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Challenges and Advantages of Solar-Powered Vaccine Cold chain Systems in India: A Review

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ABSTRACT

Introduction:
Immunization programs are essential for safeguarding populations against vaccine-preventable diseases. These programs, implemented by national governments in collaboration with international organizations, aim to provide vaccines to individuals of all age groups. India launched the Universal Immunization Programme (UIP) in 1985, which has become one of the largest immunization campaigns globally. The UIP conducts approximately 12 million regular immunization sessions annually, targeting 26 million babies and 29 million pregnant women The successful delivery of vaccines relies on a well-coordinated cold chain system, which ensures that vaccines are stored and transported within specific temperature ranges to maintain their potency. Traditional cold storage methods, such as electric refrigeration systems, face limitations in resource-constrained settings due to electricity shortages, frequent power outages, and high operating costs. This study aims to undersatnd the feasibility of use of solar power technology in vaccine cold chain systems through a asystematic review of literature
Aim: To study the use of solar technology in creating the sustainable approach towards vaccine cold chain systems in India.
Objectives: Objectives of this study are
•Assess how vaccination coverage and the reliability of the cold chain, particularly in India, are affected by solar-powered cold chain systems.
•Compare the deployment of solar-powered cold chain systems to established vaccination cold chain systems to see whether it is economically feasible.
•Identify barriers to implementing, maintaining, and repairing solar-powered vaccine cold chain systems.
Methodology: A systematic search strategy, following PRISMA guidelines, was employed to select and analyze relevant literature. Research databases and keywords were used to identify suitable studies. Inclusion and exclusion criteria were applied to select pertinent sources for analysis.
Results and Discussion: Key findings emerge from the reviewed literature, offering insights across several critical dimensions. Firstly, it becomes evident that solar-powered refrigeration systems play a substantial role in enhancing the maintenance of vaccine cold chains, especially in remote and resource-constrained areas. Furthermore, the literature sheds light on the challenges associated with global vaccine distribution, highlighting solar technology as a potent mitigating factor in overcoming these hurdles. Solar solutions are revealed to be facilitators of equitable healthcare access while simultaneously contributing to energy efficiency, aligning with sustainability goals. Additionally, the scalability of solar-powered solutions is emphasized, illustrating their adaptability to diverse contexts. Finally, the literature underscores the indispensability of supportive policies in promoting the widespread adoption of solar refrigeration technology, underlining the importance of a conducive regulatory environment for sustainable healthcare infrastructure enhancement.
Conclusion: In conclusion, this systematic review underscores the pivotal role of solar-powered refrigeration as a sustainable and effective solution for vaccine cold chain management in resource-constrained settings in India. It advocates strategic interventions, policy adjustments, and investments to fully harness solar refrigeration's potential in fortifying healthcare services and achieving Sustainable Development Goals. Collaboration among governments, NGOs, and the private sector is deemed essential for equitable vaccine access and enhanced resilience in vaccine supply chains.

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KEYWORDS: Vaccine Cold chain, Solar powered, Sustainability, Supply chain.

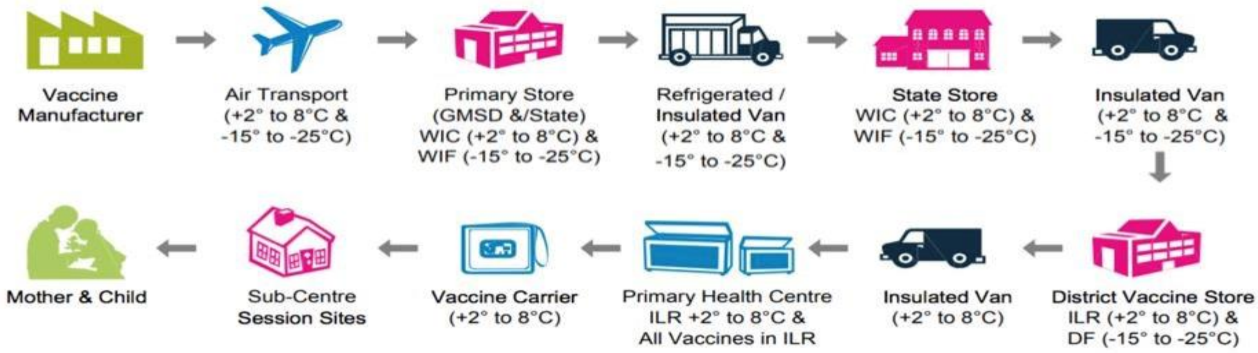
INTRODUCTION

Immunization programs are essential for safeguarding populations against vaccine-preventable diseases. These programs, implemented by national governments in collaboration with international organizations, aim to provide vaccines to individuals of all age groups. The UIP conducts approximately 12 million regular immunization sessions annually, targeting 26 million babies and 29 million pregnant women(1).

The successful delivery of vaccines relies on a well-coordinated cold chain system, which ensures that vaccines are stored and transported within specific temperature ranges to maintain their potency(2). Deviations from these temperature requirements can render vaccines ineffective. The primary objective of the vaccine cold chain is to preserve vaccines within a temperature range typically between 2°C and 8°C (35.6°F and 46.4°F). Achieving this goal involves supply chain management and maintaining optimal temperature conditions during storage, transportation, and distribution. However, traditional cold storage methods, such as electric refrigeration systems, face limitations in resource-constrained settings due to electricity shortages, frequent power outages, and high operating costs.(3)

To address these challenges, innovative cold storage technologies have emerged, providing sustainable and reliable solutions for vaccine storage in areas with inadequate or costly access to electricity(4). One promising approach is the use of solar-powered refrigeration systems. These systems harness energy from the sun to provide a continuous and environmentally friendly power source for cold storage. Solar-powered refrigeration technology offers a viable alternative to traditional electric refrigeration, particularly in regions abundant in sunlight resources(5). Its integration into vaccine cold chain management has demonstrated promising results in enhancing accessibility and effectiveness of vaccination programs (5,6)

Figure 1: Vaccine cold chain system[1]



Solar refrigeration process involves extracting heat from a specific environment to lower its temperature below the surrounding ambient temperature. Rather than relying on conventional vapour compression or absorption cycles, it aims to utilize thermoelectric effects to achieve cooling[2]. This approach offers a promising solution for reliable and sustainable vaccine storage, particularly in regions where traditional cooling methods are impractical or unavailable(7).

According to WHO, Solar refrigeration was a promising development in the early 1980s, providing an alternative to absorption technology to meet cold chain needs in remote areas(14,15). But due to lack of personal training, less awareness on technology and poor supply chain of solar it didn't achieve the success.

[1] https://www.icmr.gov.in/pdf/idrone/a_ICMR_Training_Modulle_V2.pdf

[2] In thermoelectric module refrigerator mechanical parts such as, compressor, liquid coolant, condenser coil, evaporation coil and expansionvalve are replaced by thermoelectric module. Ganesh S. Dhumal, P.A. Deshmukh

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The solar-powered vaccine cold chain system supports these SDGs by enhancing healthcare access, promoting clean energy, fostering innovation, mitigating climate change, and encouraging partnerships across the country. The implementation of a solar-powered vaccine cold chain in India aligns with several Sustainable Development Goals (SDGs) set by the United Nations(16).

This review aims to explore the intersection of vaccine cold chain management and cold storage technology, with a specific emphasis on the use of solar-powered refrigeration systems to overcome the challenges associated with inadequate and costly access to reliable electricity. By examining current research on traditional vaccine cold chain management, their benefits, limitations, and future prospects of solar-powered vaccine cold chain systems, this review seeks to understand the potential of these innovative solutions in optimizing vaccine delivery and improving immunization coverage in resource- constrained regions(17).

Effective vaccine distribution is a cornerstone of public health, especially in a country as vast and diverse as India. This literature review delves into an array of studies and assessments that focus on improving vaccine cold chain systems in India by integrating sustainable practices and solar technology. It also examines how these findings can influence the country's healthcare infrastructure development.(18,19)
Studies consistently emphasizes the importance of sustainability in vaccine distribution. Researchers have explored innovative solutions to mitigate the environmental impact of vaccine logistics. **(22)**. These units not only reduce energy consumption but also align with global sustainability objectives, making vaccine distribution more environmentally responsible.This collective emphasis on sustainability underscores the global commitment to reduce the carbon footprint of vaccine distribution while ensuring the efficacy of immunization efforts(23)

AIM AND OBJECTIVES

Aim: To study the use of solar technology in creating the sustainable approach towards vaccine cold chain systems in India.

Objectives: Objectives of this study are

- Assess how vaccination coverage and the reliability of the cold chain, particularly in India, are affected by solar-powered cold chain systems.
- Compare the deployment of solar-powered cold chain systems to established vaccination cold chain systems to see whether it is economically feasible.
- Identify barriers to implementing, maintaining, and repairing solar-powered vaccine cold chain systems

METHODOLOGY

The study design for this secondary review is systematic and follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. It involves a structured and rigorous approach to identifying, selecting, and critically evaluating relevant research studies, reports, and literature on the topic.

To ensure the study reflects recent events and provides comprehensive and up-to-date information, a systematic literature search was conducted. Relevant databases such as "Scopus" and "PubMed," Indian Government websites including the "National Health Mission," "Ministry of Health and Family Welfare," and the "National Cold Chain Management Information System," as well as international websites such as the World Health Organisation and UNICEF were included in the search. The search period spanned two months, specifically May and June 2023. The following keywords were utilized: "Immunisation Programmes," "Vaccine Cold Chain Systems," "India," "Solar Energy," "difference," "Solar powered vaccine cold chain systems," "cost effectiveness," "On-grid," "off-grid," "electricity," and various combinations thereof. Minor variations in search options necessitated slightly different search strategies for each database.

Additionally, relevant articles were identified by scanning the reference lists of the retrieved studies. On the "Scopus" database, the search strategies employed were as follows:

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Search Strategy 1: Key words (in the field of "Title, abstract, keywords"): Impact+Solar powered + Vaccine cold chain systems

Search Strategy 2: Key words (in the field of "Title, abstract, keywords"): Solar energy + difference" + On-grid electricity
Search Strategy 3: Key words (in the field of "Title, abstract, keywords"): Impact +Immunisation Programmes + India

Further refinement was performed in the "Subject Areas" and "Document Types" fields to improve the relevance of the results. The "Subject Areas" were limited to "vaccine cold chain systems" and "impact of solar energy in healthcare centers." The "Document Types" were limited to "Article" and "Proceeding Paper." On "PubMed," the initial literature collection utilized the following three search strategies: Search Strategy 7: Key words (in the field of "Title"): Immunisation Programmes + India
Search Strategy 8: Key words (in the field of "Title"): Solar powered + Vaccine cold chain systems

On Indian Government websites, specific documents and information were gathered:

The articles and documents initially identified from the reference lists of papers obtained through the database searches were also assessed using the same criteria adhering to PRISMA ***(Preferred Reporting Items for Systematic Reviews and Meta-Analyses)*** guidelines. (Figure 2).

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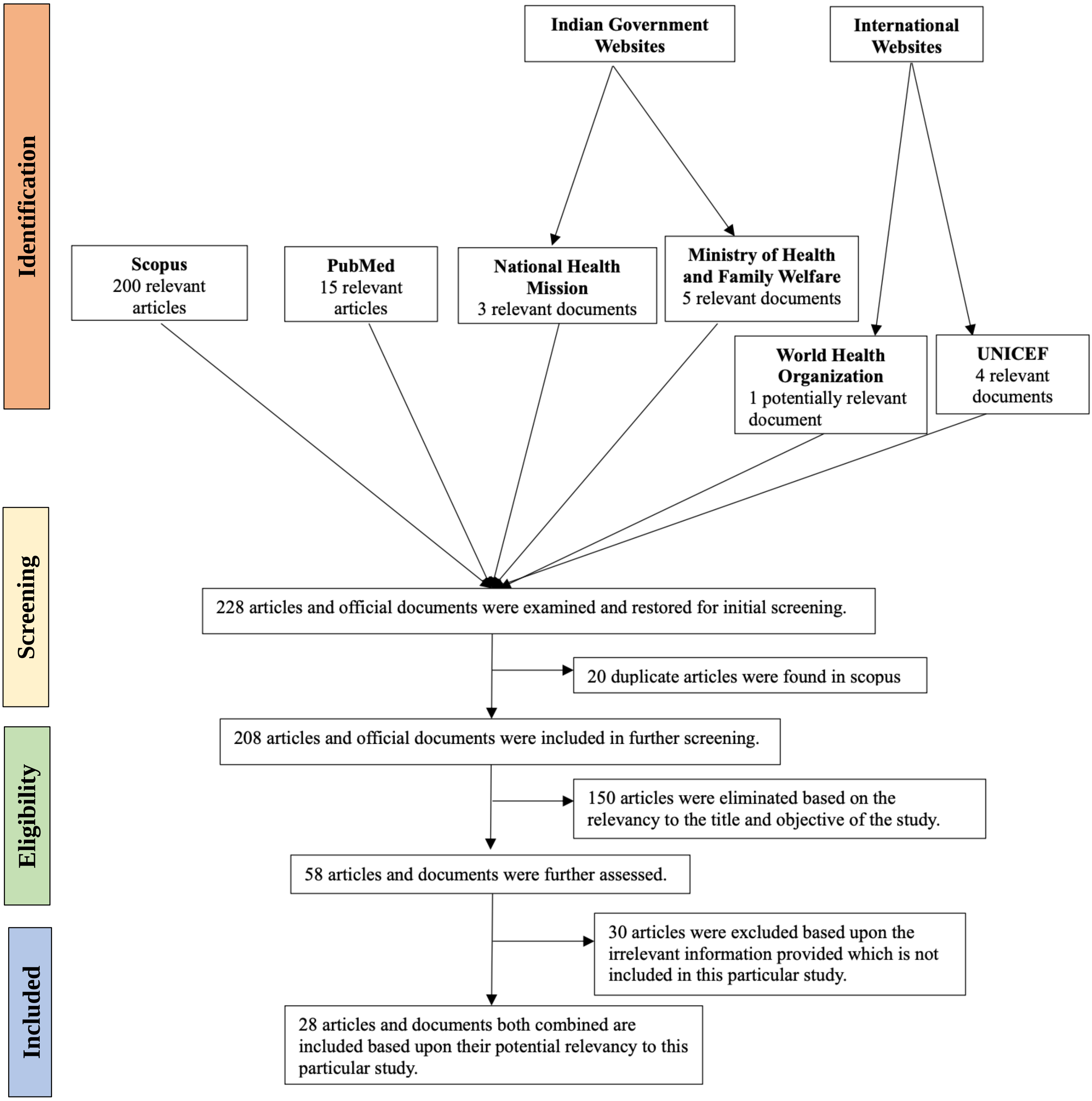

Figure 2. Flow Chart of Study Selection Process

FINDINGS AND RESULTS

Table 1: Overview of Included Studies

S.No	Author(s),Source of the study & Year of Publication	Title of the Study	Key Findings of the Study

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1	Lalith Pankaj Raj Nadimuthu & Kirubakaran Victor. Environmental science and Research- article (November 2021)	Environmental friendly micro cold storage for last-mile Covid-19 vaccine logistics	a. Maintaining covid 19 vaccines in required temperature in micro cold storage. b. Potential of micro cold storage technology to improve the sustainability and efficiency of vaccine distribution. c. Eco-friendly refrigerants and Energy-efficient components reduces greenhouse gas emissions and energy consumption. d. Development of guidelines for maintenance and effectiveness. e. Evaluates the economics feasibility and scalability of micro cold storage for vaccines.
2	Nugroho Agung Pambudi, Alfan Sarifudin, IndraMamad Gandidi, Rahmat Rom adhon Energy Reports- Review Article (November 2022)	Vaccine cold chain management and cold storage technology to address the challenges of vaccination programs	a. vaccine cold chain management cold storage technology. b. address the challenges of vaccination programs. c. Damage control of vaccines while distribution from manufacturing units to facilities. d. Highlights the storage issues.
3	Aryan Karkra, Rajkumar Chauhan and Dr. JP Kesari International Research Journal of Modernization in Engineering Technology and Science - research article (July 2021)	Feasibility Study of Solar Power Equipped Vaccine Storage Units in Rural Areas-Lesson learnt from COVID pandemic	a. Feasibility in implementation of solar powered vaccine storage units in rural areas of India. b. Vaccine distribution and importance of robust cold chain management, c. The need for decentralized storage facilities, c value of renewable energy solutions. d. Issues related to solar refrigerators are mainly the maintenance of these photovoltaic systems which requires skilled engineers and technicians, malfunctioning of the refrigerator in poor weather conditions etc. e. However, the lifespan of solar refrigerators is around 10-20 years with proper maintenance.
4	Steve McCarney, Joanie Robertson, Juliette Arnaud, Kristina Lorenson and John Lloyd Vaccine Journal- Review Article (December 2013)	Using solar-powered refrigeration for vaccine storage where other sources of reliable electricity are inadequate or costly	a. Reliable Storage b. Cost Efficiency c. Enhanced Access d. Sustainability e. Effective Energy Storage f. Community Resilience g. Adaptability h. Study results inform policy decisions, advocating solar infrastructure investments for reliable vaccine storage. i. Successful implementation hinges on partnerships among governments, NGOs, and private sectors.

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5	National Cold Chain Vaccine Management and Resource Centre The National Institute of Health and Family Welfare in collaboration with MofHw and UNICEF (April 2016)	Evaluation of Solar Hybrid Photo-voltaic System in Primary Health Centres in Maharashtra.	a. Solar hybrid systems reliably powered primary health centers. b. Cost savings were achieved due to reduced reliance on conventional electricity. c. Improved energy access positively impacted healthcare services in remote areas. d. Solar systems contributed to environmental sustainability by reducing carbon emissions. e. Maintenance and training emerged as essential factors for sustainable system operation. f. Positive policy implications were identified, promoting wider adoption of solar technologies.
6	Hui Hua, Jiajun Xub, Mengqi Liuc and Ming K. Lim, Journal of Business Research-Research Article (February 2023)	Vaccine supply chain management: An intelligent system utilizing blockchain, IoT and machine learning	a. Enhanced Transparency b. Real-time Monitoring c. Predictive Analytics, This proactive approach allows for timely interventions and prevents disruptions. e. Efficient Inventory Management f. Decentralized Data Sharing g. Improved Cold Chain Management as, IoT sensors ensure that vaccines are stored and transported within the required temperature range, safeguarding their efficacy. h. Operational Cost Savings i. Scalability and Adaptability j. Overall Efficiency Gains: The integration of blockchain, IoT, and machine learning optimizes vaccine supply chain processes, leading to faster delivery, better resource utilization, and ultimately, improved public health outcomes.
7	A study done by Central Coordinating Office The INCLEN Trust International, New Delhi (2020)	In-Depth Analysis of Cold Chain Vaccine Supply and Logistics Management for Routine Immunization in Three Indian States: An inclen program evaluation network study	a. Cold Chain Evaluation b. Temperature Control c. Stock Management d. Data Reporting f. supply chain efficiency affects immunization coverage and equity across different groups. g. Training programs for cold chain and logistics staff are examined, with suggestions for skill enhancement. h. Policy Insights

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8	Jian Sun, Mingkan Zhang, Anthony Gehl, Brian Fricke, Kashif Nawaz, Kyle Gluesenkamp, Bo Shen, Jeff Munk, Joe Hagerman, Melissa Lapsa, International Journal of Refrigeration- Research Article (January 2022)	COVID 19 vaccine distribution solution to the last mile challenge: Experimental and simulation studies of ultra-low temperature refrigeration system	a. Ultra-Low Temperature Storage Viability b. Temperature Maintenance c. Mitigating Cold Chain Breaks d. Vaccine Integrity Preservation e. Optimal Route Planning f. Resource Allocation g. Operational Efficiency h. Scalability i. Logistical Planning j. Public Health Impact
9	Yi Zhao, Xuelai Zhang*, Xiaofeng Xu, Shihua Zhang, Journal of Energy Storage- Research Article (August 2020)	Development of composite phase change cold storage material and its application in vaccine cold storage equipment	a. Composite Phase Change Material (PCM) Development suitable for cold storage applications, specifically for preserving vaccines. b. Enhanced Thermal Performance c. Vaccine Preservation d. Energy Efficiency e. Scalability and Adaptability f. Practical Implementation
10	Mohammed Raihan Uddin, Shadman Mahmud, Sayedus Salehin, Md Abdul Aziz Bhuiyan, Fahid Riazb, Anish Modid and Chaudhary Awais Salman- Energy Conservation and Management X- Research Article (July 2021)	Energy analysis of a solar driven vaccine refrigerator using environment-friendly refrigerants for off-grid locations	a. Energy efficiency of a solar-driven vaccine refrigerator. b. Solar Power Viability c. Environmental Impact d. Off-Grid Suitability e. Solar-driven vaccine refrigeration reduces the dependency on conventional energy sources. f. Temperature Control g. Technology Integration h. Healthcare Accessibility in underserved regions, where reliable vaccine storage is crucial. i. Implementations of solar-driven vaccine refrigeration systems, supporting efforts to enhance immunization programs and health outcomes.
11	Dheeraj Chandraa and Dinesh Kumarb- Omega Research Article (June 2021)	Evaluating the effect of key performance indicators of vaccine supply chain on sustainable development of mission indradhanush: A structural equation modeling approach	The key findings of this study are as follows: a. KPI Influence in the vaccine supply chain and the sustainable development of the Mission Indradhanush program. b. Immunization Coverage: Certain KPIs, such as vaccine availability and distribution efficiency, have a positive effect on achieving higher immunization coverage, a critical aspect of sustainable development in healthcare. c. Healthcare Access d. Resource Utilization in the vaccine supply chain, minimizing wastage and enhancing sustainability.

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			e. Data Accuracy f. Policy Implications g. Highlights the interconnections between KPIs and sustainable development.
12	Aniket A. Kagwade, Pranav A. Herle1, Shivraj S. Narke1, Suraj C. Patil1, Mr. P.A. Thorat- International Journal of Research Publication and Reviews- Review Article (2021)	Solar Based Vaccine Storage System	a. Potential of harnessing solar energy to ensure consistent b. Temperature Control c. Energy Efficiency d. Reliability e. Remote Accessibility f. Sustainability g. Practical feasibility of implementing solar- based vaccine storage systems in healthcare facilities. h. Ensuring the availability of potent vaccines, contributing to disease prevention and control. i. Adaptability
13	UIP- Ministry of health and family welfare, Govt. of India (December 2022)	Universal Immunization Programme in India (UIP)	a. Expanded Vaccine Coverage b. Disease Prevention c. Infant Mortality Reduction d. Epidemic Control e. The program emphasizes equitable access to vaccines, targeting vulnerable and marginalized populations to ensure that immunization services are accessible to all. f. Immunization Infrastructure g. Integrated Approach h. Awareness and Education i. Public-Private Partnership j. Global Impact
14	Shailender Kumar- Institute for Studies in Industrial Development (October 2022)	India in the Global Vaccine Market Prior To and During COVID-19: Some Structural Issues	a. The report assesses India's substantial contribution to the global vaccine market before the covid-19 pandemic as a major supplier of vaccines. b. Vaccine Self-Sufficiency by India and demand globally from India. c. Global Health Diplomacy.

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15	Ashvin Ashok, Michael Brison, Yann LeTallec, Vaccine- Review Article (April 2017)	Improving cold chain systems: Challenges and solutions	a. Infrastructure Constraints: The study identifies infrastructure challenges within cold chain systems, including inadequate storage capacity, unreliable power supply, and insufficient transportation facilities. b. Temperature Monitoring c. Technological Solutions such as IoT d. Capacity Building e. Public-Private Partnerships f. The potential of solar-powered cold chain solutions to overcome energy-related challenges in regions with unreliable electricity access. g. Integrating cold chain management with broader healthcare supply chain systems can lead to synergies and optimize resource utilization. h. Policy and Regulatory Frameworks i. Data Sharing and Analytics j. Global Implications on healthcare products.
16	Joanie Robertson, Lauren Franzel and Denis Maire , Vaccine- Review Journal (April 2017)	Innovations in cold chain equipment for immunization supply chains	a. Temperature Stability b. Technology Integration c. Energy Efficiency d. Solar-Powered Solutions e. Cold Chain Optimization f. Remote Access and Control g. Ease of Use and Maintenance h. Disease-Specific Requirements i. Customization and Adaptability j. Sustainability and Environmental Impact k. Cost-Effectiveness l. Operational Resilience
17	National Cold chain management Information System, Govt of India (2014)	National Assessment Of Solar Cold Chain Equipment Under India's Universal Immunization Programme	a. The assessment highlights the successful integration of solar-powered cold chain equipment into India's UIP. b. Vaccine Availability and Efficacy c. Improved the reliability of vaccine storage and distribution by reducing dependence on grid electricity. d. demonstrates the significance of solar cold chain systems in reaching remote and off-grid areas. e. Energy Efficiency g. Scalability and Sustainability h. Public Health Impact i. Policy Implications j. Informed decision-making for future investments in solar cold chain infrastructure, guiding efforts to enhance vaccine storage and distribution capabilities

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			in India's immunization program.
18	John Lloyda, Steve McCarneyb, Ramzi Ouhichic, Patrick Lydond and Michel Zaffrand - Vaccine- Review Article (February 2015)	Optimizing energy for a 'green' vaccine supply chain	a. Energy Efficiency Strategies b. Renewable Energy Integration c. Cold Chain Optimization d. Route Optimization e. Technological Innovations f. Collaborative Efforts g. Lifecycle Analysis h. Carbon Footprint Reduction i. Cost Savings for vaccine manufacturers and distributors. j. Energy optimization enhances the resilience of the vaccine supply chain. k. By optimizing energy usage, the vaccine supply chain contributes to improved public health outcomes through effective vaccine distribution. l. Provides sustainable and reliable solution for vaccine storage in areas with limited access to electricity.
19	Harshal Mendhe, Kiran Makade, Dhiraj Bhawanani, Rohit David, Nitin Kamble, Daneshwar Singh and Monika Dengani- Department of Community Medicine, Government Medical College, Rajnandgaon, Chhattisgarh, India- Research Article (November-December 2018)	Cold chain maintenance in Rajnandgaon and Bilaspur districts of Chhattisgarh: A process evaluation	a. Cold Chain Infrastructure Assessment b. Maintenance Practices Evaluation c. Timeliness of Maintenance d. Cold Chain Equipment Performance e. Capacity Building and Training f. Allocation of resources, budgeting, and availability of spare parts for cold chain maintenance. g. Temperature Monitoring Practices h. Compliance with Guidelines i. Recommendations for Improvement j. Impact on Immunization Services
20	Tara Azimi, Lauren Franzel and Nina Probst- Vaccine - Review Article (April 2017)	Seizing market shaping opportunities for vaccine cold chain equipment	a. Market Dynamics Assessment b. Innovative Technologies c. Private Sector Engagement d. Public-Private Partnerships e. Market Entry Strategies f. Local Manufacturing and Production g. Tailored Solutions h. Market Incentives i. Sustainability and Environmental Impact j. Capacity Building

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			k. Policy and Regulation
21	John Lloyd and James Cheyne- Vaccine- Review Article (April 2017)	The origins of the vaccine cold chain and a glimpse of the future	a. Historical Evolution b. Early Challenges faced by early vaccination programs. c. The role of innovations in refrigeration technology, packaging materials, and transportation methods in shaping the vaccine cold chain and expanding immunization coverage. d. Global Health Impact e. Temperature Control f. Vaccine Efficacy and Equity g. Modern Cold Chain Infrastructure h. Technological Advancements i. Future Challenges and Innovations j. Sustainability and Energy Efficiency k. Immunization Strategies l. Interdisciplinary Collaboration
22	Hamish Beatha, Muriel Hausera, Philip Sandwellb, Ajay Gambhira, Sheridan Fewa, Clementine L. Chambonc and Jenny Nelsona- Renewable and Sustainable Energy Transition- Research Article (August 2021)	The cost and emissions advantages of incorporating anchor loads into solar mini-grids in India	a. Economic Viability b. Energy Demand Stabilization c. Revenue Generation d. Reduced Emissions and supporting sustainable energy transition. f. Energy Access g. Policy Implications h. The research discusses the potential for hybrid mini-grid systems that combine solar power with other renewable sources, further enhancing energy reliability and system performance. i. Operational Resilience
23	Magali Cattin, Sashidhar Jonnalagedda, Solomzi Makohliso and Klaus Schönenberger- Vaccine: X (August 2022)	The status of refrigeration solutions for last mile vaccine delivery in low-income settings	a. The study assesses the existing refrigeration infrastructure for last-mile vaccine delivery in low-income settings b. Access Barriers c. The innovative solutions, such as solar-powered refrigeration units and portable cold boxes for addressing the challenges of last- mile vaccine delivery in resource-limited settings. d. Temperature Control and vaccine wastage e. Data Monitoring and Tracking f. Community Engagement g. Human Resource Capacity h. Supply Chain Integration i. Affordability and Sustainability

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			j. Health System Strengthening k. Policy and Investment l. Impact on Immunization Coverage
24	Ministry of Health and Family welfare, Govt. of India Assessment Report (2010)	Cold Chain and Logistic Management	a. Temperature Control b. Equipment and Infrastructure c. Supply Chain Visibility d. Training and Capacity Building e. Data Management f. Quality Assurance g. Cost Efficiency h. Global Reach i. Technology Integration j. Sustainability
25	Kim De Boeck*, Catherine Decouttere, Nico Vandaele, Omega- Review Article (December 2020)	Vaccine distribution chains in low- and middle-income countries: A literature review	The key findings of this study are as follows: a. Complexity of Vaccine Distribution Chains b. Supply Chain Challenges c. Last-Mile Delivery Challenges: d. Cold Chain Management e. Innovations in Distribution Strategies f. Data-Driven Decision-Making g. Capacity Building and Training h. Local Context Considerations
26	Leila A. Haidari, Shawn T. Brown, Patrick Wedlock, Diana L. Connor, Marie Spiker and Bruce Y. Lee - Vaccine- Research Article (April 2017)	When are solar refrigerators less costly than on-grid refrigerators: A simulation modeling study	The key findings of this study are as follows: a. Cost Comparison b. Solar Suitability c. Energy Efficiency d. Initial Investment e. Long-Term Savings f. Disruption Mitigation g. Geographic Variability h. Healthcare Access i. Policy Implications j. Environmental Considerations k. Scale and Implementation Trade-offs and Context
27	A guide for Managers in National Immunization Programmes- WHO in collaboration with UNICEF (2015)	Introducing Solar powered Vaccine Refrigerators and Freezer Systems.	The following points were covered in the study report released by WHO in collaboration with UNICEF: a. Introduction to Solar-Powered Systems b. Technical Specifications and Selection c. Installation and Setup d. Maintenance and Operation e. Temperature Monitoring and Data Management f. Training and Capacity Building g. Energy Efficiency and Sustainability h. Emergency Preparedness i. Resource Planning and Budgeting j. Integration with Immunization Programs k. Monitoring and Evaluation l. Global Best Practices.

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28	Solar direct Drive Study Assessment done by UNICEF in collaboration with WHO (2017)	Solar direct drive Vaccine Refrigerators and Freezers	a. Temperature Control b. Reliability in Off-Grid Areas c. Energy Efficiency d. Suitability for Remote Locations e. Low Maintenance f. Impact on Immunization Programs g. Public Health Outcomes h. Cold Chain Strengthening i. Local Empowerment Partnerships and Collaboration

The review of identified articles reveals a wide range of potential barriers to vaccine cold chain systems. It also highlights solar technology as a sustainable approach for enhancing vaccine cold chain management. Furthermore, it discusses global challenges and possible interventions, as illustrated in the Table 2. These interventions are aimed at addressing the identified limitations and improving vaccine management and the utilization of solar energy in healthcare systems.

Table 2: Barriers and Interventions

B.	**Global Vaccine Challenges:**		
i.	***Limited Innovation:***	○ India primarily focuses on generic production, rather than vaccine innovation and development.	○ Encourage research and development in vaccine innovation. ○ Foster partnerships between Indian vaccine manufacturers and global research institutions.
ii.	***Challenges in COVID-19 Vaccine Production:***	○ Scaling up COVID-19 vaccine production during the pandemic faced hurdles like supply chain disruptions, regulatory obstacles, and technology transfer issues.	○ Enhance supply chain resilience through diversified sourcing of raw materials and production capacity. ○ Streamline regulatory processes to expedite vaccine production during emergencies.
iii.	***Supply Chain Complexities:***	• Complexities in vaccine supply chains exposed issues related to raw materials, production capacity, and distribution logistics.	○ Establish a strategic reserve of critical vaccine components.
iv.	***Global Dependence:***	○ Heavy global dependence on a few vaccine manufacturers, including India, was revealed during the pandemic, highlighting the need for diversification and resilience in vaccine supply.	○ Promote vaccine production diversification in India and other countries. ○ Collaborate with international partners to build regional vaccine manufacturing capacity.
v.	***Intellectual Property and Access:***	○ Challenges in equitable vaccine distribution and availability, especially in	○ Support initiatives for equitable vaccine access, including technology-sharing

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		low-income countries, were discussed in terms of intellectual property rights and access issues.	agreements.
vi.	***Operational Challenges:***	○ Challenges related to maintenance, repair, and technical support for solar cold chain equipment were identified, emphasizing the importance of ○ Training and local capacity building.	o Expand training programs for maintenance and repair of solar cold chain equipment. ○ Establish local service centers fortimely technical support.
vii.	***Early Challenges:***	○ limitations in refrigeration technology and cold storage infrastructure. ○ Influenced the development of cold chain practices.	o Upgrade cold storage infrastructure and invest in energy-efficient refrigeration technology. o Develop mobile cold storage units forremote and underserved areas.
viii.	***System Optimization:***	○ System design, maintenance, and monitoring, while also suggesting adaptations and strategies to optimize the performance of solar direct- drive refrigerators and freezers.	o Invest in research and development to improve the performance of solar direct-drive refrigerators and freezers. o Provide technical guidance to healthcare facilities on system designand monitoring.
ix.	***Solar Charge Controller PWM (Pulse width modulation)***	○ Limited testing· • Requirement of skilled engineers and technicians • Malfunctioning in poor weather conditions and Limitedscope of the study	o Introduce thorough testing protocols to ensure the reliability and durability of PWM charge controllers. o Establish a training program to enhance the skills of engineers and technicians in maintaining and troubleshooting PWM controllers. o Develop weather-resistant enclosures or backup power solutions to mitigate malfunctioning during adverse weather conditions.
x.	***Operational Considerations***	· Complex technologies can belimited by available resources · Technological barriers may hinder operational efficiency· Electricity access issues and Cost of leveraging solar energy	o Simplify and adapt complex technologies to suit resource-constrained settings. o Provide training programs to overcome technological barriers andensure efficient operation. o Address electricity access issues through off-grid solar solutions or backup power sources.

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DISCUSSION

Vaccine distribution in low- and middle-income countries presents a multifaceted challenge, as illuminated by the comprehensive literature review conducted in this study. The complexity of these distribution chains is underscored by the involvement of multiple stakeholders, variable infrastructure, and the formidable task of reaching remote and underserved populations(29). To overcome these complexities, strategic collaboration among governmental bodies, non-governmental organizations (NGOs), and international entities becomes paramount. Public-private partnerships, for instance, have demonstrated their effectiveness in optimizing distribution logistics and expanding the reach of vaccination programs. Moreover, addressing the supply chain challenges identified, including inadequate transportation networks and unreliable electricity supply for cold chain storage, necessitates significant investments in infrastructure(11). Governments and international organizations must prioritize the enhancement of transportation infrastructure and the reliability of electricity supply to ensure the efficient distribution of vaccines. The challenges associated with reaching the last mile of the population, often attributed to geographical barriers, poor road networks, and limited access to healthcare facilities, demand innovative solution(6). The deployment of mobile clinics and community health workers has proven instrumental in overcoming these challenges, and investments in these approaches are crucial for achieving comprehensive vaccine coverage(8,11).

The maintenance of an unbroken cold chain is a linchpin of vaccine potency and effectiveness. The research findings emphasize the significance of investments in temperature monitoring technology, equipment maintenance, and robust data monitoring systems(30). Furthermore, the skills and knowledge of healthcare workers play a pivotal role in ensuring proper cold chain management. Initiatives for their training and capacity building must be given due attention. Data collection and analysis have emerged as vital components in optimizing vaccine distribution chains. Real-time monitoring, informed decision-making, and continuous improvement in distribution chains can be enabled through investments in robust data management systems. Recognizing the local socio-cultural, economic, and political context is paramount in designing effective distribution strategies(8). Tailored approaches that account for local nuances are more likely to enhance the acceptance and success of vaccination programs. Effective policies, governance structures, and regulatory frameworks are essential in ensuring equitable access to vaccines. Additionally, addressing disparities in immunization coverage calls for targeted strategies that ensure equitable access to vaccines for all(21).

The study on the cost-effectiveness of solar refrigerators presents critical insights into a sustainable solution for vaccine storage, particularly in regions with limited or unreliable grid electricity. Notably, the cost comparison between solar and on-grid refrigeration systems highlights the potential long-term savings and improved vaccine access associated with solar-powered solutions. Furthermore, the emphasis on energy efficiency in solar refrigeration aligns with sustainability goals. Prioritizing the procurement of energy-efficient solar refrigeration systems not only reduces operating costs but also contributes to environmental sustainability. Solar refrigerators' ability to mitigate disruptions in electricity supply is of paramount importance, especially in remote and underserved areas(19). Government needs to invest in solar solutions as an integral component of their emergency preparedness plans. Considering geographical factors, such as sunlight availability and climate, is essential when deploying solar refrigerators(31). Tailored solutions that account for local conditions can optimize system performance and longevity. The findings highlight the significant potential of cost- effective solar refrigerators in enhancing healthcare access in remote areas by ensuring the availability of temperature-sensitive medical products(12). Policymakers should take note of these positive findings, which call for policy adjustments and increased investments in sustainable energy solutions for healthcare(11). Lastly, the potential for scaling up the use of solar refrigeration systems should be explored, with a specific focus on proper implementation, maintenance, and monitoring. Decision- makers should weigh trade-offs and consider the unique context of healthcare settings when selecting between solar and on-grid refrigeration solutions(20).

The sustainability of solar-powered vaccine cold chain systems is a paramount consideration in ensuring the

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reliable storage and distribution of vaccines, especially in resource-constrained and off-grid regions. These systems offer multiple facets of sustainability, beginning with their remarkable energy efficiency. By harnessing renewable solar energy to power refrigeration units, they reduce dependence on conventional fossil fuels and grid electricity, resulting in both cost savings and a reduced environmental footprint(36). Over time, this energy-efficient approach proves economically sustainable, as initial investments are offset by long-term operational cost reductions(7).

Furthermore, solar refrigerators demonstrate exceptional reliability in off-grid areas, where access to consistent grid electricity is often limited or cost-prohibitive(4). Their ability to operate independently of centralized power sources ensures a continuous vaccine supply, enhancing the sustainability of immunization programs even in regions beset by infrastructure challenges. Remarkably, these systems have relatively low maintenance requirements, a critical factor in resource-limited settings, where technical expertise and resources for maintenance may be scarce(10). This reduced maintenance need makes solar refrigeration systems practical and sustainable for extended use, minimizing disruptions in vaccine supply(17,21).

The positive impact of solar-powered refrigeration on immunization programs contributes to their long- term sustainability(30). Improved vaccine availability, reduced wastage, and enhanced program efficiency result in better public health outcomes and more effective disease control. Moreover, these systems empower local communities and healthcare facilities by providing a reliable and sustainable solution for vaccine storage. This reduced dependency on external energy sources aligns with sustainability principles, fostering self-reliance and capacity-building at the community level.

From an environmental standpoint, solar-powered refrigeration decreases reliance on fossil fuels, promoting sustainability by lowering greenhouse gas emissions associated with electricity generation. It supports global efforts to mitigate climate change and aligns with environmental stewardship goals. Lastly, the potential for scalability and expansion underscores the long-term sustainability of these systems(19). By extending the adoption of sustainable energy solutions, countries can enhance the resilience and effectiveness of their healthcare infrastructure over time, aligning with broader sustainability objectives in healthcare and beyond.

CONCLUSION

In conclusion, this study highlights the critical importance of immunization programs in safeguarding populations against vaccine-preventable diseases. The Expanded Program on Immunization (EPI) and India's Universal Immunization Programme (UIP) have made significant strides in reaching millions of individuals, but their success relies heavily on a well-coordinated cold chain system. Traditional cold storage methods face limitations in resource-constrained settings, where electricity shortages and power outages are common. To address these challenges, solar-powered refrigeration systems have emerged as a promising solution. Solar energy, harnessed through solar refrigeration, offers a sustainable and reliable power source for vaccine storage, particularly in regions abundant in sunlight resources. The study highlights the successful implementation of solar-powered vaccine cold chain systems in India, aligning with various Sustainable Development Goals (SDGs) set by the United Nations. These systems enhance healthcare access, promote clean energy, foster innovation, mitigate climate change, and encourage partnerships. Key findings of the study emphasize the need for proper vaccine management, innovation in vaccine production and supply chain management, equitable vaccine access and global collaboration, investments in solar refrigeration technology and maintenance, robust data management systems for monitoring and decision-making, tailored distribution strategies considering the local context, effective policies and governance for equitable vaccine access, and energy efficiency and sustainability in healthcare.

From a sustainability perspective, the integration of solar-powered solutions not only improves healthcare services but also aligns with SDGs, addressing health, clean energy, industry and infrastructure, climate action, and partnerships. Policymakers should recognize the potential of solar refrigeration systems and invest in their implementation, ultimately contributing to healthier and more sustainable communities.

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