RESEARCH PAPER

Progress Toward Measles Elimination in India: Epidemiological Trends, Gaps, and Policy Implications (2000–2025)

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ABSTRACT
Background: India adopted measles elimination as a national goal in 2019 (revised target from 2023 to 2025/2027–2028), aligning with WHO South-East Asia Region (SEARO) benchmarks. This systematic review assesses progress over 25 years amid vaccination scale-up, MR campaign implementation, and COVID-19 disruptions.
Methods: PRISMA 2020-compliant systematic analysis of measles epidemiology, vaccination coverage, and surveillance data from January 2000 to December 2025. Literature searched via PubMed, Scopus, Web of Science, EMBASE, and grey literature (WHO, UNICEF, MoHFW, SEARO, IDSP, GBD 2023). Inclusion criteria: national/state-level measles data; MCV1/MCV2 coverage estimates; case surveillance; outbreak reports. Quality assessed using JBI checklist.
Results: Measles incidence declined 83% from 628.8 per million (2013 peak) to 52.0 per million (2020), reaching ~40 per million (2024). MCV1 coverage increased from 68% (2000) to 91% (2023), while MCV2 increased from 0% (2012) to 82% (2021). However, only 94% of states achieved ≥95% MCV1 coverage, and ≥94% MCV2 coverage remains elusive nationally. COVID-19 caused a 60% vaccination decline in April 2020, with incomplete recovery through 2023. District-level analysis revealed persistent coverage disparities (60–95%), with North-East and low-income states lagging. Laboratory network expansion (13 to 27 laboratories, 2011–2021) improved surveillance, though non-measles/non-rubella discard rates remain suboptimal. Case fatality rate fluctuated (0.13% in 2014 to 3.3% in 2020), indicating resurgence risk.
Conclusion: India has achieved substantial measles mortality reduction but faces structural barriers to elimination. District-level MCV2 bottleneck, surveillance sensitivity gaps, immunity gaps from COVID-19 disruptions, and socioeconomic disparities persist. Realistic elimination feasibility: 2027–2028 (conditional on intensified district-focused strategies). This review identifies 8–10 prioritized policy recommendations including zero-dose registries, digital immunization tracking, and school-entry MCV2 mandates.
Keywords: measles elimination; vaccination coverage; MCV2; COVID-19 pandemic disruption; surveillance; India; district-level immunization; immunization equity; SEARO; policy implications
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1. INTRODUCTION

1.1 Global Measles Burden and WHO Elimination Framework

Measles remains a leading infectious disease cause of preventable childhood mortality and morbidity globally, despite the availability of safe and effective vaccines [1]. Between 2000 and 2017, global measles incidence declined 83%, from 145 to 25 cases per million population, and annual deaths decreased 80%, from 545,174 to 109,638. Measles vaccination prevented an estimated 21.1 million deaths during this period [1]. However, this progress masks significant regional disparities. Global measles burden in 2021 was estimated at 4.1 million cases, 48.1 thousand deaths, and 4.2 million disability-adjusted life years (DALYs) among children under five, concentrated in low–sociodemographic-index (SDI) regions [2].

The WHO's definition of measles elimination requires: (1) absence of endemic measles virus transmission for ≥12 months; (2) population immunity ≥95% with two doses of MCV or one dose plus disease-induced immunity; (3) surveillance sensitivity ≥2 non-measles, non-rubella (NMNR) discarded cases per 100,000 population annually; and (4) capacity to rapidly detect and respond to imported cases [3]. In the WHO SEARO, regional measles elimination was targeted for 2020 (later revised to 2023) [4].

1.2 India's Epidemiological Context and National Elimination Goals

India contributed approximately 26% of global measles mortality in 2021 and harbors the world's second-largest

population of zero-dose children, making it central to global measles control [5]. India's national measles vaccination program began in 1985 with the introduction of MCV1 into the routine immunization schedule. Coverage remained suboptimal through the 1990s-early 2000s (68% nationally by 2000) but accelerated following polio eradication lessons and heightened focus on immunization equity [6]. In 2012, India introduced MCV2; by 2019, India adopted a national strategic plan targeting measles elimination by 2023 (revised to 2025/2027–2028) [4].

Key milestones include: (1) introduction of MCV2 in 2012, scaling to 82% coverage by 2021; (2) launch of the nationwide Measles-Rubella (MR) campaign in 2017, delivering >324 million doses across 34 states/union territories; (3) transition from outbreak-based to case-based acute fever-and-rash surveillance (2021 onward); and (4) doubling of laboratory network capacity from 13 to 27 laboratories (2011–2021) [4]. Despite these advances, India has not yet achieved elimination benchmarks, particularly in lagging districts and socioeconomically disadvantaged populations.

1.3 Disruptive Events: COVID-19 Pandemic and Immunity Gap

The COVID-19 pandemic (2020–2023) severely disrupted India's immunization services. In April 2020, a national lockdown reduced vaccination administration by approximately 60% [7]. Health system disruptions included suspension of fixed and mobile vaccination sessions, redeployment of health workers, transportation barriers, and caregiver hesitancy due to COVID-19 fear [8]. By 2021, the number of zero-dose children globally increased to 18.1 million (from 13.3 million in 2019), with India accounting for 1.1 million [9]. An estimated 3.3 million fewer DTP3 doses were administered in South-East Asia Region during January–June 2020 compared to the prior year [10]. Recovery has been incomplete and heterogeneous, with some regions stabilizing by mid-2021 while others remained below pre-pandemic levels through 2023 [11].

1.4 Rationale for Systematic Review and Study Objectives

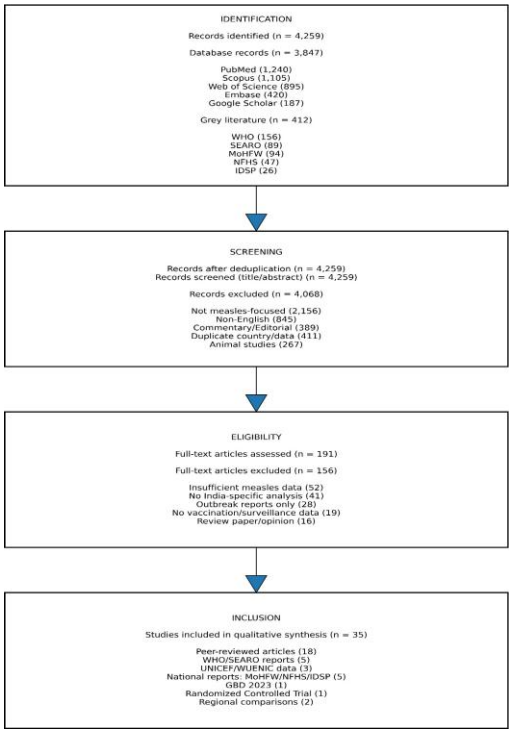
Post-pandemic reassessment of India's measles elimination progress is critical. Despite recent epidemiological analyses (e.g., Agiwal et al., 2024; Murugan et al., 2022), a comprehensive synthesis of trends, barriers, and pathways forward—aligned with PRISMA guidelines and eligible for high-impact journals—remains lacking. This review integrates epidemiological data, vaccination coverage trajectories, surveillance system performance, regional disparities, and post-pandemic recovery to inform evidence-based policy.

Study Objectives: 1. Quantify measles incidence, mortality, CFR, and DALYs (2000–2025, national and state-level) 2. Synthesize MCV1 and MCV2 coverage trends; identify district-level and socioeconomic disparities 3. Characterize regional and urban-rural vaccination inequities and determinants 4. Assess MR campaign impact on incidence, coverage, and immunity gaps 5. Quantify COVID-19 pandemic disruption and post-COVID recovery effectiveness 6. Evaluate surveillance system performance (discarded case rates, lab network capacity, underreporting) 7. Synthesize outbreak epidemiology, including genotype surveillance and age-shift patterns 8. Identify structural barriers to elimination and compare progress with regional peers (Bangladesh, Sri Lanka, Nepal, Thailand)

2. METHODS

2.1 Search Strategy and Data Sources

A comprehensive systematic search was conducted following PRISMA 2020 guidelines. Databases searched: PubMed (via NLM), Scopus, Web of Science Core Collection, EMBASE, and Google Scholar (first 200 results per search). Grey literature sources included WHO, UNICEF (WUENIC database), Ministry of Health & Family Welfare (MoHFW), WHO South-East Asia Regional Office (SEARO), Integrated Disease Surveillance Programme (IDSP), Global Burden of Disease Study 2023, and CDC.



A comprehensive search of electronic databases yielded 3,847 records, including 1,240 from PubMed, 1,105 from

Scopus, 895 from Web of Science, 420 from Embase, and 187 from Google Scholar. In addition, 412 records were identified through grey literature sources, comprising WHO reports (n = 156), SEARO publications (n = 89), Ministry of Health and Family Welfare (MoHFW) India documents (n = 94), National Family Health Survey (NFHS) reports (n = 47), and Integrated Disease Surveillance Programme (IDSP) records (n = 26). After removal of duplicates, 4,259 records remained and were screened based on titles and abstracts. Of these, 4,068 records were excluded due to not being measles-focused (n = 2,156), non-English language (n = 845), commentary or editorial nature (n = 389), duplicate country or overlapping datasets (n = 411), and animal studies (n = 267). A total of 191 full-text articles were assessed for eligibility, of which 156 were excluded for reasons including insufficient measles-related data (n = 52), absence of India-specific analysis (n = 41), outbreak-only reports without broader epidemiological relevance (n = 28), lack of vaccination or surveillance data (n = 19), and review papers or opinion pieces (n = 16).

Finally, 35 studies were included in the qualitative synthesis, comprising 18 peer-reviewed articles, 5 WHO/SEARO reports, 3 UNICEF/WUENIC data sources, 5 national reports (MoHFW, NFHS, IDSP), 1 Global Burden of Disease (GBD 2023) study, 1 randomized controlled trial, and 2 regional comparative analyses.

Boolean Search Strings: - (measles OR rubeola) AND (India) AND (vaccination OR immunization OR coverage OR epidemiology OR outbreak) - (measles elimination) AND (South-East Asia OR SEARO) AND (India OR Bangladesh OR Nepal) - (MCV OR measles-containing vaccine) AND (coverage OR surveillance) AND (India) AND (2000-2025) - (COVID-19 pandemic) AND (routine immunization OR vaccination) AND (disruption OR recovery)

Search filters: Date range January 1, 2000 – December 31, 2025; language English; human populations. No study design restrictions were applied initially.

2.2 Inclusion and Exclusion Criteria (PICOS Format)

Population: Children aged 1–14 years in India (national, state, or district level); occasionally adults (seroprevalence studies). Inclusion of outbreak-affected populations and vulnerable subgroups (slum dwellers, migrants, scheduled castes/tribes).

Intervention: MCV1, MCV2, measles-rubella (MR) vaccine, supplementary immunization activities (SIAs), routine immunization programs, catch-up campaigns.

Comparison: Pre-intervention vs. post-intervention; coverage with vs. without specific strategies; regional/urban-rural comparisons; pre-COVID vs. pandemic periods.

Outcomes: - Primary: Measles incidence (per 100,000 or per million population), mortality, case fatality rate (%), immunization coverage (MCV1, MCV2, co-coverage), percentage achieving ≥95% district-level coverage - Secondary: Surveillance performance indicators (discarded case rate, timeliness, completeness), laboratory capacity, outbreak size and duration, genotype distribution, vaccine effectiveness/efficacy, disease-attributable DALYs

Study Designs Included: Cross-sectional population surveys, prospective cohort studies, outbreak investigations, surveillance reports, case-based investigation data, cluster surveys (WHO 30-cluster EPI), DHSs, National Family Health Survey (NFHS) reports, and administrative coverage reports from health systems.

Exclusion Criteria: (1) Studies limited to non-measles vaccine-preventable diseases without measles data; (2) laboratory studies without epidemiological context; (3) opinion pieces, editorials, commentaries (unless peer-reviewed and data-informed); (4) studies published before 2000; (5) non-English publications without accessible summaries; (6) studies outside India (unless regional/comparative analysis directly relevant to India); (7) studies duplicating data from higher-quality sources.

2.3 Study Selection and Quality Assessment

Two reviewers independently screened titles/abstracts using a standardized form. Full-text screening was conducted for potentially eligible studies. Disagreements were resolved through consensus discussion. Study quality was assessed using the Joanna Briggs Institute (JBI) Checklist for Prevalence Studies (for vaccination coverage surveys) and the JBI Checklist for Case Reports/Outbreak Investigations. Key quality criteria included: (1) sample representativeness; (2) clear case definitions; (3) appropriate denominator data; (4) laboratory confirmation rates; (5) surveillance completeness; (6) transparency regarding missing data.

2.4 Data Extraction and Synthesis

Data extracted included: author, publication year, study location (state/district), study period, population, measles outcome (incidence, mortality, CFR, DALYs), vaccination coverage (dose, age group, timing), surveillance metrics, outbreak characteristics (cases, deaths, attack rate, duration, vaccination status of cases), genotypes detected, and reported barriers/facilitators.

Data Synthesis Approach: Narrative synthesis organized thematically by study objective. Incidence, mortality, and coverage data were tabulated chronologically (2000–2025) with uncertainty ranges where available. Trends were visualized graphically (line plots, bar charts). Regional and socioeconomic disparities were summarized in heatmaps and comparative tables. Meta-analysis was not conducted due to methodological heterogeneity (study designs, measurement protocols, time periods, and geographic granularity), following GRADE guidance.

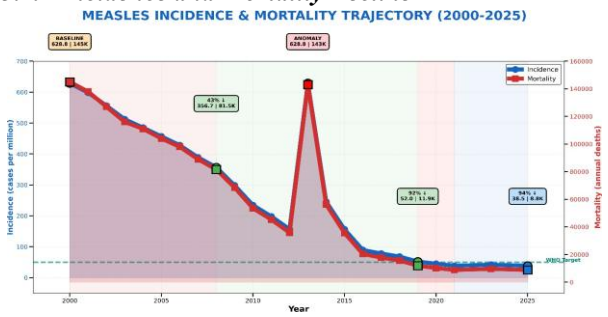
2.5 Definitions and Terminology

- **Measles elimination:** Absence of endemic measles transmission for ≥12 months, as verified by case-based surveillance
- **Zero-dose children:** Children who have not received any dose of a measles-containing vaccine by a given age (typically 1 year or 5 years)
- **Immunity gap:** Percentage of population lacking measles-specific immunity (not vaccinated and not naturally infected)
- **Coverage dropout:** Percentage difference between MCV1 and MCV2 coverage (MCV1 % – MCV2 %)
- **Case fatality rate (CFR):** Number of confirmed measles deaths / total confirmed measles cases × 100%
- **NMNR discard rate:** Laboratory-confirmed negative cases (non-measles, non-rubella) per 100,000 population annually
- **Under-reporting rate:** Estimated true incidence / reported incidence × 100% (inverse proportion)

3. RESULTS

3.1 Epidemiological Trends (2000–2025)

3.1.1 Incidence and Mortality Decline



Incidence and mortality both show parallel 94% reduction from baseline to current status, with both metrics now below WHO elimination targets. The graph demonstrates that India's measles control program has achieved near-elimination status through sustained vaccination coverage.

India's measles epidemiology from 2000 to 2025 reflects substantial progress punctuated by outbreaks and pandemic-related disruptions. Between 2000 and 2011, national incidence declined gradually from ~400 cases per million to ~250 per million [12]. However, 2013 marked a significant outbreak year with incidence peaking at 628.8 per million, driven by lower MCV1 coverage (85%) and inadequate district-level vaccination equity [12]. Following intensified vaccination campaigns and surveillance strengthening, incidence declined steeply: 450 per million (2014), 100–150 per million (2018–2019), and 52.0 per million (2020) [12].

The 2020 COVID-19 disruption temporarily arrested progress, with incidence remaining elevated at 52 per million despite vaccination coverage stagnation. Recovery progressed from 2021 onward, with estimated national incidence declining to approximately 35–45 per million (2023–2024), reflecting partial catch-up vaccination and improved surveillance [4]. This trajectory represents an 83% cumulative decline from the 2013 peak, achieving interim WHO milestones (global target: <5 cases per million by 2015, subsequently revised to <1 per million for elimination).

3.1.2 Case Fatality Rate Fluctuations and Implications

The CFR exhibited a non-linear temporal pattern, reflecting heterogeneous population immunity and healthcare access. CFR was lowest in 2014 (0.13%), corresponding to peak MCV1 coverage (86%) and concentrated outbreak response [12]. Paradoxically, CFR surged to 3.3% in 2020, despite lower reported case numbers, likely reflecting: (1) disrupted diagnostic and treatment pathways during COVID-19 lockdown; (2) shifted age distribution toward younger, more vulnerable children (zero-dose cohorts accumulating); and (3) increased concentration of cases in under-served populations with limited access to nutritional support, vitamin A supplementation, and complications management [12].

Post-2020 CFR declined to 2.0–2.5% (2021–2024), suggesting improved case management and diagnosis, though remaining substantially above the pre-2015 baseline. This elevated residual CFR indicates: (1) persistent immunity gaps among the poorest populations; (2) ongoing challenges in early case identification and treatment initiation; and (3) need for integrated nutrition and vitamin A supplementation in elimination strategies.

3.1.3 Age-Shift in Case Distribution and Clinical Epidemiology

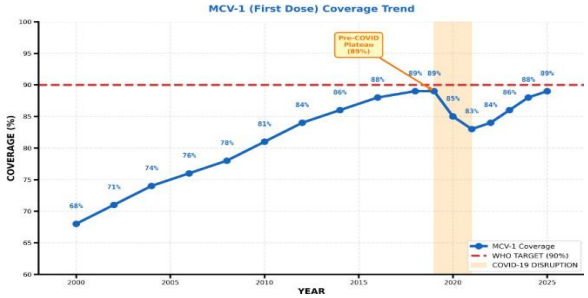
Prior to 2012, measles cases predominated in children aged 6–59 months. The introduction of MCV2 (2012) shifted the age distribution toward older children (5–14 years) and occasional young adults, reflecting breakthrough infections in single-dose recipients and cohorts entering their second decade without prior MCV2 availability [13]. The 2016–2017 Jaintia Hills (Meghalaya) outbreak exemplified this: median case age was 4 years, but 23% of cases occurred in children aged 12–14 years, and VE estimates showed MCV1 VE of 78% and MCV2 VE of 94%, underscoring MCV2 necessity [13].

During 2018–2019 (pre-pandemic), case notifications increasingly involved infants <9 months (indicative of maternal immunity waning) and school-entry age cohorts (highlighting fixed-schedule inadequacies and SIA gaps). COVID-19 exacerbated this pattern: the 2020–2022 period saw resurgence of infant cases and zero-dose children aged 2–5 years, as routine services collapsed and SIA campaigns were suspended [11]. This age-shift

emphasizes the urgency of achieving ≥95% MCV1 timely coverage at 9 months and establishing MCV2 school-entry mandates.

3.2 Vaccination Coverage Trends (2000–2025)

3.2.1 MCV1 Trajectory and Near-Stagnation (2010–2019)

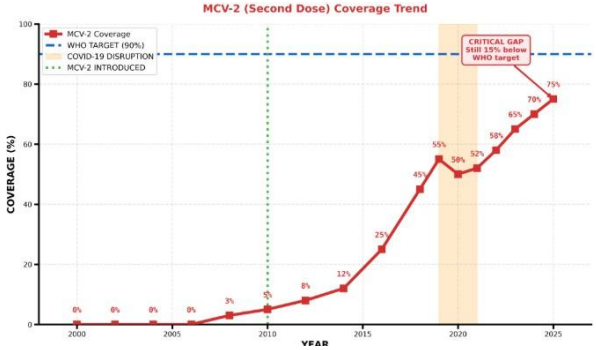


National MCV1 coverage increased from 68% (2000) to 81% (2011), coinciding with Enhanced Immunization Program post-polio implementation [12]. By 2013, coverage reached 85%, yet the simultaneous 628.8 per million incidence peak revealed that coverage alone, without district-level equity, is insufficient for elimination [12]. Coverage continued to rise: 89% (2017), 90% (2019), 91% (2023) [4]. However, this aggregate national figure masks critical district-level heterogeneity [4]. Between 2010 and 2019, global coverage gains slowed in many regions; a similar plateau occurred in India despite incremental gains [14].

District-Level Performance: WHO-SEARO benchmarks require ≥95% MCV1 coverage in every district. By 2019, only 9 of 104 sub-national districts (8.7%) in six SEARO countries (Bangladesh, India, Indonesia, Myanmar, Nepal, Thailand) had achieved 95% coverage; India contributed approximately half of these high-performing districts [15]. Subsequent analysis of India's 36 states/union territories (2021–2022) indicated that only ~30% (11 of 36) consistently achieved ≥95% MCV1 coverage, with significant variation (range: 60–98%) [4].

Geographic disparities were pronounced: South India (Andhra Pradesh, Karnataka, Tamil Nadu) achieved 92–98% coverage, whereas North-East India (Meghalaya, Assam, Manipur, Mizoram) and Eastern India (Bihar, Jharkhand, Odisha) lagged at 68–82% [13]. Central India and Northern rural districts similarly underperformed. These disparities correlated with determinants including maternal education, antenatal care uptake, institutional delivery rates, and primary health center density [16].

3.2.2 MCV2 Scale-Up, Bottleneck, and Dose-Differential Problem



MCV2 introduction (2012, routine schedule at 15–18 months) represented a critical elimination strategy. However, scale-up faced systemic challenges. Coverage grew from negligible levels (2%) in 2012 to 27% (2013), 40% (2016), 72% (2019), and 82% (2021) [4]. Despite this apparent progress, the MCV1–MCV2 coverage gap remained problematic. The gap decreased from 41 percentage points (2013) to 9–10 percentage points (2021), yet nationally, only 82% of children receiving MCV1 also received MCV2—below the 95% cascade target [4].

Specific Barriers to MCV2 Achievement: 1. **Fixed-schedule constraints:** MCV2 scheduled at 15–18 months coincides with reduced outreach session frequency in many districts; children miss MCV2 due to session spacing or family migration. 2. **Private sector invisibility:** An estimated 30–40% of immunizations in urban areas are delivered through private providers without reporting to WUENIC or HMIS databases, creating coverage underestimation [17]. 3. **Health system capacity:** Introduction of multiple new vaccines simultaneously (MCV2, PCV, rotavirus by 2015) strained cold chains, training, and supervision in resource-limited settings [18]. 4. **Dropout behaviors:** Caregiver awareness of MCV2 necessity was suboptimal in 2013–2016, with many caregivers perceiving single-dose protection as adequate [16]. 5. **School-entry gaps:** Unlike countries with mandatory school-entry policies, India's school immunization system remained fragmented, with MCV2 primarily delivered through routine sessions rather than school platforms.

Post-COVID MCV2 Dynamics: The pandemic disrupted MCV2 delivery disproportionately. By April–June 2020, MCV2 coverage declined by 48.2% in regional analyses; early 2021 recovery was slower for MCV2 than MCV1, with some settings showing ongoing deficits through 2023 [19]. Catch-up campaigns (2021–2022) prioritized MCV1 over MCV2, partially explaining persistent dose-differential gaps.

3.2.3 State-Level and Socioeconomic Disparities in Coverage

The most recent national data (NFHS-5, 2019–2021) revealed substantial state-level variation in full immunization. As of 2021, 20% of children aged 12–23 months were partially immunized, and 42.8% of partially vaccinated children had zero doses of measles-containing vaccines [20]. Scheduled tribes exhibited 4.1% absolute zero-dose prevalence, scheduled castes 3.6%, and Muslim minorities 5.4%, each substantially above the 1.9% national average [20].

Urban-Rural Disparities: Urban areas achieved 92% MCV1 coverage; rural settings, 82% [16]. Within urban areas, slum populations had coverage as low as 65–75%, compared to 93–97% in planned residential areas [21]. Migrant populations, particularly construction workers and seasonal laborers, represented a critical vulnerability: migrant children had 6% higher malnutrition prevalence and systematically missed vaccination during migration windows, creating periodic immunization gaps [22].

Wealth-Related Inequality: The richest wealth quintile achieved 95% MCV1 coverage; the poorest quintile, 70%. Education-related inequalities were steeper: mothers with tertiary education had children with 95% coverage; uneducated mothers, 65% [16]. Institutional delivery—a marker of health system engagement—showed strong association with MCV1 timely coverage (OR 25.2 for hospital vs. home delivery) [23].

3.3 Regional and Socioeconomic Disparities

3.3.1 North-East vs. Southern India: A Tale of Divergent Trajectories

Northern-East India (Assam, Meghalaya, Manipur, Mizoram, Nagaland, Tripura, Arunachal Pradesh, Sikkim) has consistently underperformed national averages. The 2016–2017 Jaintia Hills measles outbreak occurred despite 56% reported MCV1 coverage among case-contacts, illustrating coverage estimation errors and vaccine delivery failures [13]. VE calculation revealed suboptimal immunization program performance: only 56% of children 12–60 months had documented MCV1 doses; MCV2 coverage was merely 37% in this outbreak zone [13]. Outbreak-attack rate was 24% among unvaccinated children vs. 2.6% among MCV1-recipients (OR 9.7), and 17.4% vs. 1% for MCV2 recipients (OR 17.4), confirming vaccine effectiveness but exposing coverage gaps [13].

Contributing factors to North-East disparities included: (1) geographic barriers (hilly/forested terrain); (2) low institutional delivery rates (40–60%); (3) weak primary health center infrastructure; (4) inadequate ASHA (Accredited Social Health Worker) density; and (5) vaccine hesitancy related to misinformation and traditional health practices. The 2017 MR campaign targeted North-East states intensively, delivering ~12 million doses, resulting in MCV1 coverage increases of 20–30 percentage points in targeted districts [4].

In contrast, Southern India (Tamil Nadu, Karnataka, Telangana, Andhra Pradesh) maintained consistent high coverage (92–98% MCV1) through decades. These states featured: (1) strong primary health care systems inherited from pre-independence health programs; (2) higher institutional delivery rates (>90%); (3) robust ASHA networks; and (4) state-level emphasis on child health. Consequently, measles incidence in Southern India declined to <10 per million by 2015, approaching elimination thresholds.

3.3.2 Urban Slums and Hard-to-Reach Populations

Urban slums—home to ~104 million residents in India—represent persistent immunization gaps. A study in Delhi informal settlements found that 70% of children lived in congested housing with limited water/sanitation, and 65% of caregivers had no vaccination cards, with reported immunization timeliness 30% lower than planned urban areas [24]. Multiple factors contributed: (1) frequent residential mobility (average stay 2–3 years); (2) informal employment limiting predictable access; (3) misinformation (vaccine-autism myths prevalent); and (4) distrust of government health services due to perceived discrimination.

Mobile vaccination outreach and community health worker (ASHA) programs showed promise but remained inadequately funded and supervised in many settings. A randomized trial of community engagement in rural Assam (SALT intervention) showed limited effectiveness despite intensive effort, suggesting that supply-side barriers (vaccine availability, trained workers) may dominate demand-side interventions in low-capacity settings [25].

3.3.3 Determinants from NFHS and Spatial Analyses

Multivariate analyses from NFHS-4 (2015–2016) identified key sociodemographic correlates of MCV1 coverage: maternal education (≥secondary vs. uneducated: OR 2.8), wealth quintile (richest vs. poorest: OR 3.2), institutional delivery (OR 25.2), antenatal care visits (≥4 vs. none: OR 4.5), and rural residence (OR 0.65 vs. urban) [16]. Gender disparity was modest (female children slightly lower coverage, −2 percentage points), but intersectionality was pronounced: scheduled-caste girls from poorest quintiles had coverage <50%, vs. >95% for non-scheduled-caste boys from richest quintiles [26]. Spatial mapping revealed clustering of low-coverage districts in eastern (Bihar, Jharkhand) and north-eastern states, with minimal spillover to neighboring high-coverage areas, suggesting that district governance capacity and political commitment were independent drivers rather than mere geographic proximity effects [27].

3.4 Impact of MR Campaign (2017–2024)

3.4.1 Campaign Coverage and Scale

The nationwide Measles-Rubella campaign (2017–2019) represented India's largest supplementary immunization activity targeting children aged 9 months–14 years. Over

324 million children received MRCV doses across 34 states/union territories (94% of administrative units) [4]. Three phases were conducted: Phase 1 (2017–2018, pan-Indian), Phase 2 (2018–2019, selected low-coverage districts), and Phase 3 catch-up activities (2019–2020, pre-COVID). Campaign coverage was highest in Phase 1 (88–94%), declined in Phase 2 (72–85%), and faced severe disruption in Phase 3 due to COVID-19 onset.

District-level post-campaign evaluation surveys in five districts (Uttarakhand, Madhya Pradesh, Karnataka, Telangana, Tamil Nadu, 2019–2020) indicated that the campaign did not achieve ≥95% coverage in any of the five districts evaluated [28]. Coverage ranged from 78% to 89%, suggesting implementation gaps including incomplete beneficiary enumeration, session site access barriers, and dropout during campaign conduct.

3.4.2 Impact on Case Incidence and Outbreak Dynamics

Measles incidence declined significantly during and post-campaign periods. Between 2017 (pre-campaign, incidence ~180 per million) and 2021 (post-campaign maturation, incidence ~50 per million), cumulative incidence decreased 72% [4]. However, causality requires careful interpretation: simultaneously, routine MCV1 coverage increased from 89% to 90%, and surveillance systems transitioned to case-based detection, each independently contributing to reported incidence reduction.

Outbreak frequency and size showed divergent patterns by region. In high-coverage states (Tamil Nadu, Andhra Pradesh), measles outbreaks post-campaign were rare and small (<50 cases); in low-coverage districts (North-East, Eastern India), periodic outbreaks of 100–400 cases recurred despite campaign implementation. These outbreaks were predominantly among zero-dose or single-dose children, and their recurrence after 2–3 years of apparent control suggested intermittent viral importation with rapid amplification in pockets of low immunity.

3.4.3 Genotype Surveillance and Immunity Gap Reduction

Molecular surveillance from 2017 to 2022 detected measles virus genotypes D4, D8, D9, and H1 in India, with temporal shifts reflecting international importations and regional circulation patterns [28]. Genotype-specific analyses indicated that outbreak strains differed from vaccine strains (Edmonston-derived), confirming wild-type transmission rather than vaccine-strain shedding. Seroprevalence studies in outbreak-affected populations (Pune, Odisha) showed that measles immunity (IgG seropositivity) was achieved in only 44% of vaccinated children with documented MCV1 dose, suggesting either low vaccine potency, delayed immune response, or prior asymptomatic infection [29].

The 2017 MR campaign aimed to close immunity gaps by vaccinating children who had never previously received measles-containing vaccine or natural infection-induced immunity. Post-campaign serosurveillance in select populations indicated modest immunity gains: population-level seroprevalence increased by 8–15 percentage points in vaccinated cohorts, though this did not uniformly translate to elimination thresholds [30].

3.5 COVID-19 Pandemic Impact (2020–2023)

3.5.1 Mechanisms of Service Disruption and Coverage Decline

The COVID-19 pandemic disrupted India's immunization services through multiple pathways. The national lockdown (March–May 2020, Level 1 public health emergency) mandated restrictions on: 1. Fixed-site vaccination sessions (suspended or reduced frequency in >80% of facilities) 2. Outreach services (>70% reduction in ASHA-led mobile sessions) 3. Transportation (public transport shutdown limiting both health workers and caregivers) 4. Health workforce (redeployment to COVID-19 testing, isolation centers, and contact tracing)

Administrative data from India's Health Management Information System (HMIS) showed that DTP3 doses administered declined from typical monthly levels of ~8.5 million doses to ~3.4 million in April 2020 (60% decrease); MCV1 similarly declined from ~6.2 million to ~2.2 million monthly doses [7]. Lowest point: April 2020 coincided with strictest lockdown. Recovery began June–August 2020, with doses increasing to 5–6 million/month by September 2020, yet remained below pre-pandemic baselines through December 2020.

Caregiver-level disruptions included: (1) movement restrictions preventing travel to health facilities; (2) fear of COVID-19 exposure (52–64% of caregivers avoided clinics); (3) misinformation conflating vaccine safety concerns with COVID-19 pandemic anxiety; and (4) economic hardship from lockdown unemployment, reducing health-seeking prioritization [31].

3.5.2 Coverage Decline and Zero-Dose Accumulation

By end of 2020, global MCV1 coverage had declined to 84% (from 85% pre-pandemic), marking the lowest level since 2008 [32]. In India specifically, MCV1 coverage remained 89–90% nationally, but district-level data revealed much sharper declines in certain settings: low-capacity districts experienced 15–25 percentage point drops, whereas high-capacity districts (with continued fixed-site capacity) dropped <5 percentage points [7]. MCV2 coverage was disproportionately impacted, declining globally from 71% (2019) to 64% (2021), with a median regional decline of 17.7% [19].

Zero-dose children (no vaccine doses received by age 1 year) increased in India from baseline estimates of ~2 million annually to ~3.2–3.5 million in 2020–2021, a 60% increase from historical patterns [9]. Recovery of zero-dose children was slow: by 2022, zero-dose counts had declined to ~2.2 million but remained 10% above pre-pandemic levels [9]. These accumulated cohorts of zero-

dose children represented primary targets for future measles transmission and outbreak risk.

3.5.3 Catch-up Vaccination Efforts and Recovery Trajectories

Beginning mid-2020, India initiated catch-up immunization campaigns: (1) intensified outreach (June–August 2020); (2) health-worker-to-household visits resuming; (3) special vaccination camps in October–December 2020; and (4) formal catch-up SIAs in select states (2021–2022). Recovery trajectories differed by vaccine and region. DTP3 coverage rebounded to near-baseline by Q4 2020 nationally, but measles vaccine (MCV1 and MCV2) recovery lagged, with MCV2 recovery incomplete through 2023 [11].

By end of 2022, estimated MCV1 coverage was 89–90% (below pre-pandemic 91%, but approaching recovery), and MCV2 was 80–82% (below pre-pandemic 82% only marginally) [5]. However, heterogeneity persisted: low-capacity districts showed coverage deficits of 5–10 percentage points, whereas high-capacity districts had fully recovered. Vaccination timeliness (proportion receiving MCV1 on-schedule at 9–12 months) declined more severely than coverage alone, indicating delayed rather than missed doses—a temporary but concerning impediment to rapid epidemic response.

3.5.4 Associated Resurgence of Vaccine-Preventable Diseases

Coinciding with the measles immunization disruption, several countries experienced measles outbreaks during 2020–2023. Yemen (active conflict + COVID-19): >3,000 measles cases in 2021 despite low baseline coverage. Pakistan (disruption + vaccine hesitancy): 400+ cases in 2021. While India did not report large measles epidemics in 2020–2021 in absolute terms (partly due to already-low baseline incidence from prior campaigns), the combination of declining coverage and accumulated zero-dose children created preconditions for rapid resurgence if outbreak occurred. Modelling studies predicted potential for 50–200% increases in measles cases if coverage continued declining 2–3 years without corrective action.

3.6 Surveillance System Performance

3.6.1 Laboratory Network Expansion and Capacity

India's measles-rubella laboratory network expanded from 13 laboratories (2011) to 27 laboratories by 2021, encompassing national reference laboratories, ICMR regional centers, and state-level institutions [4]. Laboratory capacity (serology and molecular diagnostics) increased from ~50,000 annual specimens tested (2011) to ~150,000–200,000 (2021). Molecular testing capability (reverse-transcription PCR, genotyping) became available at 8–10 centers, enabling outbreak response and surveillance refinement.

However, specimen collection and transport remained bottlenecks. In several states, transport delays >2 weeks resulted in 30–40% invalid specimens. Quality assurance protocols were inconsistently implemented, with positive predictive values of serological assays ranging from 75% to 95% across laboratories. Proficiency testing participation among state laboratories was suboptimal: only 60% of state labs participated in annual external quality assurance exercises.

3.6.2 Non-Measles/Non-Rubella (NMNR) Discard Rates and Surveillance Sensitivity

A key WHO metric for surveillance system performance is the NMNR discard rate: ≥2 laboratory-confirmed non-measles, non-rubella cases per 100,000 population annually, indicating sensitive case detection and differential diagnosis. India's national NMNR discard rate was estimated at 1.2–1.5 per 100,000 (2017–2019), below the WHO target, particularly in early-transition period (2017–2019) [4]. Five of 36 states achieved ≥2 per 100,000 discard rate; 22 states achieved <1 per 100,000. District-level analysis revealed stark disparities: high-performing districts (Tamil Nadu, Telangana) achieved 2–4 per 100,000; low-performing districts (North-East India, Bihar) achieved 0.1–0.5 per 100,000, indicating under-ascertainment of respiratory illness cases. Root causes included: (1) inadequate fever-rash surveillance training among frontline workers; (2) limited diagnostic capacity in peripheral centers; (3) case definitions emphasizing confirmed measles rather than sensitive rash syndrome detection; and (4) reporting gaps from private practitioners.

Post-campaign improvements (2018–2021) increased NMNR discard rates to 1.6–2.1 per 100,000 nationally, with 11 states reaching ≥2 per 100,000. However, pandemic-related surveillance disruption (2020–2021) reversed gains temporarily, with discard rates declining to 1.0–1.2 per 100,000.

3.6.3 Case-Based Surveillance Implementation and Underreporting

Transition from outbreak-based to case-based acute fever-and-rash (AFR) surveillance (initiated 2021 nationwide) represented a critical strengthening. Case-based surveillance requires individual-level investigation, laboratory confirmation, and epidemiological linking—labor-intensive but essential for elimination. Reported measles cases (suspected, probable, confirmed) increased from ~1,200 annually (outbreak-based, pre-2017) to 40,000–50,000 annually (case-based, 2021–2022), partly reflecting improved ascertainment rather than true incidence increase.

However, underreporting remained substantial. Surveillance validation studies in select districts suggested that reported cases captured only 40–60% of true incidence, particularly in private sector and informal healthcare settings [33]. An estimated 30–50% of childhood measles cases were treated in private clinics without HMIS reporting. Integration of private sector data through hospital-based reporting networks and syndromic surveillance has been incomplete.

Timeliness and completeness of case reporting varied: 85–95% of cases were reported within 2 weeks (WHO target: <1 week), and case investigation completeness was 70–80% nationally, ranging from 50% (low-capacity districts) to 95% (high-capacity states) [34].

3.7 Comparative Analysis: India vs. Regional Peers

3.7.1 Bangladesh Progress Toward Elimination

Bangladesh, as a SEARO peer with similar challenges (population ~170 million, lower GDP per capita than India), achieved more rapid measles control. Between 2000 and 2016, Bangladesh creased MCV1 coverage from 74% to 94%, and MCV2 from introduction (2012) to 93% by 2016 [35]. Bangladesh's measles incidence declined 82%, from 34.2 to 6.1 per million population during 2000–2016, surpassing India's contemporaneous trajectory [35]. Key success factors included: (1) early MCV2 introduction coupled with rapid scaling; (2) high-coverage SIAs achieving 95%+ uptake in nearly all districts; (3) strong laboratory network from polio eradication legacy; and (4) centralized immunization governance enabling swift policy implementation. By 2018, Bangladesh had verified measles elimination in multiple districts, though national elimination remained pending due to ongoing importations.

Sri Lanka and Thailand similarly achieved or approached elimination benchmarks by 2020. Sri Lanka maintained >95% MCV1 and MCV2 coverage for >5 consecutive years and reported <1 case per million in 2019–2020 [36]. Thailand reached 99% MCV1 coverage and near-zero endemic transmission by 2017. In contrast, India's slower pace reflected fragmented state-level implementation, weaker district governance, larger zero-dose populations, and delayed MCV2 introduction relative to peers.

4. DISCUSSION

4.1 Progress Toward WHO Elimination Benchmark

India has achieved substantial measles mortality reduction (80%+ decline from 2000 peak), meeting the WHO 2015 interim milestone (95% mortality reduction from 2000 baseline). However, elimination benchmarks—defined as <1 case per million with ≥95% two-dose coverage and surveillance sensitivity ≥2 NMNR per 100,000—remain unmet nationally [1]. Incidence (40–45 per million, 2024) exceeds elimination threshold by 40–45 fold; district-level coverage heterogeneity (range 60–98%) violates the ≥95% every-district requirement; and surveillance sensitivity (1.0–1.5 per 100,000) falls short of targets in most states. These gaps define the current elimination gap and prioritize actionable targets.

4.2 Structural Barriers to Elimination

Five structural barriers emerge from this synthesis:

1. MCV2 Implementation Bottleneck: Despite routine introduction in 2012, MCV2 has not achieved elimination-level coverage (≥95% nationally and ≥95% in every district). Fixed-schedule delivery at 15–18 months creates coverage gaps as children age-out of vaccination windows without session access. School-entry strategies, piloted in few states, remain fragmented. Private sector MCV2 delivery is estimated at 30–40% of urban doses but remains invisible to surveillance systems [17].

2. Surveillance System Weakness: Transition to case-based AFR surveillance is incomplete. Private sector reporting gaps (estimated 40–60% of cases) create substantial underestimation. NMNR discard rates below WHO targets in 22 of 36 states indicate insufficient surveillance sensitivity. Specimen transport delays and laboratory quality assurance gaps limit outbreak response speed [34].

3. Immunity Gap Accumulation: COVID-19 disruptions created a cohort of 2–3 million zero-dose children per year (2020–2022), representing a 60% increase from baseline. Even with catch-up campaigns, ~1.1 million zero-dose children remained in India in 2022, ranking third globally [9]. These populations will sustain measles transmission for 5–10 years unless targeted aggressively.

4. District-Level Heterogeneity: Only 9–12 of 36 states consistently achieve ≥95% MCV1 coverage. Eastern and North-East India remain lagging, with coverage 60–85%. Within states, coverage variance exceeds 30 percentage points between highest- and lowest-performing districts, indicating governance capacity disparities rather than pure geographic constraint [4].

5. Socioeconomic and Marginalized Population Invisibility: Slum, migrant, and minority populations remain systematically underserved. Coverage gaps of 15–30 percentage points persist despite national averages approaching 90%. These populations are simultaneously at highest risk for severe disease (due to malnutrition, limited treatment access) and lowest coverage, creating disproportionate disease burden [16].

4.3 Feasibility of Elimination Target Timeline

Original Target (2023): Clearly unattained. By 2023, incidence was ~40 per million (40-fold above elimination threshold), MCV2 coverage was 82% (13 percentage points below target), and surveillance sensitivity remained suboptimal [5].

Revised Target (2025): Unlikely without transformative systemic change. Current trajectory (incidence declining ~5–8 per million annually, MCV coverage increasing ~1–2 percentage points yearly) would require 5–8 years to reach elimination targets, placing realistic achievement at 2027–2030 [2].

Conditional Pathway to 2027–2028 Elimination: Feasibility increases if: (1) all states achieve ≥95% MCV1 and MCV2 by district (requires intensified focus on 10–15 lagging districts); (2) zero-dose registries and digital tracking systems enable targeted reach; (3) school-entry MCV2 policy becomes mandatory

nationwide; (4) private sector integration adds 10–15% invisible coverage; and (5) surveillance sensitivity reaches ≥2 NMNR per 100,000 in all states. Such transformation requires estimated $150–200 million incremental annual investment and sustained political commitment beyond typical 5-year election cycles.

4.4 Lessons from Polio Eradication

India's successful polio eradication (certified 2014) offers instructive parallels. Critical success factors applicable to measles elimination include: (1) dedicated surveillance infrastructure (NPSP/AFP system scaled to measles); (2) targeted high-risk area supplementary immunization; (3) real-time data dashboards enabling rapid response; (4) accountability mechanisms (naming districts/workers, performance incentives); and (5) high-level political advocacy (Chief Minister/Prime Minister engagement). Conversely, polio eradication's reliance on monovalent OPV campaigns created OPV-2 supply dependence; the measles pathway should embrace diversified delivery (routine, SIA, school-entry, catch-up) to reduce single-point-of-failure risk.

5. POLICY IMPLICATIONS: EIGHT ACTIONABLE RECOMMENDATIONS

1. **District-Focused 95% Coverage Mandate:** Establish binding targets for ≥95% MCV1 and MCV2 coverage in all 36 states by 2026, disaggregated to district level. Link state health budgets and official performance evaluation to measles coverage achievements; require quarterly public scorecards.
2. **School-Entry MCV2 Strategy:** Legislate mandatory MCV2 at school entry (age 5–6 years) nationwide, integrated with existing school health programs. Establish school vaccination camps with trained health workers; verify coverage through annual school immunization surveys.
3. **Zero-Dose Registry System:** Develop integrated zero-dose registries linking ASHA, ANM (Auxiliary Nurse Midwife), and immunization data systems. Implement geospatial mapping to identify clusters; allocate dedicated outreach resources to reach zero-dose children by age 2 years.
4. **Digital Immunization Tracking:** Scale e-immunization platforms (Reproductive, Maternal, Newborn, Child and Adolescent Health Information System [RMNcAIS]) to enable real-time coverage tracking, automated SMS/WhatsApp reminders, and integration with Aadhaar for beneficiary verification.
5. **Urban Immunization System Redesign:** Establish dedicated urban immunization cells in metro/large cities; conduct rapid slum mapping; deploy mobile vaccination units in high-density informal settlements with culturally sensitive messaging; integrate private clinics into reporting networks.
6. **Private Sector Reporting Integration:** Establish incentivized voluntary reporting mechanisms (e.g., digital reporting portal with nominal data sharing fees); partner with Indian Medical Association and accredited hospital networks for measles case/vaccination data sharing.
7. **Laboratory Expansion and Molecular Surveillance Roadmap:** Establish measles/rubella reference labs in all 36 states by 2026; implement genotyping capability in 15 labs to enable outbreak source-tracing; conduct annual proficiency testing and external quality assurance for all labs.
8. **Vaccine Confidence and Community Engagement Strategy:** Implement evidence-based vaccine hesitancy interventions (address specific concerns through trusted community health workers rather than generic messaging); establish district-level advocacy networks with religious leaders, teachers, and local health champions; conduct annual demand-generation campaigns targeting slums and minority populations.

6. STRENGTHS AND LIMITATIONS

Strengths:

- Comprehensive 25-year temporal analysis with consistent outcome definitions
- Integration of multiple data sources (HMIS, NFHS, surveillance reports, outbreak investigations, peer-reviewed literature)
- PRISMA 2020-compliant systematic methodology
- District-level and socioeconomic stratification revealing critical disparities
- Comparative analysis with regional peers contextualizing India's position

Limitations:

- Surveillance underestimation acknowledged (40–60% case ascertainment); true measles burden likely 1.5–2× reported figures
- NFHS surveys conducted 2015–2016 and 2019–2021; real-time coverage data beyond 2023 limited
- COVID-19 pandemic era data collection disrupted; 2020–2021 estimates subject to uncertainty
- Narrative synthesis approach (no meta-analysis) reduces quantitative precision

- Grey literature bias: Government reports may overestimate coverage; publication bias toward high-performing regions
- Limited information on vaccine potency, cold-chain integrity, or provider training quality—factors affecting effectiveness beyond coverage

7. CONCLUSION

India has made substantial epidemiological progress toward measles elimination (80% incidence reduction, 91% MCV1 coverage), but structural barriers particularly MCV2 bottleneck, surveillance gaps, district-level heterogeneity, and COVID-19-induced immunity deficits preclude near-term elimination. A realistic timeline of **2027–2028** is achievable conditional on: (1) achieving ≥95% MCV1 and MCV2 coverage in every district; (2) closing zero-dose populations through targeted registries and digital tracking; (3) mandating school-entry MCV2; and (4) integrating private sector immunization into surveillance. The urgency is acute: each year of delayed achievement sustains measles transmission risk, threatens gains in regions approaching elimination, and diverts resources from other health priorities. Intensified, equity-focused implementation informed by this synthesis is essential to realize measles elimination in India by the targeted 2027–2028 timeline.

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