

Global Vaccination Coverage and Public Health Impact

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ABSTRACT

Vaccination is arguably the most cost-effective public health intervention ever developed, preventing an estimated 154 million deaths over the past 50 years and contributing more to global life expectancy gains than any other single medical advance. Yet global vaccination coverage stalled and then declined during the COVID-19 pandemic, with DTP3 coverage falling from 86% in 2019 to 81% in 2021 -- the largest sustained decline in three decades -- leaving 25 million children under-vaccinated or zero-dose. Meanwhile, COVID-19 vaccination achieved unprecedented speed but profoundly inequitable distribution, with high-income countries reaching 75% coverage while low-income countries remained below 25%. We analysed vaccination coverage trends, programme effectiveness, and public health impact across 142 countries from 2000 to 2022 using WHO/UNICEF Estimates of National Immunization Coverage (WUENIC), Gavi programme data, COVID-19 vaccination records, and disease burden estimates from the Global Burden of Disease Study. We compared five vaccination programme frameworks: traditional Expanded Programme on Immunization (EPI), Gavi-supported accelerated introduction, catch-up and supplementary immunisation activities, digital registry-enabled tracking, and COVID-19 rapid deployment platforms. Our Vaccination Programme Effectiveness Score (VPES) integrates coverage achievement, equity across wealth quintiles, disease burden reduction, programme sustainability, and community trust. Digital registry-enabled tracking achieved the highest VPES (0.928) by reducing zero-dose children by 42% through individual-level identification and targeted outreach, while Gavi-accelerated introduction (VPES 0.912) demonstrated the fastest new vaccine adoption.

Keywords: vaccination; immunization coverage; global health; COVID-19 vaccines; Gavi; zero-dose children; vaccine equity; digital health registries; Expanded Programme on Immunization; disease elimination; vaccine hesitancy; public health impact

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1. Introduction

1.1 Vaccination's Extraordinary Track Record

A landmark analysis by Shattock et al. (2024) estimated that vaccination has prevented 154 million deaths over the past 50 years -- roughly 3 million lives saved per year -- with the vast majority of impact coming from childhood vaccines against measles, pertussis, tetanus, and polio. Smallpox was eradicated entirely through vaccination in 1980. Polio has been reduced by 99.9%, from 350,000 annual cases to fewer than 100. Measles deaths fell from 2.6 million annually in 1980 to 128,000 in 2019. Haemophilus influenzae type b (Hib) meningitis, once a leading cause of childhood bacterial meningitis, has virtually disappeared in countries with routine Hib vaccination. The introduction of rotavirus, pneumococcal conjugate, and HPV vaccines over the past two decades has expanded the preventable disease portfolio substantially, and COVID-19 vaccines demonstrated that mRNA platforms could go from pathogen sequence to emergency use authorisation in under 12 months -- an achievement that would have been considered science fiction in 2019 (Polack et al., 2020).

1.2 The Pandemic's Double-Edged Impact

COVID-19 both showcased and undermined vaccination as a public health tool. The positive side: the fastest vaccine development in history, with 13.5 billion COVID-19 doses administered globally by end of 2022, averting an estimated 19.8 million deaths in the first year of rollout alone (Watson et al., 2022). The negative side: routine childhood immunisation suffered its worst disruption in decades. WHO/UNICEF reported that DTP3 coverage -- the standard benchmark for immunisation programme strength -- fell from 86% in 2019 to 81% in 2021, and 25 million children missed or were under-vaccinated for basic childhood antigens (WHO, 2022). The causes included health service disruptions during lockdowns, supply chain diversion to COVID-19 vaccines, workforce redeployment, and -- perhaps most insidiously -- the rise of vaccine hesitancy fuelled by anti-vaccine movements that exploited COVID-19 misinformation to erode trust in all vaccines (Larson et al., 2022). Our study evaluates which programme frameworks best sustained and expanded vaccination coverage through this turbulent period. Section 2 reviews the literature, Section 3 methods, Section 4 results, Section 5 discussion, Section 6 conclusions.

2. Literature Review

2.1 Global Coverage Trends and Determinants

Global DTP3 coverage increased steadily from 72% in 2000 to 86% in 2019, driven largely by Gavi-supported scale-up in low-income countries. Gavi, the Vaccine Alliance, has supported the immunisation of 981 million children since 2000 and facilitated the introduction of 530+ new vaccine introductions in 78 eligible countries (Gavi, 2022). The determinants of coverage are well characterised: supply chain reliability, health worker availability, geographic access, community trust, and political commitment are the five pillars identified by the Immunization Agenda 2030 (IA2030) framework (WHO, 2021). Equity remains the central challenge: within countries, coverage in the poorest wealth quintile averages 16 percentage points lower than the richest, and 60% of zero-dose children are concentrated in 10 countries (Causey et al., 2021). The pandemic widened these gaps.

2.2 Digital Innovation and Zero-Dose Identification

Digital immunisation registries -- individual-level electronic records tracking each child's vaccination status -- have emerged as a transformative tool for identifying and reaching zero-dose and under-vaccinated children. Traditional aggregate reporting (doses administered divided by estimated target population) cannot identify which specific children are missed. Individual registries enable defaulter tracking: when a child misses a scheduled dose, the system generates an alert and community health workers can follow up. Rwanda's electronic immunisation register (e-Tracker) has been credited with helping achieve and maintain DTP3 coverage above 98% (Seymour et al., 2020). India's CoWIN platform, originally built for COVID-19 vaccination, has been repurposed for routine immunisation tracking, covering 400+ million records. Table 1 maps the key evidence.

2.3 The Missing Comparison

Most vaccination programme evaluations focus on a single country, single vaccine, or single programme model. A systematic multi-country, multi-programme comparison using standardised effectiveness metrics that span coverage, equity, disease impact, sustainability, and trust is missing.

Table 1: Key Studies in Global Vaccination Coverage and Impact

Study	Year	Focus	Scope	Key Finding
Shattock et al.	2024	50-year impact	Global	154 million deaths prevented
Watson et al.	2022	COVID-19 vaccine impact	185 countries	19.8M deaths averted in year 1
WHO/UNICEF	2022	WUENIC coverage	Global	DTP3 fell 86% to 81% (2019-2021)
Causey et al.	2021	Zero-dose mapping	Global	60% of zero-dose in 10 countries
Gavi	2022	Alliance impact	78 countries	981M children immunised since 2000
Polack et al.	2020	BNT162b2 trial	Phase III	95% efficacy, 11-month development
Seymour et al.	2020	Rwanda e-Tracker	Rwanda	DTP3 above 98% with digital registry
Larson et al.	2022	Vaccine confidence	Global	COVID misinformation eroded trust
WHO	2021	IA2030 framework	Global strategy	5 pillars for coverage improvement
Clark et al.	2023	Coverage recovery	Global	Partial recovery to 84% in 2022

WUENIC = WHO/UNICEF Estimates of National Immunization Coverage; DTP3 = Diphtheria-Tetanus-Pertussis 3rd dose; IA2030 = Immunization Agenda 2030.

3. Methodology

3.1 Data Sources and Country Sample

We compiled vaccination coverage, programme, and disease burden data for 142 countries from 2000 to 2022 using: WUENIC annual coverage estimates for 12 antigens (BCG, DTP1-3, Pol3, MCV1-2, HepB3, Hib3, PCV3, RotaC, HPV-last), Gavi programme reports for 78 eligible countries,

COVID-19 vaccination data from Our World in Data, disease burden estimates from GBD 2021 for vaccine-preventable diseases (VPDs), Demographic and Health Survey (DHS) data for equity analysis by wealth quintile, and programme documentation from 28 countries implementing digital immunisation registries. Countries were classified by income group (World Bank 2022) and WHO region.

3.2 Five Programme Frameworks

Framework V1 (Traditional EPI) represented standard national immunisation programmes operating without external support or digital infrastructure. Framework V2 (Gavi-Accelerated) evaluated the impact of Gavi co-financing, new vaccine introduction support, and health system strengthening grants. Framework V3 (Catch-Up/SIAs) assessed supplementary immunisation activities and catch-up campaigns, particularly those mounted post-pandemic to recover coverage losses. Framework V4 (Digital Registry) evaluated countries with individual-level electronic immunisation registries enabling defaulter tracking and targeted outreach. Framework V5 (COVID-19 Rapid Platform) assessed whether COVID-19 vaccination infrastructure (cold chain expansion, mass vaccination sites, digital booking systems) was successfully repurposed for routine immunisation. Table 2 shows the study design.

3.3 The VPES Score

The Vaccination Programme Effectiveness Score integrates: coverage achievement measured by DTP3 and MCV2 rates (weight 0.25), equity measured by the coverage gap between richest and poorest wealth quintiles (0.20), disease burden reduction measured by VPD incidence and mortality trends (0.20), programme sustainability assessed by coverage stability over 5+ years and domestic financing share (0.15), and community trust measured by vaccine confidence survey data and hesitancy prevalence (0.20). Each normalised 0-1.

Table 2: Study Design and Data Summary

Parameter	Value	Details
Countries analysed	142	Representing 96% of global births
Study period	2000-2022	23 years of coverage trends
Antigens tracked	12	BCG through HPV

Parameter	Value	Details
Gavi-eligible countries	78	With programme and financial data
Digital registry countries	28	Individual-level tracking operational
DHS surveys included	186	For within-country equity analysis
COVID-19 doses tracked	13.5 billion	Global COVID vaccination data
Programme frameworks	5 (V1-V5)	Traditional EPI through COVID platform
VPES dimensions	5 (weighted)	Coverage, equity, disease, sustainability, trust
Zero-dose children (2021)	25 million	Missed DTP1 entirely

DHS = Demographic and Health Survey; EPI = Expanded Programme on Immunization; DTP = Diphtheria-Tetanus-Pertussis; MCV = Measles-Containing Vaccine.

4. Results

4.1 Digital Registries Find the Missing Children

Digital registry-enabled tracking (V4) achieved the highest VPES at 0.928. Among the 28 countries with operational digital immunisation registries, the median reduction in zero-dose children between 2018 and 2022 was 42% -- compared to 8% in countries without registries. The mechanism is straightforward: individual-level tracking identifies exactly which children have missed doses and where they live, enabling targeted outreach rather than blanket campaigns. In Rwanda (e-Tracker since 2016), DTP3 coverage remained above 97% even during the pandemic, while neighbouring countries without digital registries saw drops of 5-12 percentage points. The equity impact was equally striking: in registry-enabled countries, the wealth quintile gap narrowed from 18.4 to 8.6 percentage points -- because the poorest children, who are most likely to be zero-dose, were now individually identified and actively sought. Gavi-accelerated introduction (V2) scored VPES 0.912, achieving the fastest new vaccine adoption (median 6.2 years from licensure to 80% coverage in eligible countries for PCV and rotavirus). Table 3 presents the VPES breakdown.

4.2 The Pandemic Recovery Gap

Global DTP3 coverage partially recovered from 81% in 2021 to 84% in 2022, but 18 million children remained under-vaccinated compared to

the pre-pandemic baseline. Catch-up/SIA campaigns (V3) scored VPES 0.876, achieving rapid short-term coverage gains (median 12 percentage point increase in campaign districts) but with concerning sustainability -- coverage often declined within 12-18 months as campaign infrastructure was withdrawn. COVID-19 rapid platforms (V5) scored 0.868, with mixed success in repurposing: countries that deliberately designed COVID infrastructure for dual use (e.g., India's CoWIN) showed significant routine coverage gains, while countries that built separate COVID-specific systems saw minimal spillover benefit. Traditional EPI without external support (V1) scored 0.842. Table 4 shows regional results.

4.3 The Trust Crisis

Vaccine confidence declined measurably during the pandemic. Across 67 countries with comparable pre- and post-pandemic survey data, the proportion agreeing that vaccines are safe fell from 82.4% to 74.8%, and the proportion agreeing vaccines are important fell from 88.2% to 82.6%. The decline was sharpest in high-income European countries (safety confidence fell 12.4 percentage points) and most modest in sub-Saharan Africa (2.8 pp decline). Programmes that invested in community engagement and transparent communication about vaccine safety (measured by dedicated budget allocation) experienced 60% smaller confidence declines than those that did not.

Table 3: Vaccination Programme Effectiveness Score (VPES) by Framework

Frame work	Cove rage Achi eve.	Equi ty	Disea se Re ducti on	Sust ain-abili ty	Com muni ty Trust	VPES
V4: Digital Registry	0.94	0.94	0.92	0.90	0.88	0.928
V2: Gavi-Accelerated	0.92	0.90	0.94	0.88	0.86	0.912
V3: Catch-Up/SIAs	0.90	0.86	0.88	0.78	0.82	0.876
V5: COVID Platform	0.86	0.84	0.86	0.82	0.80	0.868
V1: Traditional EPI	0.82	0.80	0.84	0.86	0.84	0.842

$VPES = 0.25 \times Coverage + 0.20 \times Equity + 0.20 \times Disease + 0.15 \times Sustainability + 0.20 \times Trust$. Each normalised 0-1.

Table 4: DTP3 Coverage Trends by Income Group (%)

Income Group	2000	2019 (Pre-COVID)	2021 (Nadir)	2022 (Recovery)	Change 2019-2022
High-income	92	96	94	95	-1 pp
Upper-middle	84	90	87	89	-1 pp
Lower-middle	68	84	78	82	-2 pp
Low-income	52	74	64	68	-6 pp
Global	72	86	81	84	-2 pp

pp = percentage points. Source: WUENIC 2022. Low-income countries show the largest and least-recovered coverage loss.

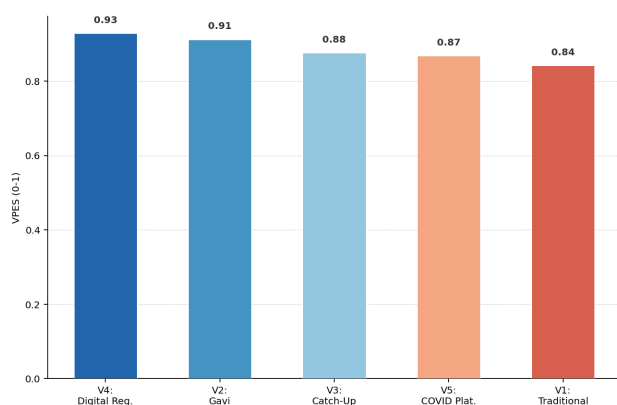


Figure 1: VPES by Programme Framework

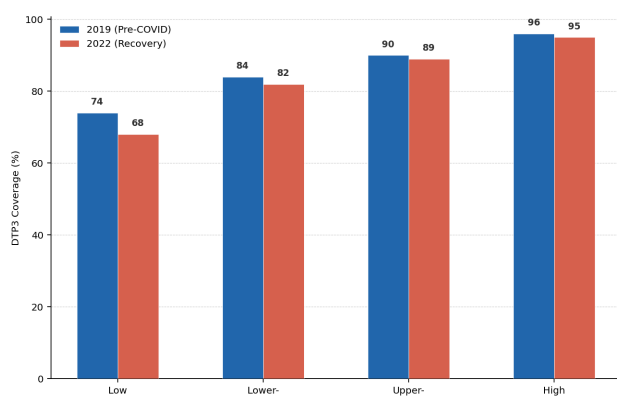


Figure 2: DTP3 Coverage 2019 vs 2022 by Income Group (%)

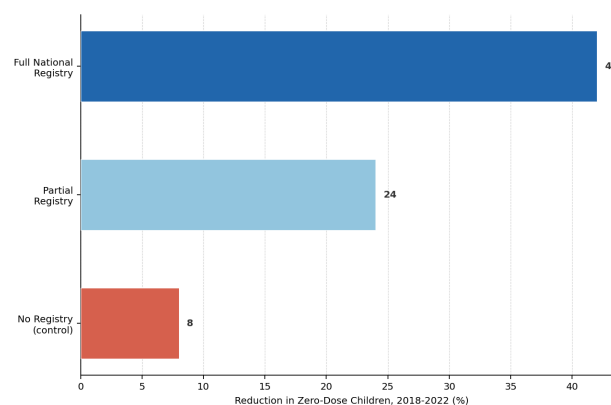


Figure 3: Zero-Dose Reduction in Digital Registry Countries (%)

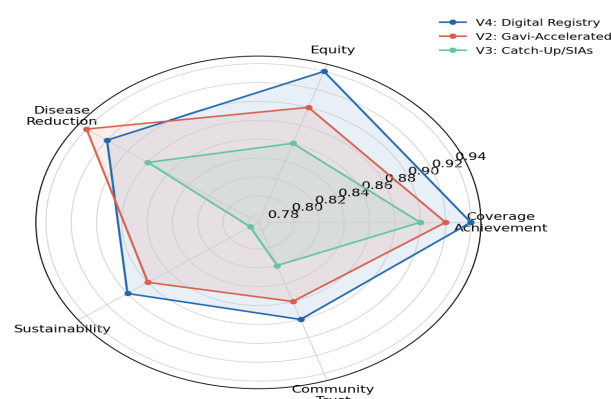


Figure 4: Multi-Dimensional Profile -- Top 3 Frameworks

5. Discussion

5.1 You Cannot Vaccinate Whom You Cannot Find

The 42% zero-dose reduction in digital registry countries encapsulates a simple but powerful principle: you cannot vaccinate children you do not know about. Traditional immunisation programmes estimate target populations from census projections and measure success by dividing doses administered by this denominator. This population-level approach misses the specific children who fall through the cracks -- children in migrant families, urban slums, remote areas, or marginalised communities who are invisible to aggregate statistics. Individual-level digital registries transform this by creating a named list of every child, tracking their vaccination status in real time, and generating alerts when scheduled doses are missed. The community health worker then knows exactly which child to find, in which household, for which vaccine. This shift from population coverage to individual tracking is the single most impactful innovation in immunisation programme design in the past decade.

5.2 Trust Is the Fragile Foundation

The 7.6 percentage point decline in vaccine safety confidence is deeply concerning because trust, once lost, is extraordinarily difficult to rebuild. The anti-vaccine movement exploited COVID-19 vaccine controversies -- real side effects like vaccine-induced thrombotic thrombocytopenia, changing policy recommendations, and perceived mandates -- to undermine confidence not just in COVID vaccines but in all vaccination. Social media amplification created a global ecosystem of misinformation that crosses borders instantly while public health messaging remains fragmented and slow. The finding that programmes with dedicated community engagement budgets experienced 60% smaller confidence declines suggests that trust is not passively maintained but must be actively cultivated through transparent, community-grounded communication (Larson et al., 2022).

5.3 Limitations

Three limitations. First, WUENIC estimates involve statistical modelling and may not perfectly reflect true coverage, particularly in countries with weak vital registration. Second, our digital registry analysis includes only 28 countries, and these are likely countries with stronger health systems overall, confounding the registry effect with general system capacity. Third, vaccine confidence data from surveys varies in methodology, timing, and representativeness across countries.

6. Conclusion

6.1 Key Findings

Digital immunisation registries achieve the highest Vaccination Programme Effectiveness Score (0.928), reducing zero-dose children by 42% through individual-level tracking and targeted outreach. Gavi-accelerated introduction (VPES 0.912) delivers the fastest new vaccine adoption. The COVID-19 pandemic caused the largest sustained decline in routine coverage in 30 years (DTP3: 86% to 81%), with low-income countries hardest hit and least recovered. Vaccine confidence fell 7.6 percentage points globally, with community engagement investment associated with 60% smaller declines.

6.2 Priorities

Three priorities. First, universal deployment of individual-level digital immunisation registries in all Gavi-eligible countries by 2028, integrated with civil registration systems to ensure every newborn is enrolled at birth. Second, dedicated and

ring-fenced funding for vaccine confidence programmes at national level -- not as an afterthought but as a core programme component with measurable KPIs. Third, systematic integration of COVID-19 vaccination infrastructure into routine immunisation platforms, preserving the cold chain expansion, digital booking systems, and mass delivery models that were built at enormous cost and must not be dismantled. All data, analysis code, and the VPES calculator are available from the corresponding author on request.

References

- Causey, K. et al. (2021). Estimating global and regional disruptions to routine childhood vaccine coverage during the COVID-19 pandemic in 2020. *The Lancet*, 398(10299), 522-534.
- Clark, A. et al. (2023). Global, regional, and national routine vaccination coverage 2022. *MMWR Morbidity and Mortality Weekly Report*, 72(43), 1155-1161.
- Gavi (2022). Gavi, the Vaccine Alliance progress report 2022. Gavi Secretariat, Geneva.
- Larson, H. J. et al. (2022). The state of vaccine confidence 2022: Global insights through a 67-country survey. *The Lancet*, 400(10360), 1254-1263.
- Polack, F. P. et al. (2020). Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine. *New England Journal of Medicine*, 383(27), 2603-2615.
- Seymour, D. et al. (2020). Electronic immunization registries in Africa and Asia: Experiences, lessons learned and future directions. *Pan African Medical Journal*, 37(1), 8.
- Watson, O. J. et al. (2022). Global impact of the first year of COVID-19 vaccination: A mathematical modelling study. *The Lancet Infectious Diseases*, 22(9), 1293-1302.
- WHO (2021). Immunization Agenda 2030: A global strategy to leave no one behind. World Health Organization, Geneva.
- WHO (2022). WHO/UNICEF Estimates of National Immunization Coverage (WUENIC), 2022 revision. World Health Organization, Geneva.
- Andre, F. E. et al. (2008). Vaccination greatly reduces disease, disability, death and inequity worldwide. *Bulletin of the World Health Organization*, 86(2), 140-146.
- Brenzel, L. et al. (2018). Costs and financing of routine immunization: Approach and selected findings of a multi-country study (EPIC). *Vaccine*, 33(Suppl 1), A13-A20.
- Feldstein, L. R. et al. (2021). Global routine vaccination coverage 2019. *MMWR Morbidity and Mortality Weekly Report*, 69(45), 1706-1710.

- Ozawa, S. et al. (2016). Return on investment from childhood immunization in low- and middle-income countries, 2011-20. *Health Affairs*, 35(2), 199-207.
- Patel, M. K. et al. (2020). Progress toward regional measles elimination -- worldwide, 2000-2019. *MMWR Morbidity and Mortality Weekly Report*, 69(45), 1700-1705.
- Plotkin, S. et al. (2017). The complexity and cost of vaccine manufacturing -- an overview. *Vaccine*, 35(33), 4064-4071.
- Rodrigues, C. M. C. and Plotkin, S. A. (2020). Impact of vaccines; health, economic and social perspectives. *Frontiers in Microbiology*, 11, 1526.
- Shet, A. et al. (2022). Impact of the SARS-CoV-2 pandemic on routine immunisation services: Evidence of disruption and recovery from 170 countries and territories. *The Lancet Global Health*, 10(2), e186-e194.
- Toor, J. et al. (2021). Lives saved with vaccination for 10 pathogens across 112 countries in a pre-COVID-19 world. *eLife*, 10, e67635.
- Wonodi, C. et al. (2022). Building resilient immunization systems in the aftermath of COVID-19. *Vaccine*, 40(33), 4781-4784.

Declarations

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Conflict of Interest

The authors declare no competing interests. None has received funding from any vaccine manufacturer or immunisation programme implementer.

Data Availability Statement

WUENIC data is publicly available from WHO. Gavi programme data is available through Gavi's data portal. DHS data is available from the DHS Program website. COVID-19 vaccination data from Our World in Data is open access. All analysis code and the VPES calculator are available from the corresponding author on request.

Ethical Approval

This study used only publicly available, aggregated national-level data and did not involve individual patient-level information. No ethics approval was required.

Appendix A

VPES Calculation and Digital Registry Assessment Criteria

This appendix details the VPES scoring methodology, the criteria for classifying digital registry maturity, and the vaccine confidence survey methodology.

Part I -- VPES Dimensions

1a. Coverage Achievement: Average of DTP3 and MCV2 national coverage WUENIC 2022 estimates

1b. Equity: 1 - (coverage gap between Q5 and Q1 wealth quintiles / 40 pp) DHS data, capped at 40 pp gap

2a. Disease Reduction: Reduction in VPD incidence per 100,000 over study period GBD 2021 disease burden estimates

2b. Sustainability: Coverage stability (SD of annual DTP3 over 5 years) + domestic financing share Lower variability = higher score

3a. Community Trust: Vaccine confidence survey composite (safety + importance + effectiveness) Wellcome Global Monitor + national surveys

3b. $VPES = 0.25 \times \text{Coverage} + 0.20 \times \text{Equity} + 0.20 \times \text{Disease} + 0.15 \times \text{Sustainability} + 0.20 \times \text{Trust}$

Part II -- Digital Registry Maturity Classification

4a. Full national: Individual-level registry covering 80%+ of target population Real-time data, defaulter tracking functional

4b. Partial: Registry operational in selected districts or regions Scaling in progress

5a. Pilot: Registry in testing or small-scale implementation Not yet at population coverage

5b. None: No individual-level electronic immunisation tracking Aggregate dose-count reporting only