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RESEARCH

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Sustainability practices and their impact on child immunisation vaccine supply chain performance in India using structural equation modelling

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Abstract

This study examines sustainable practices in the child immunisation vaccine supply chain (VSC) in Uttar Pradesh, India, to support the UN's Sustainable Development Goals (SDGs). This analysis examines the impact of social, economic, and environmental sustainability practices on the VSC's efficacy and efficiency, as well as their contribution to achieving SDG goals, including improved healthcare access and enhanced community resilience. This study employs Structural Equation Modelling (SEM) to analyse the relationships between sustainability practices and vaccine supply chain performance. Data were collected through a structured survey from different stakeholders, including healthcare workers, supply chain managers, and policymakers involved in vaccine distribution, storage, and delivery. A total of 180 valid responses were analysed to assess the direct and indirect effects of sustainability practices on the VSC. The findings highlight the interrelated nature of sustainability factors across the VSC. Social sustainability emerged as the most influential component (path coefficient: 0.868), emphasising the importance of fair labour practices, community well-being, and ethical leadership. Economic sustainability had a moderate-to-high impact (0.666), highlighting the importance of profit optimisation and cost reduction. Meanwhile, environmental sustainability had a smaller effect (0.542), indicating that, while important, it must be supported by social and economic policies for maximum benefit. The study emphasises the value of external collaboration and integrated sustainable practices in building the VSC. The research provides evidence for developing targeted interventions and policies that improve vaccine supply chain sustainability, supporting broader healthcare goals and sustainable development. Unlike previous research, which has mostly focused on logistical issues in vaccine delivery, this study incorporates sustainability factors into the examination of vaccine supply chains. This study provides policymakers, healthcare professionals, and stakeholders with valuable guidance for developing sustainable immunisation strategies in Uttar Pradesh and other similar regions



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worldwide, offering a comprehensive framework that connects sustainability practices to improved healthcare outcomes.

Keywords Sustainability, Vaccine supply chain, SEM-PLS, SDGs

1 Introduction

Immunisation of children is essential to public health, as it protects the prospects and overall welfare of societies worldwide. Vaccinating children is not just a question of health; it is also essential to sustainable development. Mapping sustainability practices within the child immunisation vaccine supply chain becomes crucial in the Indian state of Uttar Pradesh, where ongoing issues with healthcare infrastructure and access persist. Uttar Pradesh (UP) in India faces two primary challenges: a sizable population and complex socioeconomic dynamics that complicate the delivery of immunisation. The most populous state in India, UP, has serious infrastructure and socioeconomic problems that affect the provision of healthcare, including vaccinations [53]. Research reveals obstacles, including insufficient cold chain facilities, vaccine shortages, and low vaccination rates, particularly in remote and marginalised areas [7, 30]. Uttar Pradesh, one of India's most populous states, has a significant amount of work to do to ensure that immunisation services are accessible to all [93]. Factors such as sociocultural barriers, infrastructure limitations, and geographic disparities often hinder the efficient distribution and use of vaccines [33, 42]. These constraints jeopardise public health while also impeding progress towards broader sustainable development goals (SDGs). Child immunisation coverage in UP remains low due to fragmented VSC, socioeconomic inequities, and infrastructure gaps. Existing research focuses mostly on logistics, but fails to include the integration of social, economic, and environmental sustainability factors, which are critical for long-term effectiveness and alignment with the UN SDGs [53, 58, 81]. This creates a major gap and prevents the underprivileged section from accessing life-saving vaccines. This gap is critical because inefficient VSC practices not only hinder universal immunisation coverage but also retard progress toward several SDGs, particularly SDG 3 (Good Health and well-being), SDG 9 (Industry, Innovation and Infrastructure), SDG 10 (Reduced Inequalities), SDG 12 (Responsible Consumption and Production), SDG 16 (Peace, Justice and Strong Institutions), and SDG 17 (Partnerships for the Goals) [26]. Efforts to strengthen vaccination supply networks that do not incorporate sustainability principles risk becoming short-term, donor-dependent, and mismatched with larger development plans. There is consequently an urgent need to build a holistic and evidence-based approach to assess how different sustainability characteristics influence VSC performance and, as a result, contribute to child immunisation results and SDG achievement. Addressing this gap requires a thorough understanding of how sustainability practices impact VSC performance, enabling the development of robust, equitable, and sustainable immunisation policies for Uttar Pradesh. This study investigates the sustainability of the vaccine supply chain for child immunisation programmes in Uttar Pradesh, focusing on how its components (logistics, cold chain, workforce, financing, and monitoring) align with environmental, economic, and social sustainability dimensions. A comprehensive framework for addressing LMIC issues such as health, education, gender equality, poverty alleviation, and environmental sustainability is offered by the SDGs of the United Nations [61]. The SDGs established by the United Nations offer a

comprehensive framework for tackling global issues such as disparities in healthcare and environmental sustainability. A systematic approach to resolving these concerns is linking sustainable VSC practices to particular SDGs. As an illustration, Goal 12 (Responsible Consumption and Production) emphasises the importance of efficient resource utilisation in vaccine manufacturing and distribution. In contrast, Goal 3 (Good Health and well-being) stresses the significance of guaranteeing universal access to vaccines, Goal 9 (industry, innovation, and infrastructure), Goal 10 (Reduced inequalities), Goal 16 (Peace, justice, and strong institutions), and Goal 17 (Partnerships for the goals) (The 2030 Agenda for Sustainable Development's 17 Sustainable Development Goals 2023.).

In this context, aligning child immunisation VSC practices with the United Nations SDGs offers a comprehensive framework for addressing these challenges. Considering environmental, social, and economic sustainability in the supply chain for childhood vaccinations is necessary when mapping out sustainable practices [1, 37]. This entails developing local capacity building for sustainable healthcare delivery, ensuring fair access to vaccines for underserved communities [73], and streamlining transportation routes to minimise carbon emissions. This study aims to address these issues by investigating how sustainable practices within the child immunisation VSC can be aligned with the United Nations SDGs, using structural equation modelling (SEM) to identify key correlations and interventions that improve both health outcomes and sustainable development in Uttar Pradesh. The present research employs SEM to investigate the interrelationships among various components of the VSC and their role in accomplishing sustainable development objectives. This study aims to clarify the complex effects of immunisation programmes that extend beyond their direct health consequences by examining the vaccine supply framework within its broader context. Structural equation modelling is a powerful analytical tool for assessing the complex interactions between various variables in the vaccine supply chain and their effects on sustainable development indicators [52]. By quantifying these relationships and identifying leverage points for intervention, policymakers can maximise the impact of immunisation programmes and allocate resources efficiently [33]. In addition to contributing to existing knowledge on public health and development, this study provides valuable insights for healthcare practitioners and policymakers involved in the creation and implementation of immunisation initiatives. This research aims to support evidence-based decision-making and cross-sector collaboration in achieving a healthier and more equitable future by elucidating the relationship between vaccine supply chains, childhood immunisation, and the Sustainable Development Goals. This paper aims to answer the following research questions:

- RQ1: What key social, economic, and environmental sustainability practices are currently integrated into the child immunisation vaccine supply chain in Uttar Pradesh, and how do they align with relevant SDGs?
- RQ2: How do these sustainability practices directly and indirectly influence the operational performance and effectiveness of the vaccine supply chain in Uttar Pradesh?
- RQ3: How can the identified sustainability–performance linkages guide evidence-based policy and programmatic interventions to strengthen the child immunisation vaccine supply chain and advance progress towards the SDGs?

Based on the above research questions, this study aims to achieve the following research objectives:

Research Objectives

- RO1: To identify the sustainable development practices currently embedded within the child immunisation vaccine supply framework in Uttar Pradesh.
- RO2: To analyse the direct and indirect sustainability practices through which child immunisation programmes contribute to broader sustainable development outcomes in Uttar Pradesh.
- RO3: To examine the interrelationships between key components of the vaccine supply chain and sustainable development indicators, assessing their impact on supply chain efficiency and immunisation outcomes.
- RO4: To provide evidence-based insights for policymakers and healthcare stakeholders to design targeted interventions and policy frameworks that enhance the sustainability and effectiveness of the child immunisation vaccine supply chain in Uttar Pradesh, aligning with the UN Sustainable Development Goals (SDGs).

This study is based on the Triple Bottom Line (TBL) framework, which emphasises social, economic, and environmental sustainability, and Systems Theory, which sees the VSC as an interconnected system in which changes in one component affect overall performance. These frameworks drove the study's design by categorising variables into sustainability dimensions and utilising Structural Equation Modelling (SEM) to examine their systemic interrelationships and effects on VSC efficiency and effectiveness. This paradigm is consistent with and contributes to six UN Sustainable Development Goals (SDGs):

- SDG 3 (Good Health and well-being): Improve equitable immunisation coverage;
- SDG 9 (Industry, Innovation, and Infrastructure): enhance cold chain systems and logistics;
- SDG 10 (Reduced Inequalities): Reaching marginalised and isolated groups;
- SDG 12 (Responsible Consumption and Production): Ensure efficient resource usage and reduce waste.
- SDG 16 (Peace, Justice, and Strong Institutions): improve governance and transparency.
- SDG 17 (Partnerships for the Goals) encourages cross-sector engagement.

This study presents an integrated framework for guiding policy and practice in sustainable child immunisation in Uttar Pradesh, connecting sustainability practices to supply chain performance and SDG outcomes as shown in Fig. 1.

The subsequent sections of this work include a literature review, Conceptual Framework and Hypothesis Development, Research Methods, and an exposition of the results and analysis. The discussion portion will connect the findings to the overarching goals of sustainable development, and the paper finishes with recommendations for policy and practice designed to enhance immunisation programmes and facilitate the attainment of SDGs in Uttar Pradesh.

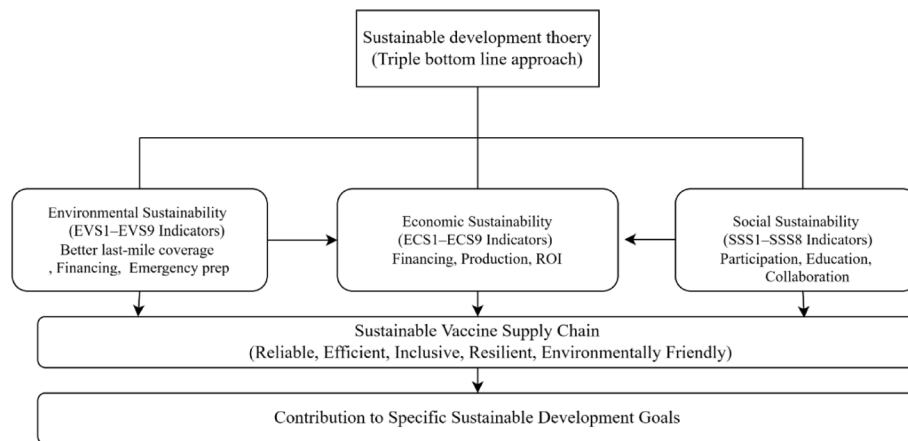


Fig. 1 The theoretical or conceptual framework guiding this study

2 Literature review

A key component of public health, childhood vaccinations lower morbidity and mortality from diseases that vaccines can prevent. However, ensuring that everyone has access to vaccines is challenging, especially in areas with limited resources, such as Uttar Pradesh, India. This literature review looks at the research that has already been done on mapping the SDGs of the United Nations to the supply chain for child vaccines in Uttar Pradesh. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique was employed to identify and evaluate key indicators influencing the sustainability of child immunisation VSC across three dimensions, with a focus on Uttar Pradesh's outreach regions. A systematic literature review was conducted using the PRISMA technique, as shown in Fig. 2, to identify the factors contributing to a sustainable child immunisation VSC within these dimensions. This approach enabled a comprehensive and unbiased evaluation of existing research, supporting the selection of factors most pertinent to the study area. A comprehensive and relevant evidence base was ensured by selecting the literature using databases such as Scopus, Web of Science, and Google Scholar. The search focused on studies published between 2015 and 2025, using keywords including “vaccine supply chain,” “sustainability,” “child immunisation,” and “Uttar Pradesh/India.” Only peer-reviewed journal articles, conference papers, and policy reports were included. Studies were screened based on relevance to vaccine supply chain sustainability, clarity of methodology, and empirical or conceptual contribution. Duplicates, non-English publications, and studies lacking methodological rigour were excluded. This structured approach ensured that only high-quality and contextually relevant literature informed the study.

2.1 Sustainability in vaccine supply chains

The significance of sustainable practices in the vaccine supply chain is emphasised by both [28, 119]. Yadav's LAG framework and Carvalho's MO-MILP model provide specific tools for achieving this. The relationship between internal procedures, as described by [75], emphasises the importance of taking a comprehensive approach. To meet the increasing demand for vaccines, [91] emphasise the importance of sustainable vaccine development and highlight the necessity of low-middle income nation (LMIC) cooperation as well as cutting-edge technologies. Vaccines present unique supply chain design

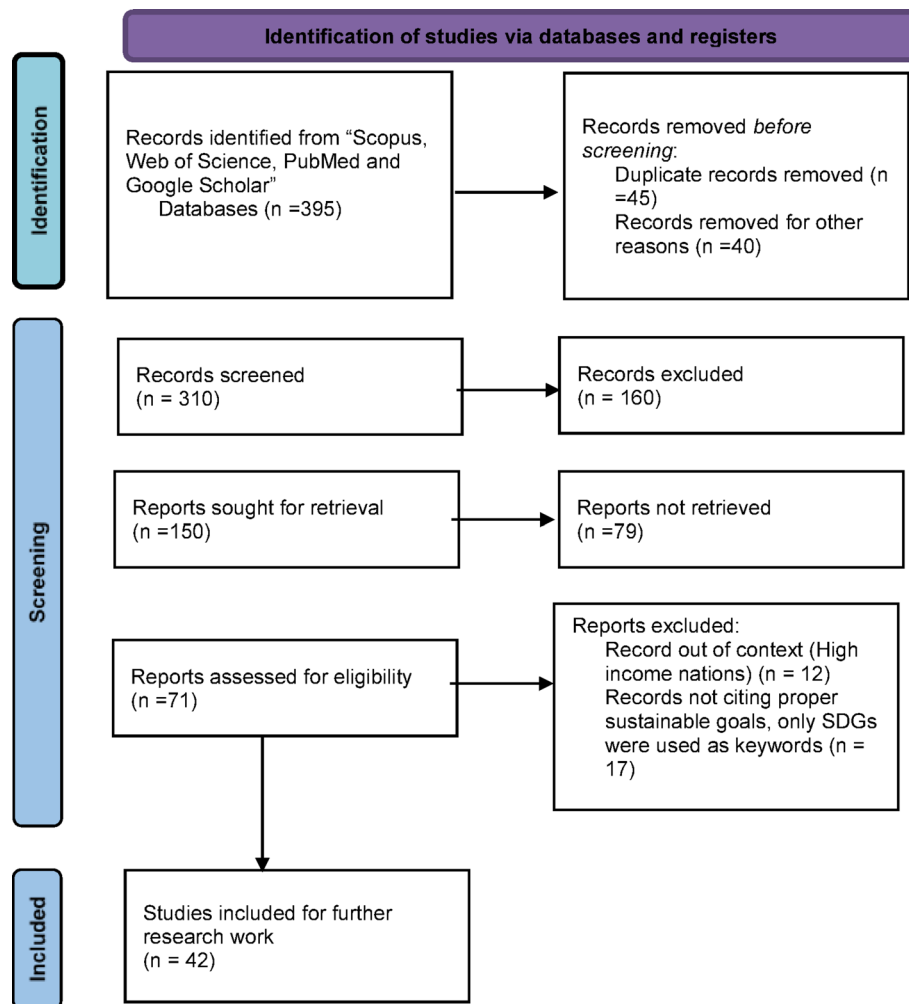


Fig. 2 PRISMA technique to find relevant literature

challenges that can be addressed by choices made at various levels of the supply chain. The network of the vaccine supply chain in the future must be sustainable and take stakeholders' preferences for KPIs into account [62]. Several studies recommend incorporating sustainable practices into the supply chain for vaccines. For example, lowering carbon emissions and increasing vaccine distribution and storage efficiency can be achieved by implementing cutting-edge technologies like solar-powered refrigeration and cold chain logistics optimisation [78]. Initiatives aimed at increasing community engagement and capacity can also enhance vaccination acceptance and uptake, supporting the SDGs for health and well-being [92]. Together, these studies highlight the significance of sustainability in the VSC and offer insightful advice on how to put it into practice. To establish a comprehensive framework for sustainable practices in the child immunisation VSC in Uttar Pradesh, we can define forty indicators through an extensive literature survey, field visits, and semi-structured interviews under three key dimensions: Environmental, Economic, and social dimensions. A panel of eight experts was purposively selected based on their extensive experience in vaccine supply chain management, immunisation programmes, public health logistics, and cold-chain operations. The panel included officials from the Government Health Department, cold-chain

managers responsible for vaccine storage and distribution, and professionals with expertise in healthcare supply chain management. All experts had at least five years of relevant professional experience and direct involvement in immunisation or vaccine logistics activities. The experts evaluated the initial set of 40 indicators for relevance, clarity, and applicability to the child immunisation vaccine supply chain in Uttar Pradesh. Based on their evaluations, indicators that did not meet the minimum content validity requirements were removed or revised. The final Content Validity Index (CVI) achieved was 0.75, which is considered acceptable for retaining indicators for subsequent analysis. As a result, 32 indicators were finalised and used in the study. These indicators listed in Table 1 help in monitoring and enhancing the sustainability of the supply chain.

2.2 Application of SEM in public health research

Lemmens et al., [62] and Trump et al., [113] both highlight the need for a sustainable and resilient vaccine supply chain, with Lemmens emphasising the unique challenges of vaccine distribution and Trump advocating for the application of resilience analytics. Mukherjee et al., [76] further explores the factors impacting the COVID-19 vaccine supply chain, using structural equation modelling to identify key variables. Andiç-Mortan and Gonul Kochan, [10] proposed a closed-loop vaccine supply chain model to minimise wastage and threats, integrating disease transmission and supply chain dynamics. While Thirupathi and Vinodh [110] found a structural relationship between economic prosperity, environmental well-being, social well-being, performance management, and research and development in the Indian automotive component sector. In Tamil Nadu, India, Vinodh and Joy, [110, 116] also verified a relationship between organisational performance and sustainable manufacturing techniques. Together, studies such as Algarni et al., [9] demonstrated how SEM can be used to comprehend and advance sustainable practices across a range of industries. These studies collectively underscore the importance of a robust and adaptable vaccine supply chain, and the potential of structural equation modelling in understanding and optimising its performance.

2.3 Gaps in current research

Although the body of literature as shown in Tables 1 and 2 has significantly advanced our understanding of sustainability in VSC, several substantial study gaps remain [50, 98]. A thorough framework outlining the integration of sustainable practices at every stage of the vaccine supply chain, from production to distribution and administration, needs to be developed. Existing studies often focus on specific aspects of sustainability, such as supply chain efficiency or environmental impact, without providing a comprehensive view [63, 118]. Comprehensive quantitative assessments are lacking, despite some studies discussing the environmental impact of vaccine supply chains qualitatively [44, 72]. To measure the energy use, carbon footprint, and other environmental indicators associated with various vaccine distribution strategies and technologies, research is necessary. Although it is widely acknowledged that stakeholder collaboration is crucial to advancing sustainability in vaccine supply chains, empirical studies examining the dynamics of multi-stakeholder partnerships are scarce. To achieve sustainability goals, researchers should examine the roles, responsibilities, and challenges faced by various stakeholders, including governmental bodies, non-profit organisations, and businesses in the private sector. In addition to immediate economic and environmental gains, VSC should be

Table 1 Various dimensions with validated indicators used in this study

Dimension	Objectives	Indicator number	Indicator description	Source
Environmental sustainability	Better last-mile coverage results Refrigeration of vaccines Better prepared for emergency Factors	EVS1	Cold Chain Carbon Footprint: Greenhouse gas emissions from the cold chain.	(Grandsir et al., [41]; [45])
		EVS2	Renewable Energy Usage: Use of renewable energy in storage and transport.	Hren et al., [48], Wang, [118]
		EVS3	Waste Management Efficiency: Rate of recycling and disposal of vaccine waste.	Barai and Bhanvase, [16], Maleki, [69]
		EVS4	Packaging Sustainability: Use of eco-friendly materials for packaging.	Özkan Karabacak et al., [86], Rahman, [90]
		EVS5	Water Usage Efficiency: Water consumption in vaccine production.	Abbasi et al., [2], Sinnei, [105]
		EVS6	Chemical Management: Handling and disposal of chemicals in vaccine production.	Singh et al., [104]
		EVS7	Emission Controls in Transportation: Use of low-emission transportation methods.	Gessner et al., [37]
		EVS8	Energy Efficient Storage Facilities: Adoption of energy-saving storage technologies.	Chung and Kwon, [24], Coyne, [25]
		EVS9	Biodiversity Impact: Effect on local biodiversity due to production and distribution.	Sanyé-Mengual et al., [99]
Economic sustainability	Financing and Funding Production Return on Investment	ECS1	Cost-Effectiveness: Overall cost efficiency of the supply chain.	Bialas et al., [22]
		ECS2	Supply Chain Resilience: Adaptability to disruptions without major cost impacts.	Zhao et al., [122]
		ECS3	Local Sourcing Index: Extent of using local materials and services.	Luo et al., [68], Yigitcanlar, [120]
		ECS4	Investment in Sustainable Technologies: Funding for sustainable innovations.	Bai and Lin, [14]
		ECS5	Inventory Management Efficiency: Effective vaccine stock management.	Nahofti Kohnneh et al., [80], Shibabaw, [103]
		ECS6	Market Dependency: Reliance on external markets for supply.	Pulles et al., [89]
		ECS7	ROI for Sustainability Initiatives: Economic benefits from sustainable practices.	Niyommaneerat et al., [84]
		ECS8	Funding Diversification: Variety in funding sources for stability.	Ben Lahouel et al., [18]
		ECS9	Economic Impact on Local Communities: Influence on local economies.	Jehan et al., [54]

Table 1 (continued)

Dimension	Objectives	Indicator number	Indicator description	Source
Social sustainability	Participation& Collaboration Education	SSS1	Immunisation Coverage Rate: Rate of scheduled immunisations.	Newcomer et al., [83]
		SSS2	Healthcare Worker Training and Support: Training quality for healthcare workers.	Bhatti et al., [21]
		SSS3	Community Engagement and Education: Efforts to involve and educate communities.	Babaei et al., [13]
		SSS4	Equitable Vaccine Distribution: Fair distribution across regions and communities.	Babaei et al., [13]
		SSS5	Cultural Sensitivity in Vaccine Delivery: Respect for local cultural practices.	Dickson et al., [31]
		SSS6	Impact on Local Employment: Job creation in the vaccine supply chain.	Kochakkashani et al., [56], Zaoui, [121]
		SSS7	Public Health Outcome Improvement: Improvements in public health from immunisation.	Lubanga et al., [67], Mouteyica, [74]
		SSS8	Feedback Mechanism Effectiveness: Efficiency of feedback systems for improvement.	Dawson et al., [27]
Sustainable supply chain management	Reliable and Sustainable vaccine supply chain	SDG 3	Good Health and Well-being	(The 2030
		SDG 9	Industry, Innovation, and Infrastructure	Agenda for
		SDG 10	Reduced Inequalities	Sustainable
		SDG 12	Responsible Consumption and Production	Development's
		SDG 16	Peace, Justice, and Strong Institutions	17 Sustainable
		SDG 17	Partnerships for the Goals	Development Goals (SDGs), 2020)

resilient and consider long-term effects. To evaluate an intervention's long-term viability, specifically its ability to adapt to changing environmental conditions, technological advancements, and socioeconomic contexts, research is necessary. Ultimately, addressing these research gaps will enhance our understanding of how sustainable practices can be effectively integrated into vaccine supply chains, ultimately improving Indian health outcomes, environmental stewardship, and equitable access to vaccines (Table 2).

3 Conceptual framework and hypothesis development

A theoretical structure or model known as a conceptual framework serves as a basis for comprehending a specific phenomenon, issue, or field of study. It describes the fundamental ideas, precepts, and theories that direct investigation or analysis in a particular field. This academic research helped us organise our thoughts, define key indicators that contribute to sustainable practices, under various perspectives, and develop hypotheses or propositions. It provides a roadmap for understanding the relationships between different UN SDGs and sustainable practices, therefore helping to ensure that research findings are logically grounded and theoretically sound. Figure 3 shows the diagram of the conceptual framework used in this research paper. Based on the conceptual framework, this research seeks to investigate the connections between sustainable practices and the UN Sustainable Development Goals, and how these relate to the VSC.

The following set of hypotheses is proposed in this research:

H1: Social Sustainable Practices will positively impact the Sustainable vaccine supply chain.

Table 2 Summary of literature review to identify research gap

S.NO	Author	Findings	Research gap
1	Jahed et al., [51]	Sustainable vaccine supply chain optimisation considering cost, emissions, and jobs	No empirical validation using stakeholder data; limited social sustainability indicators
2	Torshizi et al., [111]	Resilient and sustainable COVID-19 vaccine supply chain with reverse logistics	Focused on optimisation rather than stakeholder perceptions
3	Rekabi et al., [94]	Sustainable-resilient vaccine supply chain network design	Lacks SDG integration and empirical sustainability assessment
4	Lawrence, [60]	Vaccine supply chain resilience analytics framework	Mostly conceptual and qualitative
5	Nagariya et al., [79]	Sustainability assessment in healthcare supply chains	Limited vaccine-specific sustainability metrics
6	Gupta et al., [43]	Sustainable healthcare logistics evaluation	No integrated SEM-based sustainability model
7	Vaishnavi and Suresh, [115]	Environmental sustainability in healthcare distribution	Social and economic dimensions overlooked
8	Gomes et al., [39]	Vaccine distribution efficiency analysis	Sustainability dimensions not jointly evaluated
9	Bhatt et al., [20]	Cold-chain optimisation for vaccines	Environmental and social outcomes not assessed
10	Paul et al., [88]	Environmental impacts of healthcare logistics	Lack of quantitative sustainability modelling
11	Shah et al., [101]	Carbon footprint assessment in vaccine logistics	No stakeholder collaboration analysis
12	Arifoğlu et al., [12]	Sustainable distribution under uncertainty	Developing-country empirical evidence lacking
13	Al Theeb et al., [8]	Multi-objective vaccine supply network design	Limited focus on SDGs
14	Loehr, [65]	Sustainable vaccine delivery modelling	No behavioural or social dimension analysis
15	Baryannis et al., [17]	Vaccine supply chain risk identification and control strategies	Sustainability outcomes not investigated
16	Salmeró & Apte, [97]	Industry-based resilience assessment	Quantitative sustainability framework absent
17	Decouttere et al., [29]	Sustainable supply chain governance review	Healthcare and vaccine sectors underexplored
18	Abdul-Rahman et al., [4]	Vaccine equity and public health outcomes	Supply chain sustainability dimensions not integrated
19	Sudusinghe and Seuring, [107]	Social sustainability in healthcare delivery	Economic and environmental interactions ignored
20	Robertson et al., [95]	Vaccine supply chain sustainability review	Lack of empirical testing
21	Nogueira et al., [85]	Triple Bottom Line applications in healthcare	Vaccine-specific evidence limited
22	Zhou, [123]	Resource-based sustainability capabilities	No SEM validation
23	Anilkumar et al., [11]	Sustainable healthcare operations	Stakeholder collaboration insufficiently analysed
24	Eksioglu et al., [32]	Vaccine supply chain network design	Focuses on logistics efficiency only
25	Koyuncu et al., [57]	Sampling approaches in healthcare studies	Does not address sustainability integration
26	Fisher et al., [34]	Reliability and construct validation	Not vaccine supply-chain focused
27	Uribe-Sánchez et al., [114]	Predictive power assessment	Sustainability constructs not examined
28	Hubley, [49]	Discriminant validity framework	Methodological contribution only
29	Settanni et al., [100]	Advanced SEM procedures	Does not address vaccine sustainability applications
30	Beta et al., [19]	AI-enabled pharmaceutical supply chain resilience	Sustainability-performance relationships remain underexplored

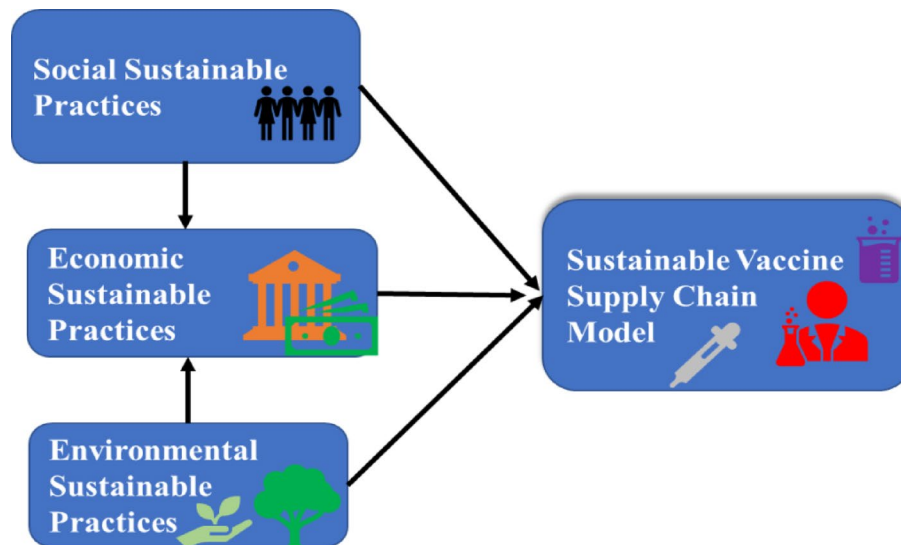


Fig. 3 Conceptual framework for sustainable vaccine supply chain model

Studies show that socially responsible behaviours can positively affect the supply chain for vaccines. de Carvalho et al., [28] emphasise the need for a multi-objective approach and stress the importance of considering social concerns when designing and planning sustainable vaccine supply chains. This is further corroborated by ([77]; who demonstrate the relationship between internal procedures and organisational learning and social sustainability in the COVID-19 vaccine supply chain. The larger advantages of vaccination are emphasised by both [92] and [59]. These advantages include the role of vaccination in sustainable healthcare systems and the necessity of a sustainable business model for vaccine development. All of these studies suggest that incorporating socially sustainable practices into the vaccine supply chain could enhance its overall sustainability and efficacy.

H2: Social Sustainable Practices will positively impact Economic Sustainable practices.

A positive correlation exists between social and economic sustainability practices, according to several studies. Social sustainability practices, particularly those focused on human factors, have been demonstrated to enhance the economic performance of small businesses and the apparel supply chain [71, 107]. According to (Navarro [82], financial institutions that demonstrate robust social responsibility practices tend to exhibit superior economic performance. (Haddach et al., [46] subsequently emphasised the importance of integrating environmental, social, and lean practices to improve overall firm performance. All of these results suggest that socially and economically sustainable practices can mutually benefit one another.

H3: Environmentally Sustainable Practices will positively impact economically sustainable practices.

Studies consistently demonstrate the beneficial relationship between ecologically and economically sustainable practices. Businesses that adopt environmentally friendly practices tend to have fewer financial constraints, according to ([15], particularly in highly competitive and emission-intensive industries. This was corroborated by [38], who showed that environmentally friendly supply chain practices improve company

performance. Last but not least, (Rusinko [96]) emphasised the possible benefits of environmentally friendly manufacturing techniques for competitiveness. The combined findings of these studies suggest that environmentally friendly actions can contribute to economic sustainability.

H4: Economically Sustainable Practices will have a positive impact on the Sustainable vaccine supply chain.

According to research from the literature, the sustainable supply chain for vaccines can benefit from economically sound practices. The necessity of a multi-objective approach that considers social, environmental, and economic factors in planning and designing the vaccine supply chain is emphasised by [28]. This is further supported by Loehr [65] who emphasises the significance of vaccine administration procedures that are financially sound. While Rappuoli and Hanon [92] emphasise the necessity of a sustainable business model in vaccine development, ([64] highlight the role that energy efficiency plays in lowering distribution costs. All of these studies suggest that the efficacy and efficiency of the vaccine supply chain can be improved through the use of economically viable methods.

H5: Environmentally Sustainable Practices will positively impact the Sustainable vaccine supply chain.

It has been demonstrated that the introduction of ecologically friendly procedures into the vaccination supply chain improves the chain's overall sustainability. Yadav and Kumar, [119] highlighted the significance of improving cold chain technology, coordinating supply chain stakeholders, and using sustainable packaging. de Carvalho et al., [28] provided additional support for this by presenting a multi-objective and multi-period mixed-integer linear programming (MO-MILP) model that considers social, environmental, and economic factors in designing and planning a sustainable vaccine supply chain. Both [64, 65] emphasise how energy-efficient and environmentally friendly distribution systems can cut expenses and their negative effects on the environment. Together, these studies underscore the potential of environmentally friendly methods to enhance the sustainability of the vaccine supply chain.

4 Research method

Studies have shown that PLS-SEM has benefits in certain circumstances, particularly when combined with SMART PLS. Goodhue et al., [40] and Afthanorhan et al. [6] discovered that while PLS-SEM is less accurate than LISREL, it is still as effective as other methods at detecting paths. It is more resilient, though, to mild deviations from normalcy. Afthanorhan and Afthanorhan, [6] provided additional support for PLS-SEM use, arguing that it is a more valid and reliable method for confirmatory factor analysis. For smaller sample sizes, Sharma and Kim, [102] suggested PLS-based bootstrapping, and Hair et al., [47] emphasised the value of AMOS CB-SEM for intricate relationships between several constructs. Using SmartPLS 4, researchers can apply SEM, a sophisticated statistical technique that lets them examine intricate relationships between variables inside a theoretical framework.

This work employed SmartPLS 4 as the principal instrument for SEM owing to its notable advantages compared to other SEM tools, such as AMOS, which is especially

relevant to our research environment. SmartPLS 4 is particularly adept at managing intricate models with multiple indicators and constructs, aligning with our study's objective to examine the interrelations among social, economic, and environmental sustainability practices within the VSC. A primary rationale for using SmartPLS is its superior capacity to manage smaller sample sizes compared to covariance-based SEM tools, such as AMOS [3]. Due to the difficulties in collecting extensive data from stakeholders in Uttar Pradesh, where obtaining trustworthy information is problematic, SmartPLS provides enhanced resilience in yielding significant results from smaller datasets [70]. Furthermore, SmartPLS 4 demonstrates superior capability in managing non-normal data distributions, a prevalent challenge in real-world datasets such as ours, which encompass diverse data from many sectors, including healthcare practitioners, vaccine suppliers, and policy administrators [23, 98]. Our capacity significantly enhances our research by providing increased flexibility and precision in predicting path models, rendering it a more suitable option than AMOS. A significant feature of SmartPLS is its foundation in the partial least squares (PLS) algorithm, which prioritises the maximisation of explained variance in dependent variables, an essential factor for investigating intricate correlations, such as those between sustainability practices and SDG outcomes. This enables us to identify leverage points in the vaccination supply chain where sustainable practices can exert the most significant influence. Utilising SmartPLS 4, we can implement bootstrapping techniques to evaluate the stability and relevance of the predicted pathways, hence enhancing the trustworthiness of our results [106]. This feature is essential for assessing our model's complex and multifaceted relationships. Ultimately, the selection of SmartPLS 4 over AMOS was influenced by its adaptability to smaller and non-normally distributed datasets, its efficacy in estimating complex models, and its capacity to address the specific requirements of our research on the sustainability of the vaccine supply chain in Uttar Pradesh.

4.1 Development of research instrument

The development of the questionnaire was a multi-step process that involved careful selection of constructs and items based on both theoretical grounding and practical relevance to the child immunisation VSC in Uttar Pradesh. The constructs and items were drawn from existing literature on sustainability practices in supply chains, healthcare delivery, and SDGs. The first step was an extensive review of existing validated instruments from previous studies focused on sustainability and supply chain practices in healthcare. This helped identify relevant constructs and items that had been previously tested in similar contexts. A comprehensive literature review and field visit were conducted to identify items and constructs validated in previous studies related to sustainable supply chain management, healthcare logistics, and immunisation programmes, particularly existing frameworks in sustainable supply chain management (SCM), as well as studies focusing on sustainability in healthcare or public health delivery. Vaccination-specific supply chain literature to ensure that our constructs align with real-world challenges. Using insights from the literature, constructs, and items relevant to the local context aligned with the objectives of child immunisation and sustainability in Uttar Pradesh. Both direct impacts (e.g., equitable vaccine distribution) and indirect impacts (e.g., reduced healthcare disparities) were categorised under different dimensions. Once the items are developed, validating them before they are used in a full-scale survey is

crucial. This was done through expert validation in which experts from public health, vaccine supply chain management, and sustainability were consulted to ensure that our items and constructs were appropriate and comprehensive. Their feedback ensured the relevance of the constructs to the local context and helped refine the wording of the items. To strengthen our validation, a pilot test was conducted with a small sample of 30 respondents, including stakeholders involved in vaccine distribution, storage, and delivery. This sample represented a cross-section of the target population, ensuring a mix of insights from different segments (e.g., healthcare workers, logistics personnel, and policy officers). The pilot test aimed to assess the clarity and relevance of the items to the respondents. To evaluate the reliability and internal consistency of the constructs using Cronbach's alpha, we set a threshold of 0.70 for acceptable internal consistency, a standard measure for ensuring that items within a construct are reliably correlated [112]. Based on the pilot test results, some items were reworded for clarity, and two items were removed due to low factor loadings in the pilot test analysis. Additionally, feedback from respondents led to minor adjustments in the wording of questions related to technical terms, ensuring that they were easily understood across various stakeholder groups. The final questionnaire consisted of 32 items, distributed across the three main constructs: social, economic, and environmental sustainability practices. Each item was framed to allow respondents to reflect on their experiences and knowledge of the vaccine supply chain, ensuring the data collected was accurate and actionable.

The study presents a questionnaire as shown in Appendix 1, intended to evaluate socially sustainable practices, economically sustainable practices, environmentally sustainable practices, and sustainable vaccine supply chains, four major concepts associated with the vaccine supply chain. The questionnaire items were developed and refined based on the existing literature, yielding a total of 32 items distributed among the four constructs. Respondents were asked to rate each item on a Likert scale with 1 representing strongly disagree and 5 representing strongly agree. The streamlined format for the responses was designed to accommodate the lengthy questionnaire. A pre-test was performed to assess the validity of the questionnaire by gauging the readability, clarity, and accuracy of the response format. The data collected were tested through a pilot study with a small number of participants who were representative of the intended audience. This makes it easier to find any unclear areas, inconsistent wording, or problems with the instrument's construction. Based on comments obtained during the pilot testing stage, modifications were made. Online methods were used for data collection, enabling effective and broad participation. The design of the questionnaire and the format of the responses were specifically designed to gather information about sustainable practices that aid in achieving the United Nations SDGs. This method made evaluating every aspect of the immunisation campaign easier, providing insightful information for future planning and execution tactics.

4.2 Data collection

The data collection process was initiated after the instruments were selected. To get the answers to the questionnaire created during the research instrument design process, data collection techniques included online surveys and in-person interviews. Field visits were conducted to health centres in various districts of Uttar Pradesh, India. To determine the sample size, Cochran's formula [5] was used:

Table 3 Demographic profile of the respondents ($N = 180$)

Demographic profile	Category 1	Category 2	Category 3
Gender	120 (Male)	60 (Female)	0 (Other/Prefer not to say)
Age	70 (18–30 years)	90 (31–50 years)	20 (Above 50 years)
Education	50 (High school or less)	90 (Bachelor's degree)	40 (Advanced degree)
Employment status	80 (Employed)	50 (Unemployed)	50 (Student)
Income level	60 (Low income)	70 (Middle income)	50 (High income)
Location	70 (Urban)	60 (Rural)	50 (Suburban)

$$n_0 = z^2 p(1 - P) / e^2$$

where:

- $Z = 1.96$ (for a 95% confidence level).
- $P = 0.5$ (assumed proportion of stakeholders with relevant knowledge).
- $e = 0.06$ (6% margin of error).

$$n_0 = (1.96)^2 \times 0.5 \times (1 - 0.5) / (0.06)^2 = 267.1$$

Since the target population size (N) is 10,000, the adjusted sample size is calculated using the finite population correction formula:

$$n = 1 + \frac{n_0}{1 + \frac{n_0 - 1}{N}}$$

$$n = 1 + 267.1 / 1 + (267.11 - 1) / 10000 \approx 260$$

Thus, the final sample size is 260 respondents.

The questionnaire was distributed to around 260 participants and explained sustainable practices. After various call-ups and online consultations, 200 responses were obtained. Twenty data points were removed due to missing data or multiple responses, and 180 data points were included in a further study. The demographic profile of 180 respondents is provided in Table 3. The demographic profile of the respondents reveals a diverse composition across several key categories, providing a broad understanding of the participants involved in the study. Gender representation is almost equitable, with 120 males, 60 females, and 0 respondents identifying as “Other” or “Prefer not to disclose.” The bulk of participants, numbering 90, belong to the 31–50 age bracket, followed by 70 in the 18–30 range and 20 over 50, signifying a plurality of middle-aged persons. The majority of respondents held a bachelor's degree (90), while 50 had a high school education or lower, and 40 held advanced degrees, indicating a highly educated group. Of the respondents, 80 are employed, 50 are unemployed, and 50 are students, indicating a robust workforce alongside notable representation of other demographics. The income distribution is balanced, with 70 respondents classified as middle-income, 60 as low-income, and 50 as high-income. Seventy participants are located in metropolitan areas, sixty in rural areas, and fifty in suburban areas, providing a diverse range of perspectives from varied living circumstances. This demographic diversity facilitates a thorough comprehension of the study's results across various societal categories.

5 Data analysis and results

There are two primary stages to the Partial Least Squares Structural Equation Modelling (PLS-SEM) approach: measurement modelling and structural modelling. The relationships between latent constructs and observed variables are determined during the measurement phase. This stage is crucial for understanding the model's multidirectional statistical relationships. PLS-SEM is flexible in handling both formative and reflective measurement styles. The characteristics of endogenous structures and their modifications are represented in the structural model by reflective measures. The predictor parameters are altered to express these measures. Single-headed arrows from latent constructs to indicator variables are used in this context to represent reflective indicators. In PLS-SEM, the coefficients connected to these relationships are known as external loads.

5.1 Descriptive statistics

Table 3 presents the demographic profile of the respondents who completed the questionnaire used in the survey. Field visits were conducted in four districts of Uttar Pradesh. Apart from these districts, the study also included one regional vaccine store, three state vaccine stores, and four government hospitals to collect data. At the initial stage of the study, thirty-two indicators were discussed with eight experts of VSC in the state to validate the questionnaire based on their reliability and validity. The credibility and efficacy of a questionnaire in precisely measuring the intended constructs depend on its ability to demonstrate both content validity and reliability. The questionnaire exhibited excellent reliability with a Cronbach's alpha coefficient of 0.90, indicating high internal consistency among its items. The experts confirmed that all items were relevant and representative of various dimensions of satisfaction, resulting in a content validity index of 0.75, indicating strong content validity. The questionnaire was distributed to around 260 participants and explained sustainable practices. After various call-ups and online consultations, 200 responses were obtained. Twenty data points were removed due to missing data or multiple responses, and 180 data points were included in a further study.

5.2 Assessment of the measurement PLS-SEM model

The research presents extensive results using a two-way assessment framework that incorporates both a structural and measurement model within partial least squares structural equation modelling (PLS-SEM). Reflective indicators are carefully assessed for accuracy and applicability because they show a strong correlation and relationship among themselves. The proposed conceptual model comprises four multidimensional latent variables, as illustrated in Fig. 4, indicating that several observed variables (indicators) are required to capture the impacts associated with them. The study employs a total of 32 indicators, as outlined in Table 4, which presents the loading factors for these indicators. The methodology emphasises the advantages of PLS-SEM, such as its lower sensitivity to sample size and the lack of stringent data normalisation requirements, by highlighting various facts of multivariate analysis measurement and validation. Multicollinearity results confirm the normality of the indicators and the absence of multicollinearity (VIF). For example, in our case, if a VIF value of 2.497 is reported for ECS5, this falls well within the acceptable range (between 1 and 5). This value suggests a moderate correlation between the predictor variables, but not enough to raise concerns about

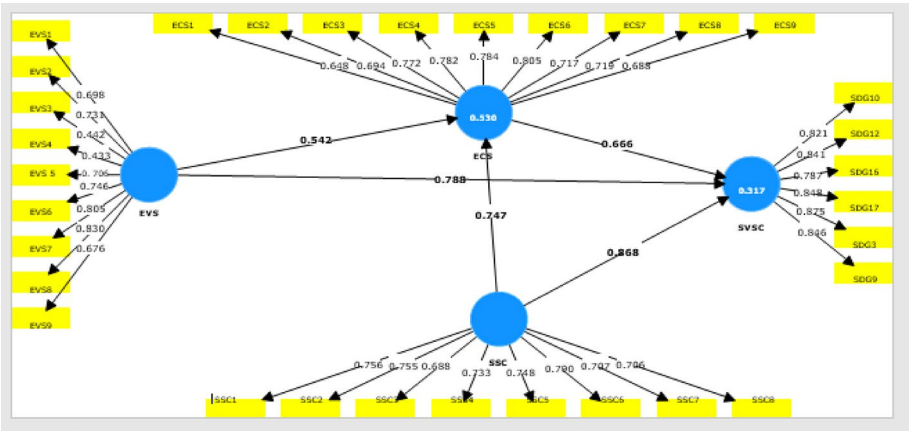


Fig. 4 Conceptual SEM model for sustainable child immunisation vaccine supply chain

Table 4 Construct reliability and validity

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
ECS	0.885	0.884	0.908	0.625
EVS	0.847	0.874	0.879	0.658
SSC	0.880	0.885	0.904	0.642
SVSC	0.914	0.917	0.933	0.700

multicollinearity. The 2.497 value implies that the variance of the associated predictor is inflated by about 2.5 times due to its correlation with other predictors. In SEM, multicollinearity can affect the reliability of path estimates between latent variables and the indicators used to measure them. However, VIF values below 5 indicate that collinearity is unlikely to compromise the model's robustness. The model can still produce reliable path estimates, and the relationships between variables remain interpretable. Therefore, a VIF of 2.497 falls within an acceptable range, indicating that the predictors are sufficiently independent to avoid multicollinearity issues that could compromise the model's validity. However, this level of inflation is unlikely to significantly impair the model's estimates. The collinearity statistics, including VIF, help confirm that your model is robust, meaning the estimates for each path or relationship are reliable and can be interpreted with confidence. Low to moderate multicollinearity ensures that the observed relationships between the variables are more likely due to true effects rather than statistical distortions. Thus, VIF values around 2.497 support the robustness and reliability of your SEM model and suggest that the estimates you are interpreting reflect genuine relationships between the constructs. Reliability and measurement standards are carefully assessed. High predictive reliability is indicated by indicator reliability ratings that exceed the minimum threshold of 0.4 and approach the target level of 0.7. Composite reliability, which measures internal consistency, shows values higher than 0.6, indicating strong internal consistency among reflective frequency factors. Average Variance Extracted (AVE) measures that exceed the commonly recognised minimum value of 0.5 for each structural parameter, as recommended by Gentle et al., [36], confirm convergent validity. Table 5 establishes discriminant validity, which is assessed using the square root of AVE (provided in Table 4) measures by [35]. All square root values exceed correlated

Table 5 Fornell-Larcker criterion analysis for checking discriminant validity

	ECS	EVS	SSC	SVSC
ECS	0.725			
EVS	0.654	0.677		
SSC	0.590	0.461	0.736	
SVSC	0.297	0.363	0.414	0.837

Table 6 Factor Outer loadings for indicators

	ECS	EVS	SSC	SVSC
ECS1	0.639			
ECS2	0.695			
ECS3	0.764			
ECS4	0.779			
ECS5	0.784			
ECS6	0.804			
ECS7	0.722			
ECS8	0.719			
ECS9	0.688			
EVS1		0.698		
EVS2		0.731		
EVS3		0.442		
EVS4		0.433		
EVS5		0.706		
EVS6		0.746		
EVS7		0.804		
EVS8		0.830		
EVS9		0.676		
SDG10				0.818
SDG12				0.833
SDG16				0.786
SDG17				0.850
SDG3				0.879
SDG9				0.851
SSS1			0.756	
SSS2			0.755	
SSS3			0.688	
SSS4			0.732	
SSS5			0.748	
SSS6			0.790	
SSS7			0.707	
SSS8			0.706	

values, indicating discriminant validity. Overall, the methodology confirms the validity and reliability of the study's findings by highlighting the robustness of the techniques used to validate the measurement and structural models (Table 6).

5.3 Assessment of the structural PLS-SEM model

This section presents the model fit and results of the structural analysis of the conceptual models. The proposed model's fit to the observed data is assessed using model fit indices, which include the Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardised Root Mean Square Residual (SRMR). The model, with a CFI value of 0.95, a TLI value of 0.90, an RMSEA

value of 0.03, and an SRMR value of 0.04, indicates that the model's fitness is true and correct. The findings showed that the R^2 values for ECS and SVSC were, respectively, 0.533 and 0.317. The in-sample predictive power of the model is supported by the R^2 values, which must be above 0.10 [87]. All latent constructs in the proposed model were specified as reflective constructs. The reflective specification was considered appropriate because the observed indicators represent manifestations of the underlying sustainability dimensions, and changes in the latent constructs are expected to influence all associated indicators simultaneously. The significance of the structural relationships was evaluated using the non-parametric bootstrapping procedure available in SmartPLS. Following the recommendations of [47], 5000 bootstrap subsamples were generated using bias-corrected and accelerated (BCa) confidence intervals at the 95% confidence level. Path coefficients were considered significant when the corresponding confidence intervals did not include zero and the p -values were below the recommended significance threshold. Using 5000 resamples and the Bootstrap resampling method, the significance of direct paths and estimated standard errors was determined. The choice of 5000 resamples ensures that many possible sample variations are tested, providing a robust assessment of how the model behaves across different data samples. A higher number of resamples, such as 5000, yields more precise estimates of confidence intervals and standard errors than smaller resample sizes (e.g., 500 or 1000). In our analysis, using 5000 bootstrapped resamples ensures that the model's findings are robust and reliable. It validates the model by demonstrating that the results are consistent across various simulated versions of your dataset, thereby increasing confidence that the identified relationships are both statistically significant and meaningful. Table 7 shows the final status of various hypotheses adopted in this study. Based on the values and results presented in Table 7, it is evident that a statistically significant interaction between the structured framework and all indicators has also been identified. The results of testing five hypotheses regarding the connections between various sustainability practices and their impact on the Sustainable Vaccine Supply Chain (SVSC) are presented in the table. Each hypothesis includes the path coefficient (β), standard deviation (SD), t -value, and p -value that correspond to the relationship between a particular set of sustainability practices and the SVSC. All hypotheses were supported at p -values below 0.05. Hypothesis H2 had the highest p -value (0.035) but remained statistically significant at the 0.05 level.

6 Findings

The collection of hypotheses in this study provides insightful information about the connections between various sustainable practices in the context of the Child Immunisation VSC in Uttar Pradesh. These theories were tested using SEM-PLS analysis to comprehend how social, economic, and environmental sustainability practices interact and affect the overall sustainability of the VSC. The results showed that socially sustainable practices have a positive impact on the supply chain of sustainable vaccines. According to this theory, H1, social sustainability initiatives like healthcare education and community involvement should have a positive impact on the long-term viability of the vaccine supply chain. Strong community relationships and raising awareness of the value of vaccinations can improve the efficacy and accessibility of vaccine delivery, ultimately leading to a more sustainable vaccine supply chain. The second proposed hypothesis, H2, that socially sustainable Practices will have a positive impact on economically

Table 7 Parameters of the structural model

Hypothesis	Relationship	Path coefficient (β)	SD	t-Value	P value	Decision
H1	SSC $\rightarrow$ SVSC	0.868	0.017	43.6	0.001	Supported
H2	SSC $\rightarrow$ ECS	0.747	0.066	16.8	0.035	Supported
H3	EVS $\rightarrow$ ECS	0.542	0.024	24.4	0.015	Supported
H4	ECS $\rightarrow$ SVSC	0.666	0.072	5.54	0.002	Supported
H5	EVS $\rightarrow$ SVSC	0.788	0.032	8.8	0.007	Supported

sustainable practices, was also accepted. According to this hypothesis, social sustainability practices in the vaccination supply chain are likely to have a positive impact on economic sustainability practices. Economic burdens related to preventable diseases can be decreased by enhancing access to immunisation services and empowering communities through healthcare education. This can then result in financial advantages, such as higher productivity and lower medical costs, which support economic sustainability. The third proposed hypothesis, H3, that Environmentally Sustainable Practices will have a positive impact on economically sustainable practices, was accepted. According to this theory, the economic sustainability of the vaccine supply chain will be positively impacted by environmentally friendly practices, such as effective cold chain management and waste reduction programmes. The adoption of eco-friendly technologies and procedures can reduce vaccine storage, transportation, and disposal expenses, enhancing economic viability and sustainability. In this study, the fourth and fifth hypotheses, H4 and H5, which posited that Economically Sustainable Practices would have a positive impact on the Sustainable vaccine supply chain and that Environmentally Sustainable Practices would have a positive impact on the Sustainable vaccine supply chain, were also accepted based on *p*-values and t-statistics obtained from structural SEM analysis. According to the H4 hypothesis, waste reduction programmes and effective cold chain management are examples of environmentally friendly practices that can positively impact the economic sustainability of the vaccine supply chain. Vaccine storage, transportation, and disposal costs can be reduced by utilising environmentally friendly technologies and procedures, increasing sustainability and economic efficiency. Ultimately, the H5 hypothesis implies that the vaccine supply chain will be more resilient if environmentally friendly practices are implemented. A more sustainable vaccine supply chain can result from reducing the environmental impact of vaccine production and distribution by adopting eco-friendly initiatives, such as waste management plans and the use of renewable energy. The SEM model employed in this study provided valuable insights into the interactions between Environmental Sustainability (EVS), Economic Sustainability (ECS), and Social Sustainability (SSC), as well as their combined impact on SVSC. The findings highlight the multiple sustainability characteristics, with each dimension uniquely contributing to sustainable behaviours throughout supply chains. This model highlights the interdependencies within the VSC framework, particularly emphasising sustainable supply chain practices and external collaboration as pivotal elements in achieving sustainability goals. The strong connections suggest that efforts to enhance SSC and EVS can significantly impact the success of SVSC, making these areas crucial focal points for strategic improvement. The model emphasises the relationships between four fundamental constructs: environmental sustainability (EVS), economic sustainability (ECS), social sustainability (SSC), and sustainable supply chain management (SVSC). Key findings show that EVS (path coefficient: 0.788) and SSC (path coefficient: 0.868) are

strong predictors of SVSC, highlighting their importance in achieving sustainable supply chain management. While ECS contributes less directly to SVSC, it is an essential construct that is influenced by both EVS ($r=0.542$) and SSC ($r=0.747$). This emphasises the interconnectedness of the categories, with economic sustainability serving as the foundation for environmental and social sustainability, which drives supply chain sustainability. Economic Sustainability (ECS) obtained an R^2 value of 0.533, indicating that Social Sustainability (SSC) and Environmental Sustainability (EVS) jointly explained 53.3% of the variance in economic sustainability practices. This reflects substantial explanatory power and highlights the strong interdependence among sustainability dimensions within the vaccine supply chain. The endogenous construct SVSC achieved an R^2 value of 0.317, indicating that SSC, ECS, and EVS collectively explained 31.7% of the variance in sustainable vaccine supply chain performance. This suggests that while sustainability dimensions significantly contribute to SVSC, additional contextual, technological, policy-related, and institutional factors may account for the remaining 68.3% of unexplained variance.

Critical observations of this study are:

1. Environmental sustainability: EVS showed intermediate factor loadings, implying that some environmental indicators contributed more than others. This demonstrates the variety in the effectiveness of various environmental techniques, such as resource efficiency, waste reduction, and pollution control, in achieving sustainability outcomes. The relatively low route coefficient (0.542) from EVS to SVSC indicates that, while environmental initiatives are essential, they may need to be supplemented by complementary economic and social policies to maximise their impact on supply chain sustainability.
2. Economic sustainability: ECS demonstrated high factor loadings across various metrics, emphasising its significance in maintaining long-term financial viability, cost efficiency, and value generation in sustainable supply chains. The route coefficient (0.666) from ECS to SVSC indicates a moderate-to-high influence, suggesting that economically sustainable techniques, such as profit optimisation and cost control, are necessary but insufficient for achieving supply chain sustainability.
3. Social sustainability: SSC emerged as the most significant dimension, as shown by its high path coefficient (0.868) with SVSC. This research underscores the importance of addressing social issues, including fair labour practices, community well-being, and ethical supply chain governance, in achieving sustainability. SSC indicators' consistently high factor loadings indicate a well-integrated and widely acknowledged importance of social sustainability in supply chain activities.
4. Sustainable supply chain management: SVSC is based on the integrated contributions of environmental, economic, and social elements. The model demonstrates that while all dimensions are critical, social sustainability plays a more significant role. This implies that supply chains prioritising ethical standards and stakeholder inclusion are more likely to achieve sustainability.

7 Discussion

The findings offer new empirical insights into the interactions of sustainability elements within VSC, a domain where integrated research is currently scarce, particularly in the context of public health in India. This chapter analyzes the results, connecting them to

existing literature, theoretical frameworks, and practical applications, while emphasising the distinctive contributions of this study.

7.1 Linkage of findings to theory and literature

The findings of this study provide empirical evidence regarding the relationships among social sustainability (SSC), economic sustainability (ECS), environmental sustainability (EVS), and sustainable vaccine supply chain (SVSC) performance. The results largely support previous research on healthcare and sustainable supply chain management while also providing new insights from the context of child immunisation programmes in Uttar Pradesh, India.

The strongest relationship identified in this study was between social sustainability and sustainable vaccine supply chain performance ($SSC \rightarrow SVSC$, $\beta = 0.868$, $p < 0.001$). This finding is consistent with previous studies that emphasise the importance of stakeholder engagement, community participation, healthcare workforce development, and equitable access in improving healthcare supply chain performance. For example, Lemmens et al., [62] highlighted that public trust and community engagement are critical determinants of successful vaccination programmes, while Chung et al. [24] reported that social inclusion and healthcare accessibility significantly improve supply chain effectiveness. The strong influence observed in the present study may be attributed to the unique demographic and socioeconomic characteristics of Uttar Pradesh, where awareness, community acceptance, and last-mile healthcare delivery play a decisive role in vaccination coverage. The results also indicate that environmental sustainability has a substantial positive impact on sustainable vaccine supply chain performance ($EVS \rightarrow SVSC$, $\beta = 0.788$, $p = 0.007$). This finding aligns with studies by Tetteh et al. [108] which demonstrated that environmentally responsible practices such as efficient cold-chain management, renewable energy adoption, and waste reduction improve healthcare logistics performance. However, unlike several earlier studies that treated environmental sustainability primarily as a compliance requirement, the present study demonstrates that environmental practices directly contribute to supply chain sustainability outcomes. This stronger effect may reflect the increasing importance of energy-efficient vaccine storage systems and environmentally responsible logistics operations in resource-constrained healthcare environments. Economic sustainability was also found to significantly influence sustainable vaccine supply chain performance ($ECS \rightarrow SVSC$, $\beta = 0.666$, $p = 0.002$). This result is consistent with research by Chowdhury et al. (2022) and Fathollahi-Fard et al. (2023), who reported that cost efficiency, resource utilisation, and financial viability are essential for maintaining resilient healthcare supply chains. However, the relatively lower coefficient compared with social sustainability suggests that financial considerations alone may not guarantee sustainable vaccine delivery in developing regions. Instead, economic performance appears to be strengthened when combined with social and environmental initiatives.

The positive influence of social sustainability on economic sustainability ($SSC \rightarrow ECS$, $\beta = 0.747$, $p = 0.035$) further supports the argument that social investments can generate economic benefits. This finding is in line with Stakeholder Theory, which proposes that organisations achieve long-term economic success by addressing stakeholder needs. Similar observations were reported by [55, 117] who found that healthcare programmes emphasising social inclusion and community participation often achieve greater

operational efficiency and lower service delivery costs. Improved public awareness and vaccine acceptance can reduce wastage, improve demand forecasting, and increase resource utilisation, thereby contributing to economic sustainability. Similarly, environmental sustainability significantly influenced economic sustainability ($EVS \rightarrow ECS$, $\beta = 0.542$, $p = 0.015$). This finding supports the Triple Bottom Line framework and corroborates studies by [9] and [66], which demonstrated that environmentally sustainable practices often create long-term economic benefits through reduced energy consumption, lower transportation costs, and improved operational efficiency. In the context of vaccine supply chains, investments in renewable energy-powered cold-chain infrastructure and sustainable waste management practices may reduce operational costs while simultaneously enhancing environmental performance.

Overall, the findings reinforce the principles of the Triple Bottom Line (TBL), Stakeholder Theory, and Resource-Based View (RBV). The results suggest that sustainable vaccine supply chains cannot be achieved through economic or environmental initiatives alone. Rather, social sustainability acts as the primary driver, while environmental and economic sustainability provide complementary support. This integrated perspective extends previous research by empirically demonstrating how sustainability dimensions interact and jointly contribute to vaccine supply chain performance within a developing-country healthcare context.

7.2 Contribution to practice

This study provides evidence-based guidance for policymakers in Uttar Pradesh:

1. Practically, the results indicate that social investments (SSC), training healthcare workers, engaging local leaders, and community education are the most powerful levers for improving last-mile delivery and coverage rates. This offers a strategic pathway for policymakers: prioritising social interventions produces both economic and environmental co-benefits.
2. The evidence that EVS strengthens ECS shows that sustainability can be economically self-reinforcing. Policies promoting solar-powered cold chain units and eco-friendly packaging reduce operational costs, proving that green innovation is not just ethically desirable but also financially viable.
3. The SEM-based decision-support approach developed here helps policymakers allocate funding to sustainability interventions with the highest ROI, a contribution that moves beyond descriptive results to provide an actionable tool for public health logistics.

7.3 Unique contribution of this study

Unlike prior studies that focused mainly on logistics efficiency, this study integrates SEM-based empirical evidence with SDG mapping, providing a holistic sustainability model tailored to child immunisation programmes. This research highlights that social sustainability is not merely a soft outcome but a quantifiable driver of supply chain performance. While prior studies have often examined these sustainability dimensions in isolation, this research offers a holistic and interconnected framework that captures how these dimensions reinforce one another within a critical public health context. It is one of the first studies to empirically quantify the interdependencies among SSC, ECS, and EVS in the context of a developing country's immunisation supply chain. It bridges

sustainability science and public health logistics by operationalising SDGs as measurable supply chain outcomes. The study offers real-time policy guidance by demonstrating how SEM findings can be integrated into feedback loops between frontline health workers and policymakers to dynamically optimise vaccine distribution and generate context-specific evidence from Uttar Pradesh, a high-need and under-researched region, thereby expanding the knowledge base on sustainable VSC models in low-resource settings.

8 Implication

This study integrates environmental, social, and economic elements to explore how child immunisation programmes support sustainability. It suggests the use of renewable energy, equitable vaccination distribution, and local sourcing for policymakers to improve vaccine supply chains. This study supports both academic research and real-world applications in public health and sustainable development.

8.1 Theoretical implications

The study contributes to the growing body of literature on the relationship between immunisation programmes and the United Nations' Sustainable Development Goals (SDGs). By demonstrating how child immunisation frameworks, directly and indirectly, influence multiple SDGs (such as SDG 3 on health, SDG 9 on infrastructure, and SDG 12 on sustainable consumption), this research offers a conceptual framework for understanding vaccination programmes not only as health interventions but also as drivers of broader sustainable development outcomes. This study introduces specific environmental, economic, and social sustainability indicators (such as cold chain carbon footprint, cost-effectiveness, and equitable distribution) in the context of child immunisation programmes. These indicators enhance the theoretical understanding of how vaccine supply chains can be evaluated through the lens of sustainability, providing a multidimensional perspective that extends beyond cost and health outcomes. The theoretical advancement here is using SEM to explore the relationships between vaccine supply chain components and sustainable development indicators. SEM provides a quantitative method for mapping the intricate linkages between supply chain factors (such as cold chain efficiency, local sourcing, and community engagement) and their impact on sustainability outcomes, thereby paving the way for future research in similar contexts. Sustainability in Public Health Supply Chains: The research highlights the theoretical intersection of public health supply chains with environmental and economic sustainability. Traditionally, public health programmes focus on health outcomes. However, this study expands the framework to include the environmental and economic impacts of vaccine delivery, such as carbon emissions and local economic benefits, thereby adding depth to the supply chain management literature.

8.2 Practical implications

The paper provides policymakers with evidence-based vaccine supply chain sustainability recommendations for Uttar Pradesh. Solar-powered vaccine refrigeration and low-emission vehicles are examples. These SDG-aligned recommendations help policymakers prioritise sustainable technologies that reduce environmental impact and maintain vaccine efficacy. This research helps decision-makers optimise resource allocation by identifying crucial supply chain component-sustainability outcomes links using SEM.

Investing in energy-efficient storage systems or community education campaigns based on their health and sustainability impacts can make them more cost-effective and successful. The findings highlight equitable vaccine delivery in underprivileged areas. To ensure no neighbourhood is left behind, policymakers may monitor immunisation coverage and adjust resources using data. This improves public health and SDG 10 (Reduced Inequalities) by decreasing immunisation gaps. The research highlights local sourcing in vaccination supply chains, which has economic effects. Using local resources and services strengthens supply chains and supports local economies. Financial incentives can encourage local sourcing and reduce dependency on foreign markets, contributing to SDG 8 (Decent Work and Economic Growth). The study emphasises healthcare worker training and community engagement in vaccination. This means governments and NGOs should fund healthcare worker capacity-building and involve local populations in vaccinations. These initiatives can boost immunisation rates, especially in rural and marginalised communities, and public health system trust. Research suggests cross-sector cooperation (SDG 17) between commercial firms, non-profits, and government agencies to build more resilient and sustainable supply chains. Collaborations on low-emission transportation, biodegradable vaccine packaging, and sustainable storage can promote a holistic approach to public health infrastructure development.

9 Conclusion, limitations, and future directions

In conclusion, all of the study's tested hypotheses are confirmed, demonstrating a strong positive correlation between various sustainability practices (social, economic, and environmental) and their impact on the sustainability and economic sustainability of Uttar Pradesh's vaccine supply chain. Policymakers and other stakeholders can enhance sustainable development outcomes in healthcare delivery systems by leveraging the valuable insights these findings provide. Ultimately, through an extensive literature review and SEM-PLS analysis, this research sought to address the various research questions posed in Sect. 1 of this paper. The current vaccination supply framework does not significantly contribute to several of the United Nations' Sustainable Development Goals. Through this proposed research framework, VSC can make significant contributions to UN SDGs 3, 9, 10, 12, 16, and 17. This study on Uttar Pradesh's child immunisation programmes supports sustainability directly and indirectly. Effective cold chain management to reduce vaccine waste, the promotion of environmentally friendly vaccine storage techniques, and the execution of community outreach initiatives to boost vaccination rates are examples of direct sustainability practices. Indirect sustainability practices include lowering the financial burden of healthcare costs on vulnerable populations, building community resilience against diseases, and empowering women through healthcare education. When taken as a whole, these methods support more general sustainable development goals like enhanced social justice, economic stability, and health. The Partial Least Squares (PLS) method of SEM can help clarify the intricate connections between vaccine supply chain elements and sustainable development metrics in Uttar Pradesh. By modelling both direct and indirect relationships between variables, SEM enables researchers to capture the complexity of sustainability practices and their influence on development outcomes. SEM can quantify the contribution of each component to sustainable development and identify critical linkages by analysing data on cold chain management, vaccine distribution, community engagement, and health indicators.

The study's conclusions can help inform the development of evidence-based policies and programmatic interventions by shedding light on the effectiveness of Uttar Pradesh's current frameworks for vaccine supply. The connections between sustainability practices and the Sustainable Development Goals have been demonstrated to enable policymakers to focus resources on areas with the most significant potential to achieve sustainable development goals. SDGs 3 (Good Health and Well-being) and SDG 17 (Partnerships for the Goals), for instance, can be explicitly aligned with interventions to strengthen healthcare delivery systems, enhance community engagement, and improve cold chain infrastructure. Stakeholders can work to strengthen the child immunisation vaccine supply framework and advance progress toward achieving the SDGs by incorporating these findings into policy formulation and programme design.

The study encountered obstacles related to the accessibility and accuracy of information from multiple stakeholders, including governmental agencies, private sector entities, and healthcare organisations. Inconsistent or incomplete data, particularly from specific regions within Uttar Pradesh, may have impacted the reliability of the structural equation modelling. The research encountered limitations concerning sample size and its representation across Uttar Pradesh. Data collected from certain districts may not have fully represented the entire state's population, potentially limiting the generalizability of the findings. The study sample included a higher proportion of male and urban respondents, which may have influenced perceptions of social sustainability indicators, particularly those related to healthcare accessibility, community engagement, and equitable vaccine distribution. Therefore, the findings may not fully capture the perspectives of female stakeholders and rural communities, limiting their generalizability. External factors, including political changes, unexpected health crises (such as COVID-19), or alterations in public health policies, may have impacted the VSC; however, the study found these variables challenging to account for.

Future studies should collect more comprehensive and diverse statistics from a broader range of districts to ensure a more accurate representation of Uttar Pradesh's demographic and socioeconomic diversity. A larger and more diverse sample size might help reduce potential biases and increase the generalizability of the findings. Statistical techniques, such as Harman's single-factor test, can be used to determine that no single factor accounts for the majority of variance. Incorporating real-time data-collecting tools, such as digital health records and geospatial mapping, could also improve the precision and responsiveness of study results. Longitudinal studies that monitor vaccination supply chain efficiency over time would provide more detailed insights into long-term patterns, recurring difficulties, and the efficacy of various policy measures. The structural model explains 31.7% of the variance in SVSC performance, indicating that social, economic, and environmental sustainability practices are important determinants of supply chain sustainability. However, approximately 68.3% of the variance remains unexplained, suggesting that additional factors outside the scope of the current model may also influence vaccine supply chain performance. These factors may include government policies and regulatory frameworks, political commitment, healthcare infrastructure quality, digital health technologies, cold-chain capacity, transportation network reliability, stakeholder coordination mechanisms, public-private partnerships, vaccine hesitancy, community trust, emergency preparedness, and funding availability. Furthermore, external disruptions such as pandemics, natural disasters, geopolitical instability, and supply

shortages can significantly affect vaccine distribution efficiency and sustainability. Technological advancements, including blockchain, Internet of Things (IoT), artificial intelligence (AI), and real-time monitoring systems, may also contribute to improved supply chain resilience and sustainability outcomes. Therefore, while the present model provides valuable insights into the role of sustainability dimensions, future research should incorporate these contextual, technological, institutional, and behavioural variables to develop a more comprehensive understanding of sustainable vaccine supply chain performance. Further research should investigate the transformative impact of upcoming technical breakthroughs on improving the sustainability of the vaccine supply chain. Blockchain, IoT, and AI technologies have the potential to transform supply chain management by increasing transparency, traceability, and predictive analytics. For example, blockchain technology can provide secure and tamper-proof record-keeping, reducing the risk of counterfeit vaccines and supply chain fraud. IoT-enabled smart sensors could enable real-time monitoring of storage conditions, ensuring that vaccines remain at the appropriate temperatures during shipping and storage. AI-powered predictive models can enhance demand forecasting, minimise waste, and optimise distribution efficiency. These developments would be especially advantageous in resource-constrained countries like Uttar Pradesh, where logistical constraints, limited infrastructure, and supply chain inefficiencies frequently impede vaccine access. Comparative studies of Uttar Pradesh and other states or regions, both within India and LMIC, could provide valuable insights into best practices and regional challenges. Such studies could aid in identifying effective solutions that have been effectively applied elsewhere and assessing their viability in the context of Uttar Pradesh's healthcare infrastructure and socioeconomic factors. Researchers can provide policymakers and stakeholders with meaningful information for optimising vaccination distribution networks by comparing healthcare systems with varying levels of technological integration, governance models, and logistical frameworks. A more comprehensive understanding of sustainability practices across different locations with diverse healthcare infrastructures and population dynamics would provide a more nuanced view of vaccination supply chain management. These findings could help to shape targeted policy suggestions, enhance budget allocation, and increase collaboration among government agencies, healthcare providers, and technology developers. Ultimately, a more data-driven and technology-enabled approach to vaccination supply chain management could enhance the overall resilience and sustainability of immunisation programmes, particularly in areas with significant public health challenges.

Appendix 1

Questionnaire

Questionnaire for SEM Study

Purpose: This questionnaire aims to assess the sustainability of the vaccine supply chain for child immunization programs in Uttar Pradesh.

Instructions: Please tick (✓) the number that best represents your opinion, where 1 = Strongly Disagree and 5 = Strongly Agree.

For example, if you think EVS1 contributes strongly to Environmental sustainability, tick 5 and it does not have any significant contribution, tick 1(so on vice-versa).

Part A: Demographic information

Gender (Male / Female / Other)	Response: _____
Age (18–30 / 31–50 / Above 50)	Response: _____
Education (High school or less / Bachelor's / Advanced)	Response: _____
Employment status (Employed / Unemployed / Student)	Response: _____
Income level (Low / Middle / High)	Response: _____
Location (Urban / Rural / Suburban)	Response: _____

Part B: Main questionnaire items**Environmental sustainability (EVS)**

Statement	1	2	3	4	5
Cold chain carbon footprint (EVS1)	☐	☐	☐	☐	☐
Renewable energy usage (EVS2)	☐	☐	☐	☐	☐
Waste management efficiency (EVS3)	☐	☐	☐	☐	☐
Packaging sustainability (EVS4)	☐	☐	☐	☐	☐
Water usage efficiency (EVS5)	☐	☐	☐	☐	☐
Chemical management (EVS6)	☐	☐	☐	☐	☐
Emission controls in transportation (EVS7)	☐	☐	☐	☐	☐
Energy efficient storage facilities (EVS8)	☐	☐	☐	☐	☐
Biodiversity impact (EVS9)	☐	☐	☐	☐	☐

Economic sustainability (ECS)

Statement	1 Strongly disagree	2	3	4	5 Strongly agree
Cost-effectiveness (ECS1)	☐	☐	☐	☐	☐
Supply chain resilience (ECS2)	☐	☐	☐	☐	☐
Local sourcing index (ECS3)	☐	☐	☐	☐	☐
Investment in sustainable technologies (ECS4)	☐	☐	☐	☐	☐
Inventory management efficiency (ECS5)	☐	☐	☐	☐	☐
Market dependency (ECS6)	☐	☐	☐	☐	☐
ROI for sustainability initiatives (ECS7)	☐	☐	☐	☐	☐
Funding diversification (ECS8)	☐	☐	☐	☐	☐
Economic impact on local communities (ECS9)	☐	☐	☐	☐	☐

Social sustainability (SSS)

Statement	1 Strongly disagree	2	3	4	5 Strongly agree
Good health and wellbeing (SDG 3)	☐	☐	☐	☐	☐
Industry, innovation, and infrastructure (SDG 9)	☐	☐	☐	☐	☐
Reduced inequalities (SDG 10)	☐	☐	☐	☐	☐
Responsible consumption and production (SDG 12)	☐	☐	☐	☐	☐
Peace, justice and strong institutions (SDG 16)	☐	☐	☐	☐	☐
Partnerships for the goals (SDG 17)	☐	☐	☐	☐	☐

Sustainable development goals (SDGs)

Statement	1 Strongly disagree	2	3	4	5 Strongly agree
Immunization coverage rate (SSS1)	☐	☐	☐	☐	☐
Healthcare worker training and support (SSS2)	☐	☐	☐	☐	☐
Community engagement and education (SSS3)	☐	☐	☐	☐	☐
Equitable vaccine distribution (SSS4)	☐	☐	☐	☐	☐
Cultural sensitivity in vaccine delivery (SSS5)	☐	☐	☐	☐	☐
Impact on local employment (SSS6)	☐	☐	☐	☐	☐
Public health outcome improvement (SSS7)	☐	☐	☐	☐	☐

Statement	1 Strongly disagree	2	3	4	5 Strongly agree
Feedback mechanism effectiveness (SSS8)	☐	☐	☐	☐	☐

Part C: Additional comments

Please share any additional suggestions or comments:

Author contributions
Conceptualization, A.K. and O.J.S.; methodology, S.M.P.; software, N.K.; validation, P.K.M., M.K. and S.J.; formal analysis, A.K.; investigation, A.K., O.J.S. and S.M.P.; resources, N.K., P.K.M. and M.K.; data curation, A.K.; writing—original draft preparation, A.K.; writing—review and editing, S.J.; visualization, O.J.S.; supervision, S.M.P.; project administration, M.K.; funding acquisition, S.J. All authors have read and agreed to the published version of the manuscript.

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Data availability
The questionnaire used for the survey and the datasets generated and analysed during the current study are available at the following link: <https://doi.org/10.5281/zenodo.18410270>.

Declarations

Ethics approval and consent to participate
This study did not involve human clinical trials or animal experiments and was therefore exempt from such reviews, as it consisted solely of a survey questionnaire. The study protocol was reviewed and approved by the ethical guidelines of the Ethics and Review Committee of the National Institute of Technology Patna (NITPERC) on 5 December 2022 (approval date), for research conducted by Ambuj Kumar (Approval number: NITPERC/0512-1/2022) in accordance with the principles of the Declaration of Helsinki, for research involving human subjects. Informed consent to participate in the study was obtained from all individual participants prior to data collection.

Consent for publication
Not applicable.

Competing interests
Sandeep Jagtap declares they are an Editorial Board Member of Discover Sustainability and confirms that they were not involved in the handling or decision-making of their own submission. The authors declare no other competing interests.

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