed tools limit forecasting and timely corrective action. Countries that linked temperature monitoring with logistics systems improved visibility and response. (14,17) reported that Tanzania's remote temperature monitoring (RTM) programme enhanced equipment performance oversight, and India's eVIN showed positive ROI with better stock management and temperature tracking at scale.

Sub-Saharan Africa: Power reliability and distance dominate risk; RTM and solar direct-drive help, while drones are being used for just-in-time delivery in difficult terrain (10,23,31,37,58) .

South Asia: Large, dense networks with stronger national programmes; digital tools (eVIN) and formalised governance frameworks have improved stock visibility and accountability, though rural last-mile challenges persist (17).

Latin America: Urban hubs often have stronger infrastructure and PAHO technical norms, but riverine/mountainous areas still face access and hold-time issues, requiring tailored cold-box and route solutions (6).

Geography dictates risk exposure; economics determines whether operations (energy, maintenance, supervision) are funded; and policy governs standards, contracts, and data interoperability. Durable improvement comes from costed O&M, harmonised equipment portfolios, and integrated RTM-eLMIS governance, not from hardware alone.

Technological and operational innovations

Over the past decade, innovations in vaccine cold chain management have surged, offering new solutions to longstanding challenges but with varied scalability and impact (46).

Solar direct-drive refrigerators have emerged as a reliable option in off-grid settings. For instance, the deployment of solar-powered units manufactured by SureChill and Vestfrost has been vital to the success of the malaria vaccine rollout across parts of sub-Saharan Africa, enabling uninterrupted storage in regions without dependable electricity (37,50).

Integration of temperature tracking with logistics systems has transformed oversight. Gilbert (17) revealed that Tanzania's integrated EIR-eLMIS significantly reduced stock-outs over time, marking progress over previous paper-based systems. A broader multi-country evaluation in Guinea, Honduras, Rwanda, and Tanzania found that eIR and eLMIS systems improved workflow and reduced stock-outs, with increased data accuracy and high user satisfaction.

Drone logistics have shown promise in overcoming geographic barriers. Zipline's partnership with Ghana's health service has enabled efficient vaccine deliveries, improved availability and reducing stockouts (45). Modeling studies in Niger and LMICs reveal that drone hub deployment can increase vaccine availability by 70–220% depending on budget and population distribution (31). Drone delivery solutions have also been tested in India via the World Economic Forum's "Medicine from the Sky" initiative.

Passive cold boxes with long hold times and freeze protection offer robust temperature control during transport (34,36). For ultra-low-temperature requirements, cryoshippers (holding below –150 °C) have been used successfully to distribute cryopreserved vaccines like PfSPZ in Africa, offering power-independent reliability (26).

Emerging technologies such as blockchain-powered smart contracts are being explored to enhance transparency and traceability in the cold chain, especially for ultra-sensitive deliveries like COVID-19 vaccines. Low-cost Internet of Things(IoT) enabled systems like "ALIVE" offer portable, real-time environment tracking to ensure last-mile storage integrity (18,27).

Synthesis and implications

The vaccine cold chain systems in developing countries are built on similar frameworks but operate with very different capacities and outcomes. While all systems aim to maintain vaccine potency through tiered storage, transport, and monitoring, the degree of reliability varies greatly (22,29,65). Infrastructure gaps such as unstable power, long transport routes, and aging equipment combine with human resource shortages and weak data systems to create fragile points along the chain (1,49). These challenges are compounded by policy fragmentation and underfunded maintenance, which often prioritize equipment procurement over sustainable operations (8,44).

At the same time, the findings show clear areas of progress. Solar-powered refrigerators, real-time temperature monitoring, and integrated stock management tools are helping improve visibility and control. Drone deliveries, although still largely pilot-based, have demonstrated how innovative approaches can overcome geographic and logistical barriers. Where countries have invested in training, governance, and preventive maintenance alongside technology, the benefits are more durable. For example, India's eVIN platform improved stock visibility and reduced vaccine losses, while Zipline's drone network in Ghana showed measurable improvements in last-mile delivery(5).

These insights suggest that strengthening vaccine cold chains requires more than equipment alone. Countries must cost and fund the total lifecycle of assets, from energy and transport to training and service contracts. Policies must harmonize procurement and asset management across national and sub-national levels. Integrating temperature and stock data into health information systems can shift programs from reactive to proactive management (19,66).

Inconsistencies and gaps

Despite growing literature, evidence on vaccine cold chain performance in developing countries remains uneven. Studies use varied indicators such temperature excursion rates, stock-outs, equipment uptime, cost-effectiveness making comparison across contexts difficult (32). Data quality is often limited, with many reports based on small audits, donor-funded pilots, or facility surveys rather than nationally representative assessments (11). Few studies evaluate the full cost of ownership, including maintenance and energy, or link cold chain performance directly to coverage and health outcomes.

Behavioural and governance issues are also underexplored. Most reports focus on hardware and infrastructure, with less attention to staff practices, supervision, or policy enforcement. Innovations like drones, IoT monitoring, and digital dashboards are often documented as pilots, with little evidence on long-term sustainability, integration, or impact at scale (8,23,27). Finally, there is minimal analysis of environmental sustainability, such as energy efficiency, climate resilience, or waste management in cold chain systems.

Another gap is the limited integration of behavioural and governance perspectives. Most documents emphasize devices and infrastructure, while fewer explore user compliance, motivation, decision-making, or policy enforcement. Research on private sector roles, third-party logistics, and financing models is sparse, as is evidence on environmental sustainability (energy efficiency, waste disposal). Many innovative tools (e.g., drones, IoT monitoring, GIS dashboards) are described in early pilots with limited follow-up on scalability, cost-effectiveness, and long-term maintenance. Interoperability between data systems (LMIS, RTM, DHIS2) and the effect on program outcomes are under-documented.

FUTURE DIRECTIONS

To strengthen vaccine cold chains in developing countries, future work must move beyond equipment procurement to focus on sustainability and integration. Countries should prioritize harmonized performance metrics, covering excursions, wastage, stock visibility, and cost to enable consistent tracking and benchmarking. Large-scale operational research is needed to evaluate innovations like solar direct-drive refrigerators, IoT-based remote monitoring, drones, and e-LMIS platforms, not just in pilots but during routine use and emergency campaigns.

Investment in people and processes is as important as technology. Continuous training, supportive supervision, and clear service contracts can improve reliability. Policy reforms should clarify governance, funding, and asset management, while fostering partnerships with private and community actors. Integrating cold chain data with broader health information systems will support proactive decision-making. Environmental considerations like energy efficiency, renewable power, and safe waste management must be incorporated to ensure resilience in the face of climate change and evolving vaccine needs.

CONCLUSION

Vaccine cold chain systems remain a cornerstone of immunization in developing countries, yet they face persistent weaknesses. Infrastructure gaps, power instability, geographic barriers, and underfunded maintenance threaten vaccine quality and timely delivery, while fragmented policies and limited workforce capacity add to the strain. Emerging solutions show clear promise but are still unevenly deployed and often donor dependent. The findings revealed that technology alone is not enough. Sustainable progress requires investments in governance, financing, training, and data integration, alongside innovations.

REFERENCE

1. Adeyemo, K. S., Mbata, A. O., & Balogun, O. D. (2021). The Role of Cold Chain Logistics in Vaccine Distribution: Addressing Equity and Access Challenges in Sub-Saharan Africa. International Journal of Multidisciplinary Research and Growth Evaluation, 2(1), 893–901. https://doi.org/10.54660/.ijmrge.2021.2.1.893-901
2. Al Qahtani, M., Mohsen Elserafy, M., Kumar Thampi, U., & Veettil, S. T. (2022). 24/7 Cold Chain Management System by Primary Health Care Corporation to support the National COVID-19 Mass Vaccination Program. Journal of Emergency Medicine, Trauma and Acute Care, 2022(1). https://doi.org/10.5339/jemtac.2022.qhc.56
3. Arogundade, L., Akinwumi, T., Molemodile, S., Nwaononiwu, E., Ezika, J., Yau, I., & Wonodi, C. (2019). Lessons from a training needs assessment to strengthen the capacity of routine immunization service providers in Nigeria. BMC Health Services Research, 19(1), 664. https://doi.org/10.1186/s12913-019-4514-2
4. Ashok, A., Brison, M., & LeTallec, Y. (2017). Improving cold chain systems: Challenges and solutions. Vaccine, 35(17), 2217–2223. https://doi.org/10.1016/j.vaccine.2016.08.045
5. Atiga, O., Tanzubil, B. J., Asaana, J., Ayamba, E. C., Seidu, M. T., & Mohammed, I. (2024). Shortening The Last-Mile: Impact of Zipline Medical Drone Delivery on The Operations of Hard-to-Reach Healthcare Facilities in Northern Ghana. AFRICAN JOURNAL OF APPLIED RESEARCH, 10(1), 178–200. https://doi.org/10.26437/ajar.v10i1.677
6. Betancourt-Cravioto, M., & Zhang, P. (2022). The future of immunization financing in Latin America and the Caribbean. Atlantic Council, Adrienne Arsht Latin America Center. ISBN 978-1-61977-259-5.. ISBN: 978-1-61977-259-5
7. Bogale, H. A., Amhare, A. F., & Bogale, A. A. (2019). Assessment of factors affecting vaccine cold chain management practice in public health institutions in east Gojam zone of Amhara region. BMC Public Health, 19(1), 1433. https://doi.org/10.1186/s12889-019-7786-x
8. Brison, M., & LeTallec, Y. (2017). Transforming cold chain performance and management in lower-income countries. Vaccine, 35(17), 2107–2109. https://doi.org/10.1016/j.vaccine.2016.11.067
9. Comes, T., Bergtora Sandvik, K., & Van De Walle, B. (2018). Cold chains interrupted: The use of technology and information for decisions that keep humanitarian vaccines cool. Journal of Humanitarian Logistics and Supply Chain Management, 8(1), 49–69. https://doi.org/10.1108/JHLSCM-03-2017-0006
10. Emelike, S. C. (2025). A Review of Challenges and Opportunities in Vaccine Logistics in Low-Resource Settings. Texila International Journal of Public Health, 13(3). https://doi.org/10.21522/TIJPH.2013.13.03.Art006
11. Endriyas, M., Solomon, T., Belayhun, B., & Mekonnen, E. (2018). Poor quality data challenges conclusion and decision making: Timely analysis of measles confirmed and suspected cases line list in Southern Nations Nationalities and People's Region, Ethiopia. BMC Infectious Diseases, 18(1), 77. https://doi.org/10.1186/s12879-018-2983-2

12. Fahrni, M. L., Ismail, I. A.-N., Refi, D. M., Almeman, A., Yaakob, N. C., Saman, K. M., Mansor, N. F., Noordin, N., & Babar, Z.-U.-D. (2022). Management of COVID-19 vaccines cold chain logistics: A scoping review. Journal of Pharmaceutical Policy and Practice, 15(1), 16. https://doi.org/10.1186/s40545-022-00411-5
13. Federspiel, F., & Ali, M. (2018). The cholera outbreak in Yemen: Lessons learned and way forward. BMC Public Health, 18(1), 1338. https://doi.org/10.1186/s12889-018-6227-6
14. Fritz, J., Herrick, T., & Gilbert, S. S. (2021). Estimation of health impact from digitalizing last-mile Logistics Management Information Systems (LMIS) in Ethiopia, Tanzania, and Mozambique: A Lives Saved Tool (LiST) model analysis. PLOS ONE, 16(10), e0258354. https://doi.org/10.1371/journal.pone.0258354
15. Frost, D., Mahmud, M., Kaiser, M. S., Musoke, D., Henry, P., & Islam, S. (2021). Innovative approaches to strengthening health systems in low- and middle-income countries: Current models, developments, and challenges. Health Policy and Technology, 10(4), 100567. https://doi.org/10.1016/j.hlpt.2021.100567
16. Geneti, L., Shallo, S. A., Yebasa, M. A., & Daba, D. B. (2024). Health workers' knowledge and practices toward vaccine cold chain management and its associated factors in a resource-limited setting of Sheger, Oromia, Ethiopia: A multicenter cross-sectional study. BMC Pediatrics, 24(1), 786. https://doi.org/10.1186/s12887-024-05284-y
17. Gilbert, S. S., Bulula, N., Yohana, E., Thompson, J., Beylerian, E., Werner, L., & Shearer, J. C. (2020). The impact of an integrated electronic immunization registry and logistics management information system (EIR-eLMIS) on vaccine availability in three regions in Tanzania: A pre-post and time-series analysis. Vaccine, 38(3), 562–569. https://doi.org/10.1016/j.vaccine.2019.10.059
18. Gilbert, S. S., Thakare, N., Ramanujapuram, A., & Akkihal, A. (2017). Assessing stability and performance of a digitally enabled supply chain: Retrospective of a pilot in Uttar Pradesh, India. Vaccine, 35(17), 2203–2208. https://doi.org/10.1016/j.vaccine.2016.11.101
19. Goodarzian, F., Navaei, A., Ehsani, B., Ghasemi, P., & Muñuzuri, J. (2023). Designing an integrated responsive-green-cold vaccine supply chain network using Internet-of-Things: Artificial intelligence-based solutions. Annals of Operations Research, 328(1), 531–575. https://doi.org/10.1007/s10479-022-04713-4
20. Guignard, A., Praet, N., Jusot, V., Bakker, M., & Baril, L. (2019). Introducing new vaccines in low- and middle-income countries: Challenges and approaches. Expert Review of Vaccines, 18(2), 119–131. https://doi.org/10.1080/14760584.2019.1574224
21. Hagedorn, B., Cooper, J., Odutolu, O., Ojukwu, O. M., & Loevinsohn, B. (2025). How decentralized facility financing improved supply chains and product availability in primary healthcare centers, a randomized trial in Nigeria. Public and Global Health. https://doi.org/10.1101/2025.07.21.25331940
22. Haidari, L. A., Connor, D. L., Wateska, A. R., Brown, S. T., Mueller, L. E., Norman, B. A., Schmitz, M. M., Paul, P., Rajgopal, J., Welling, J. S., Leonard, J., Chen, S.-I., & Lee, B. Y. (2013). Augmenting Transport versus Increasing Cold Storage to Improve Vaccine Supply Chains. PLoS ONE, 8(5), e64303. https://doi.org/10.1371/journal.pone.0064303
23. Hasanat, R. T., Arifur Rahman, Md., Mansoor, N., Mohammed, N., Rahman, M. S., & Rasheduzzaman, M. (2020). An IoT based Real-time Data-centric Monitoring System for Vaccine Cold Chain. 2020 IEEE East-West Design & Test Symposium (EWDTS), 1–5. https://doi.org/10.1109/EWDTS50664.2020.9225047
24. HEIKE, W. (2017). Framework for the evaluation of cost-effectiveness of drone use for the last-mile delivery of vaccines (master's thesis, University of Barcelona, ISGlobal).
25. Igboanugo, J. C., & Akobundu, U. U. (2020). Evaluating the Resilience of Public Health Supply Chains During COVID-19 in Sub-Saharan Africa. International Journal of Computer Applications Technology and Research, 09(12).
26. James, E. R., Church, L. W. P., Hoffman, S. L., Richie, T. L., Robertson, B. D., Hickey, P. W., Schwartz, D. J., Logan, P. T., Asare, T. D., Jones, M. L., Bay, J. L., Roschel, A. K., Pfeiffer, J. L., Acosta, R. W., Schiavi, E., Acosta, A. M., Noble, M., Henkel, T., & Young, C. (2024). Piloting delivery of PfSPZ vaccines for malaria through a cryogenic vaccine cold chain to travel and military medicine clinics. Journal of Travel Medicine, 31(3), taae007. https://doi.org/10.1093/jtm/taae007
27. Jiang, S., Jia, S., & Guo, H. (2024). Internet of Things (IoT)-enabled framework for a sustainable Vaccine cold chain management system. Heliyon, 10(7), e28910. https://doi.org/10.1016/j.heliyon.2024.e28910

28. Kanja, L. W., Karimi, P. N., Maru, S. M., Kayumba, P. C., & Hitimana, R. (2021). Factors that affect vaccines availability in public health facilities in Nairobi city county: A cross-sectional study. Pan African Medical Journal, 38. https://doi.org/10.11604/pamj.2021.38.72.21580
29. Kartoglu, U., & Ames, H. (2022). Ensuring quality and integrity of vaccines throughout the cold chain: The role of temperature monitoring. Expert Review of Vaccines, 21(6), 799–810. https://doi.org/10.1080/14760584.2022.2061462
30. Kartoglu, U., & Milstien, J. (2014). Tools and approaches to ensure quality of vaccines throughout the cold chain. Expert Review of Vaccines, 13(7), 843–854. https://doi.org/10.1586/14760584.2014.923761
31. Kolter, M. (2021). Optimization of Vaccine Supply Chains in Low- and Middle-Income Countries Utilizing Drones. University of Applied Sciences Munich Bachelor of Engineering in Engineering and Management, 2019
32. Kumar, N., & Jha, A. (2017). Temperature excursion management: A novel approach of quality system in pharmaceutical industry. Saudi Pharmaceutical Journal, 25(2), 176–183. https://doi.org/10.1016/j.jsps.2016.07.001
33. Lloyd, J., & Cheyne, J. (2017). The origins of the vaccine cold chain and a glimpse of the future. Vaccine, 35(17), 2115–2120. https://doi.org/10.1016/j.vaccine.2016.11.097
34. Lundbeck, H., Hakansson, B., & Lloyd, J. S. (1978). A cold box for the transport and storage of vaccines. Bulletin of the World Health Organization, 56 (3): 427-432 (1978)
35. Makinen, M., Kaddar, M., Molldrem, V., & Wilson, L. (2012). New vaccine adoption in lower-middle-income countries. Health Policy and Planning, 27(suppl 2), ii39–ii49. https://doi.org/10.1093/heapol/czs036
36. Managing Health Supply Chain, M. (2022). Passive Cold Chain Transportation (Logistics Operational Guide (LOG)). World Food Programme. https://www.wfp.org/
37. McCarney, S., Robertson, J., Arnaud, J., Lorenson, K., & Lloyd, J. (2013). Using solar-powered refrigeration for vaccine storage where other sources of reliable electricity are inadequate or costly. Vaccine, 31(51), 6050–6057. https://doi.org/10.1016/j.vaccine.2013.07.076
38. Modlin, J. F., Schaffner, W., Orenstein, W., & Bandyopadhyay, A. S. (2021). Triumphs of Immunization. The Journal of Infectious Diseases, 224(Supplement_4), S307–S308. https://doi.org/10.1093/infdis/jiab123
39. MUNSHI F, DEBNATH S, SENAN A, PETERS T, GREENING P, & WANG X. (2022). Vaccine cold-chain challenges for fast-track mass COVID-19 vaccination in Bangladesh. International Institute of Refrigeration (IIR). https://doi.org/10.18462/IIR.ICCC2022.1115
40. Myers, D. J., Jessupa, S., McCarney, S., Gueye, A., Diesburga, S. P., Little, J., Muller, N., & Lennon, P. (2019, November). Evaluation of Energy Harvest Control Systems Used with Solar Direct Drive Vaccine Refrigerators and Freezers in Senegal [PATH]. www.path.org
41. Namuhaywa, M. M. (2013). Cold Chain and Logistics Management for Expanded Program on Immunization in Busia and Namayingo Districts. Open Science Repository Medicine, open-access, e23050464. https://doi.org/10.7392/openaccess.23050465
42. Nestory, B., Anasel, M., Nyandwi, J. B., & Asingizwe, D. (2022). Vaccine management practices among healthcare workers in Morogoro, Tanzania: A cross-sectional study. Journal of Pharmaceutical Policy and Practice, 15(1), 95. https://doi.org/10.1186/s40545-022-00496-y
43. Nidhi Shashikumar. (2025). Optimizing supply chain efficiency in healthcare using predictive modeling and data analytics. International Journal of Science and Research Archive, 15(1), 1331–1341. https://doi.org/10.30574/ijsra.2025.15.1.1107
44. Numbi, F. K. M., & Kupa, B. M. (2017). The potential of next-generation supply chains to ease DRC's "Casse-tête." Vaccine, 35(17), 2105–2106. https://doi.org/10.1016/j.vaccine.2016.11.096
45. Ospina-Fadul, M. J., Kremer, P., Stevens, S. E., Haruna, F., Okoh-Owusu, M., Sarpong, G. K., Osei-Kwakye, K., Joshua, B., & Sakyi, O. (2025). Cost-Effectiveness of Aerial Logistics for Immunization: A Model-Based Evaluation of Centralized Storage and Drone Delivery of Vaccines in Ghana Using Empirical Data. Value in Health Regional Issues, 46, 101066. https://doi.org/10.1016/j.vhri.2024.101066
46. Pagliusi, S., Dennehy, M., & Homma, A. (2020). Two decades of vaccine innovations for global public good: Report of the Developing Countries' Vaccine Manufacturers Network 20th meeting, 21–23 october 2019, Rio de Janeiro, Brazil. Vaccine, 38(36), 5851–5860. https://doi.org/10.1016/j.vaccine.2020.05.062

47. Pambudi, N. A., Sarifudin, A., Gandidi, I. M., & Romadhon, R. (2022). Vaccine cold chain management and cold storage technology to address the challenges of vaccination programs. Energy Reports, 8, 955–972. https://doi.org/10.1016/j.egyr.2021.12.039
48. Prosser, W., Spisak, C., Hatch, B., McCord, J., Tien, M., & Roche, G. (2021). Designing supply chains to meet the growing need of vaccines: Evidence from four countries. Journal of Pharmaceutical Policy and Practice, 14(1), 80. https://doi.org/10.1186/s40545-021-00368-x
49. Rashid, M. M.-U. (2020). Identifying constraints in vaccine supply chain: A Case study of Finnish Red Cross.
50. Robertson, J., Franzel, L., & Maire, D. (2017). Innovations in cold chain equipment for immunization supply chains. Vaccine, 35(17), 2252–2259. https://doi.org/10.1016/j.vaccine.2016.11.094
51. Rusnack, M. (2021). COVID Vaccine Transport, Storage, and Distribution: Cold Chain Management to Ensure Efficacy. INNOVATIONS in Pharmacy, 12(4), 5. https://doi.org/10.24926/iip.v12i4.4225
52. Sáfadi, M. A. P. (2023). The importance of immunization as a public health instrument. Jornal de Pediatria, 99, S1–S3. https://doi.org/10.1016/j.jped.2022.12.003
53. Saidu, Y., Gu, J., Ngenge, B. M., Nchinjoh, S. C., Adidja, A., Nnang, N. E., Muteh, N. J., Zambou, V. M., Mbanga, C. M., Agbor, V. N., Ousmane, D., Njoh, A. A., Flegere, J., Diack, D., Wiwa, O., Montomoli, E., Clemens, S. A. C., & Clemens, R. (2023). The faces behind vaccination: Unpacking the attitudes, knowledge, and practices of staff of Cameroon's Expanded program on Immunization. Human Resources for Health, 21(1), 88. https://doi.org/10.1186/s12960-023-00869-7
54. Saraswati, L. D., Ginandjar, P., Budiyono, Martini, Udiyono, A., & Kairul. (2018). Vaccines Cold Chain Monitoring: A Cross-Sectional Study at Three District In Indonesia. IOP Conference Series: Earth and Environmental Science, 116, 012082. https://doi.org/10.1088/1755-1315/116/1/012082
55. Shao-jun Jiang, Z. Z., and Wen-yan Song. (2023). A Real-Time Surveillance System for Vaccine Cold Chain Based o n Internet of Things Technology. Journal of Information Processing Systems, 19(3), 394–406. https://doi.org/10.3745/JIPS.04.0279
56. Shen, A. K., Fields, R., & McQuestion, M. (2014). The future of routine immunization in the developing world: Challenges and opportunities. Global Health: Science and Practice, 2(4), 381–394. https://doi.org/10.9745/GHSP-D-14-00137
57. Sinnei, D. K., Karimi, P. N., Maru, S. M., Karengera, S., & Bizimana, T. (2023). Evaluation of vaccine storage and distribution practices in rural healthcare facilities in Kenya. Journal of Pharmaceutical Policy and Practice, 16(1), 25. https://doi.org/10.1186/s40545-023-00535-2
58. TMSA. (2023, August). Cold Chain Challenges in Remote and Rural Areas: Delivering Vital Goods [Http://temperaturemonitorsolutions.co.za/].
59. To, O., My, I., Eo, A., Oo, A., Fo, A., Am, A., & Co, A. (2019). Challenges in the Logistics Management of Vaccine Cold Chain System in Ile-Ife, Osun State, Nigeria. Journal of Community Medicine and Primary Health Care. 31 (2) 1-12
60. Tsega, A. Y., Hausi, H. T., Steinglass, R., & Chirwa, G. Z. (2014). IMMUNISATION TRAINING NEEDS IN MALAWI. East African Medical Journal Vol. 91 No. 9 September 2014
61. Walldorf, J. A., Date, K. A., Sreenivasan, N., Harris, J. B., & Hyde, T. B. (2017). Lessons Learned from Emergency Response Vaccination Efforts for Cholera, Typhoid, Yellow Fever, and Ebola. Emerging Infectious Diseases, 23(13). https://doi.org/10.3201/eid2313.170550
62. WHO, U. (2014). Achieving immunization targets with the comprehensive effective vaccine management (cEVM) framework (Vol. 2). WHO/UNICEF.
63. Woldemichael, B., Bekele, D., & Esmael, A. (2018). Cold Chain Status and Knowledge of Vaccine Providers at Primary Health Care of Units Bale Zone, Southeast Ethiopia: Cross-sectional Study. Immunome Research, 14(1). https://doi.org/10.4172/1745-7580.1000152
64. Yadav, P. (2015). Health Product Supply Chains in Developing Countries: Diagnosis of the Root Causes of Underperformance and an Agenda for Reform. Health Systems & Reform, 1(2), 142–154. https://doi.org/10.4161/23288604.2014.968005
65. Yakum, M. N., Ateudjieu, J., Walter, E. A., & Watcho, P. (2015). Vaccine storage and cold chain monitoring in the North West region of Cameroon: A cross-sectional study. BMC Research Notes, 8(1), 145. https://doi.org/10.1186/s13104-015-1109-9
66. Zarekar, M., Al-Shehabi, H., Dörner, R., Weishaar, H., Lennemann, T., El Bcheraoui, C., & Bernasconi, A. (2025). The impact of information and communication technology on immunisation and immunisation

programmes in low-income and middle-income countries: A systematic review and meta-analysis. eBioMedicine, 111, 105520. https://doi.org/10.1016/j.ebiom.2024.105520

67. Zipursky, S., Djingarey, M. H., Lodjo, J.-C., Olodo, L., Tiendrebeogo, S., & Ronveaux, O. (2014). Benefits of using vaccines out of the cold chain: Delivering Meningitis A vaccine in a controlled temperature chain during the mass immunization campaign in Benin. Vaccine, 32(13), 1431–1435. https://doi.org/10.1016/j.vaccine.2014.01.038