WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
Coden USA: WJPRAP Impact Factor 8.63
Volume 15, Issue 14, 543-555. Review Article ISSN 2277–7105

THE LAST MILE IS THE HARDEST: VACCINE EQUITY, MANUFACTURING RESILIENCE, AND INDIA'S ONE HEALTH MODEL AFTER COVID-19

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Article Received on 25 June 2026,
Article Revised on 05 July 2026,
Article Published on 16 July 2026,
https://doi.org/10.5281/zenodo.21367488

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How to cite this Article: Saranya Tadimeti*, Harish Guggila (2026). The Last Mile Is The Hardest: Vaccine Equity, Manufacturing Resilience, And India's One Health Model After Covid-19. World Journal of Pharmaceutical Research, 15(14), 543–555.

ABSTRACT

Scientific speed is necessary but insufficient for public-health impact: vaccines save lives only when they are manufactured at scale, distributed equitably, delivered through functioning systems, and accepted by the populations they protect. This review examines the access side of the post-COVID-19 vaccine transformation, with India as its analytical anchor. Following PRISMA-ScR guidance, literature from PubMed, Scopus, and Web of Science (2000–2025, focus 2019–2025) and institutional sources (WHO, CEPI, Gavi) the data was synthesised across manufacturing, equity-financing, One Health, life-course, delivery-systems, and hesitancy domains. The 2021 export pause exposed a "single-hub" vulnerability that catalysed decentralisation, including the WHO Mrna technology-transfer hub (2023). India's One Health manufacturing—exemplified by Indian Immunologicals Limited's integrated human–animal portfolio for rabies and foot-and-mouth disease—illustrates source-control of zoonoses. We further examine life-course immunisation amid demographic ageing, India's delivery architecture (Universal Immunisation Programme, Mission Indradhanush, Co-WIN/U-WIN, and ASHAs), and the SAGE framework for vaccine hesitancy. Persistent constraints, like financing, TRIPS and know-how asymmetries, adult-schedule integration, and a projected 18-million health-worker shortfall by 2030—underscore that platform speed must be matched by equitable governance and last-mile systems.

KEYWORDS: Vaccine supply; One Health; Life-course immunisation; Advance Purchase Commitments; Vaccine equity.

1. INTRODUCTION

Science creates the vaccine; trust and systems create immunisation. The COVID-19 pandemic made this distinction unavoidable: rapid platform innovation delivered effective vaccines within a year, yet access remained profoundly unequal, and the determinants of impact lay as much in manufacturing, financing, delivery, and trust as in molecular design.

Vaccination is among the most cost-effective public-health interventions known, returning an estimated US$44 for every US$1 invested in low- and middle-income countries(Ozawa et al., 2016), but that return is realised only where doses reach arms.

Beyond COVID-19, the pandemic pushed the vaccine industry into a phase of growth and diversification, with advance market commitments, public–private partnerships, and strategic investment driving roughly a 30% increase in vaccine candidates and manufacturing capacity between 2019 and 2025 (GVMR, 2025). India was central to this effort, producing over 60% of the world's vaccines by volume and supplying affordable doses to low- and middle-income countries (Chavda et al., 2022). Manufacturers including the Serum Institute of India, Bharat Biotech, Biological E, and Indian Immunologicals Limited demonstrated how platform readiness, regulatory maturity, and One Health integration can convert scientific capability into large-scale public-health benefit. This review synthesises the equity, manufacturing, and delivery dimensions of that transformation, asking what it takes for vaccines to reach people—and what the world can learn from India's model.

1.2. Review_Methodology

This narrative review followed PRISMA-ScR guidance. We searched PubMed, Scopus, and Web of Science, supplemented by WHO, CEPI, and Gavi repositories, for publications from January 2000 to December 2025, emphasising peer-reviewed sources from 2019–2025. For this article, search strings prioritised the access and systems domains: "Vaccine supply chain", "One Health"; "Vaccine equity"; "Advance Purchase Commitments"; "Life-course immunisation" and "pandemic preparedness". Inclusion was limited to peer-reviewed original research, systematic reviews, meta-analyses, and authoritative institutional reports; conference abstracts without full texts, opinion pieces, industry newsletters as primary sources, and items lacking verifiable authorship were excluded.

2. The Economics of Vaccination and the Case for Equity

Historically, the vaccine industry has been prone to market failure: high R&D costs collide with uncertain demand, discouraging investment in products for low-income markets. Governments and global bodies have broken this cycle through advance purchase commitments and emergency clinical-trial financing that de-risk development. In India, the Indian Council of Medical Research and the Department of Biotechnology acted as co-architects of innovation, backing landmarks such as Covaxin (a public–private partnership with Bharat Biotech) and ZyCoV-D, demonstrating that when the public sector absorbs financial risk, vaccines shift from reactive commodities to strategic national assets (Behera et al., 2022).The equity argument follows directly: if public investment de-risks supply, the resulting capacity should serve global, not only the domestic-need.

3. India's Platform Readiness and Vaccine Self-Reliance

India's response showcased institutional preparedness through platform diversification and a strategic drive toward self-reliance. Bharat Biotech's Covaxin (BBV152), developed with the ICMR–National Institute of Virology, achieved end-to-end indigenous capability from BSL-3 strain isolation to DCGI Emergency Use Authorisation on 3 January 2021, demonstrating expertise in whole-virion inactivated platforms (Bharat Biotech, 2021).The Serum Institute of India (SII) scaled Covishield (AZD1222) and Covovax (NVX-CoV2373) to over one billion doses within the first year, validated by India's domestic milestone of 1.5 billion administered doses by January 2022 and SII's status as the largest single COVAX supplier (Serum Institute of India, 2021; Singh et al., 2022). Zydus Lifesciences added further diversity with ZyCoV-D, the world's first authorised human DNA-plasmid vaccine for human use, delivered needle-free in a thermostable three-dose regimen (Ledesma-Feliciano et al., 2023). Catalysed by the Department of Biotechnology investments, these milestones mark India's evolution from high-volume contract manufacturer to platform-driven innovator.

4. The Indian Manufacturing Landscape

India's industry currently supplies roughly 60% of global vaccine doses. Drawing on the WHO data, it meets about 70% of WHO demand for essential vaccines such as DPT and BCG and around 90% of measles-vaccine demand. (Dr. Rajesh Jain, 2021).The pandemic accelerated structural growth: advance purchase agreements and R&D funding from Gavi, CEPI, and BARDA, alongside the domestic Atmanirbhar Bharat initiative, helped the sector shift from high-volume generic manufacturing toward flexible, platform-based production capable of faster, locally driven responses.

5. One Health in Action: The Indian Immunologicals Limited Model

EDITORIAL DISCLOSURE

IIL is an author affiliation of this manuscript. This section relies exclusively on publicly verifiable data — WHO prequalification records, the IIL Annual Report (2023), and FAO programme documentation — and should be read in the context of the conflict of interest declared in Section 13.

Indian Immunologicals Limited (IIL), an NDDB-owned public enterprise founded in 1982 and incorporated in 1999, operates an integrated vaccine manufacturing network that spans human and veterinary biologicals and is therefore a useful case study for One Health–oriented vaccine production and deployment. Headquartered in Hyderabad with manufacturing sites at Gachibowli (Hyderabad), Karakapatla (Hyderabad), and Ooty (Tamil Nadu), IIL reports facility compliance with WHO-GMP standards and prevailing ISO certifications; these operational baselines support its role in both domestic immunization programmes and selected international procurement channels.

5.1 Human vaccine portfolio: Rabies

IIL's principal human vaccine is Abhayrab, a lyophilised, purified inactivated Vero-cell rabies vaccine derived from the L. Pasteur 2061/Vero strain, manufactured at the Human Biologicals Institute in Ooty. Abhayrab, replaced older nerve-tissue rabies vaccines in India's procurement mix and has been distributed domestically and to multiple LMICs; company and regional procurement records cited in the draft indicate cumulative supply on the order of hundreds of millions of doses since licensure, and a substantial domestic market share in the human rabies segment. For programmatic interpretation, it is relevant that cell-culture rabies vaccines (Vero-cell platforms) offer improved purity and safety relative to nerve-tissue formulations and are therefore suitable for both post-exposure prophylaxis (PEP) and mass vaccination procurement frameworks used by WHO/UNICEF and other procurers.

5.2 Veterinary portfolio: FMD and endemic livestock vaccines

IIL maintains a broad veterinary portfolio that includes FMD (oil-adjuvanted inactivated formulations marketed as Raksha-Ovac), brucellosis, PPR, haemorrhagic septicaemia/black quarter, and multi-component vaccines for poultry and companion animals. The FMD vaccine line is programmatically significant because national control of FMD requires sustained mass vaccination campaigns, cold-chain logistics, and antigenic matching to circulating serotypes; IIL's supply to India's National Animal Disease Control Programme (NADCP) and reported contributions to FAO/WOAH regional programmes illustrate its operational role in those programmatic efforts. It should be emphasized that while FMD control has major economic and trade implications and reduces animal morbidity and mortality, FMD is not typically a direct zoonotic threat to humans; its One Health relevance is therefore predominantly via protection of livelihoods, food security, and the socio-economic conditions that indirectly influence human vulnerability.(King, 2019).

5.3 One Health rationale and pathway logic

IIL's combined human–animal portfolio exemplifies two distinct One Health pathways. First, direct zoonotic prevention: mass dog vaccination and reliable human PEP reduce human rabies incidence by interrupting transmission at the animal reservoir and providing clinical prevention for exposed humans.

Second, indirect socio-economic protection: livestock immunization (e.g., against FMD, PPR) preserves household incomes and food security in rural communities where human–animal interactions are frequent, thereby strengthening community resilience to broader infectious-disease threats and enabling sustained access to health services.. (Food and Agriculture Organization et al., 2021). (World Organization for Animal Health, 2024).

5.4 R&D pipeline and technology transitions

Presented analytically, IIL is best positioned in the review as an operational example of how integrated human–animal vaccine manufacture can align with One Health objectives: direct zoonotic risk reduction (World Organization For Animal Health & World Health Organization, 2018), livestock production and livelihood protection (FMD and other veterinary vaccines), and a strategic posture toward platform modernization (emerging biologics).

6. Global Vaccine Equity: COVAX and Financing

India was central to the COVAX initiative. SII became its largest manufacturer, committing to supply Covishield to 64 lower-income countries at roughly US$3–5 per doses far below the US$20–30 charged for mRNA vaccines in wealthier nations. (GAVI Staff, 2020b; Serum Institute of India, 2021).

Beyond COVAX, a suite of financial instruments drove industry growth. Gavi's Advance

Market Commitments guaranteed minimum purchase prices, de-risking investment for LMIC markets (GAVI Staff, 2020a), while BARDA, via Operation Warp Speed, mobilised roughly US$18 billion for at-risk manufacturing and clinical acceleration (Jackson et al., 2020; Winch et al., 2021).Following the onset of the COVID-19 pandemic, the IMF and regional financial arrangements mobilised US$90.11 billion in financing, complemented by the IMF's Catastrophe Containment and Relief Trust (CCRT) and the World Bank's vaccine bonds, which provided liquidity for vaccine procurement and broader pandemic response measures (Stubbs et al., 2021). Together, these instruments compressed a decadal timeline to under twelve months, showing that financial agility is a prerequisite for scientific speed in a crisis.

7. From Centralised Risk to Decentralised Resilience

India's catastrophic second wave in April–May 2021 exposed the "single-hub" vulnerability of the global supply chain. Export restrictions prioritising 1.4 billion domestic citizens delayed COVAX deliveries and impeded LMIC programmes (Pushkaran et al., 2023). The crisis catalysed a shift from centralised to decentralised manufacturing and regional production mandates, most notably the WHO mRNA Technology Transfer Programme, whose South Africa hub at Afrigen Biologics (Cape Town) was inaugurated on 20 April 2023. (Herder & Benavides, 2024).

7.1 The TRIPS Debate and the Path to Self-Sufficiency

The global industry operates within a web ofagreements balancing commercial viability against human survival. The Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement, administered by the WTO, protects vaccine patents(Syam & Abbas, 2025). During the pandemic, Médecins Sans Frontières led a high-profile call for a TRIPS waiver, arguing that patent rules should be temporarily suspended to enable generic manufacturing in developing nations (MSF supports India and South Africa ask to waive COVID-19 patent rights, 2020)—opening a global debate on whether vaccines are proprietary assets or public goods.

The debate underscored a deeper truth: legal waivers alone are insufficient without physical infrastructure and technical know-how. This realisation accelerated three responses—technology-transfer hubs such as the WHO mRNA hub now sharing technology with 15 Global South partners; regional manufacturing initiatives such as the Partnership for African Vaccine Manufacturing, targeting an increase in local production from 1% to 60% by 2040; and voluntary licensing, through which innovators partner with manufacturers such as SII to produce generic versions while balancing proprietary rights with access(Dutt et al., 2024). NGO industrialisation, exemplified by PATH and UNICEF, further catalysed heat-stable formulation and cold-chain strengthening with Indian manufacturers.

8. The Shift Toward Life-Course Immunisation

8.1 Emographic and Strategic Foundations

The move towards lifelong immunisation is driven by demographic ageing: by 2030, an estimated 1.4 billion people will be aged 60 or older (Stancu et al., 2023). Tetanus, diphtheria, and acellular pertussis (Tdap) vaccines protect adolescents and adults and support the “cocooning” strategy that shields newborns from pertussis (See, 2025).Maternal immunisation — Tdap, influenza, and RSV monoclonal antibodies—confers passive infant immunity (Amin et al., 2026), while older adults gain protection from high-dose influenza, pneumococcal, and newer RSV vaccines such as Arexvy and Abrysvo (Pangrazzi & Weinberger, 2025).This marks a strategic shift from infant-centric programmes to protection across the life course.

COVID-19 catalysed a 72% surge in adult vaccination demand globally (IQVIA Institute for Human Data Science, 2023). The WHO Global Vaccine Market Report 2024 noted substantial growth in COVID-19 vaccine revenues from 2021–2023, and CEPI and Gavi broadened their mandates toward adolescent and maternal portfolios in LMIC’s. (GLOBAL MARKET STUDY, 2024).

8.2 Structural Challenges in Implementation

Only about 30% of countries have integrated adult schedules into primary care. Out-of-pocket costs for vaccines such as shingles or RSV range from US$150 to US$300 per dose. And a projected global shortage of 18 million health workers by 2030 threatens the scalability of life-course programmes. (GLOBAL MARKET STUDY, 2024).Overcoming these barriers is now recognised as a prerequisite for lifelong health security under the IA2030 agenda.

9. India’s Delivery Model: From Policy to Last Mile

9.1 Universal Coverage and Mission Indradhanush

India is an emerging model for LMICs. The Universal Immunisation Programme (UIP) reaches 30 million children and pregnant women annually, supported by Mission Indradhanush, which targeted 272 high-focus districts to close coverage gaps (Dhawan et al., 2023). The National Technical Advisory Group on Immunisation (NTAGI) guides the antigen introduction, such as PCV and rotavirus. (Dr. Pradeep Haldar, 2023, 2023; Ministry of Health and Family Welfare, 2019) Post-COVID, ICMR and MoHFW surveillance indicate a measurable rise in adult influenza and typhoid vaccination concentrated in urban centres, though nationally representative data are needed to quantify the shift. Meeting IA2030 targets requires balancing national surge programmes with decentralised, primary-care-led integration.

9.2 Digital Public Infrastructure: Co-WIN and U-WIN

India has redefined the standard for digital public infrastructure. Co-WIN managed an unprecedented 2.2 billion doses and has since evolved into the U-WIN portal—the permanent digital backbone of the UIP. Launched in 1978 as the Expanded Programme on Immunisation and renamed the Universal Immunisation Programme in 1985, the programme provides free protection against 12 preventable diseases. (Arjun et al., 2023)Through U-WIN, India has digitalised the immunisation life cycle for 2.9 million pregnant women and 2.6 million newborns annually, with NTAGI ensuring evidence-based policy in a manner analogous to the U.S. Advisory Committee on Immunization Practices.(PIB, 2025).

9.3 ASHAs: The Human Bridge to Last mile

Digital platforms and international agreements remain subordinate to the role of Accredited Social Health Activists (ASHAs). This one-million-strong, all-women workforce is the indispensable human infrastructure connecting India's high-tech policy to its rural and tribal communities. ASHAs navigate cultural taboos, bridge linguistic differences, and conduct door-to-door mobilisation to identify unvaccinated children. As the physical "vial-to-vein" link, they convert national mandates into community-level action, ensuring the last mile is a personalised clinical encounter rather than a mere logistical delivery. (Dr. Shalini Singh et al., 2024).

10. Trust and Vaccine Hesitancy: The SAGE Framework

Scientific innovation alone cannot achieve public-health impact; vaccines save lives only when administered to populations that trust and can access them. COVID-19 brought vaccine hesitancy—the delay in acceptance or refusal of vaccination despite available services—into sharp focus. An "infodemic" of social-media misinformation, amplified by geopolitical tension and unprecedented development speed, challenged public confidence in unanticipated ways (Al-qahtani et al., 2025).

The WHO SAGE Working Group frames hesitancy through the "Three Cs": **Confidence** (trust in vaccine safety and the health system), **Complacency** (perceived low disease risk leading to inaction), and **Convenience** (structural ease of access, both physical and informational). India's response showed that transparent, multi-channel communication—via Aarogya Setu, Doordarshan, and community radio—was most effective when paired with the empathy of an ASHA's home visit. This synergy improved uptake even in historically hesitant groups, a reminder that while science creates the vaccine, trust creates immunisation.(Ana Bolio et al., 2024).

11. DISCUSSION

The post-COVID equity story turns on a single proposition: 'distribution- not- discovery', was the binding constraint. India's experience demonstrates how public risk-absorption, platform readiness, and integrated One Health manufacturing can convert scientific capability into population-scale benefit. While the 2021 export pause shows how a single-hub model, concentrates global risk. The resulting pivot toward decentralised manufacturing, technology transfer, and regional self-sufficiency represents the most consequential structural legacy of the pandemic for global health. The transferability of the Indian model rests on decades of public-sector investment, a vast skilled workforce, and diverse industrial scale. Whether its components—digital infrastructure, last-mile human networks, and One Health integration—can be replicated where those preconditions are absent remains the central open question, and one this review can frame but not yet resolve.

12. CONCLUSION

Vaccines reach people only when manufacturing, financing, delivery, and trust align. India's post-COVID experience—supplying roughly 60% of global vaccine volume and about 43% of COVAX deliveries at a fraction of high-income prices—illustrates both the power and the fragility of a concentrated supply model. The pandemic's structural legacy is a deliberate move toward decentralised manufacturing, technology transfer, and regional self-sufficiency, alongside a broadening from childhood to life-course immunisation amid demographic ageing and a looming health-workforce shortfall. India's One Health manufacturing, digital infrastructure (Co-WIN/U-WIN), and last-mile ASHA network offer a candidate template for LMIC health sovereignty, while the SAGE framework reminds us that trust is as decisive as supply. The overarching lesson is that platform speed must be matched by equitable governance and resilient delivery; without both, scientific capability does not become immunisation.

13. Limitations and Conflict of Interest

As this is a structured narrative review rather than a systematic review with meta-analysis, source selection reflects the author's judgement, and selection bias cannot be excluded. Additionally, the literature search was predominantly restricted to English-language publications, introducing a possible language bias. Several claims rest on institutional reports rather than peer-reviewed primary data. Most importantly, IIL is an author affiliation, and Section 5 discusses IIL's One Health model, constituting a direct conflict of interest. To mitigate this, the IIL section relies exclusively on publicly verifiable sources (WHO prequalification records, the IIL Annual Report 2023, and FAO documentation), and readers should weigh that material accordingly.

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