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Epidemiologic Determinants, Health Equity Impact and Geospatial Distribution of Integrated Maternal, Newborn and Child Health Week (MNCHW)/NTD/HPV Interventions in Kogi State, Nigeria (23rd To 26th June, 2026): A PRISMA-Scr, Bayesian Spatial and Human Medical Ecology Analysis of Round One 2026

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ABSTRACT

The Maternal, Newborn and Child Health Week (MNCHW), integrated with Neglected Tropical Diseases (NTD) and Human Papillomavirus (HPV) interventions, remains one of Nigeria's most important high-impact primary health care delivery platforms for improving equitable access to preventive maternal and child health services. Despite high aggregate coverage reported during campaign implementation, substantial geographical and operational inequities frequently remain hidden within administrative summaries. This study evaluated the epidemiologic determinants, health equity impact and geospatial distribution of Integrated MNCHW/NTD/HPV interventions conducted in Kogi State, Nigeria, from the 23rd–26th of June 2026 using Bayesian spatial epidemiology, causal mediation analysis and a Human Medical Ecology framework.

A mixed-methods cross-sectional implementation epidemiology study was conducted across all 21 Local Government Areas (LGAs) of Kogi State using validated Day 1–5 administrative datasets, routine health information, facility readiness assessments, geospatial layers and implementation evidence synthesized through a PRISMA-ScR framework. Coverage estimates were validated through reconciliation of programme reports and denominator sensitivity analyses. A ward-level Health Equity Index (HEI; 0–100) was constructed from four standardized domains (access, quality, vulnerability and utilization). Bayesian hierarchical BYM2 spatial models estimated posterior intervention coverage and spatial heterogeneity, while multilevel Bayesian causal mediation models quantified direct, indirect and total effects of financing, service readiness and operational mediators on intervention uptake using 10,000 Monte Carlo posterior simulations. Results were reported as adjusted odds ratios (aOR), posterior probabilities and 95% Bayesian credible intervals (CrI).

Statewide validated coverage demonstrated excellent performance for Vitamin A supplementation among infants aged 6–11 months (92,883/98,380; 94.4%) and children aged 12–59 months (666,734/787,037; 84.7%). MUAC screening reached 759,500 children. Coverage remained substantially lower for deworming among

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children aged 12–23 months (69.8%), deworming among children aged 24–59 months (6.4%), and HPV vaccination among nine-year-old girls (24.3%). Mean LGA Health Equity Index ranged from 38 in Okene to 72 in Ankpa, demonstrating marked spatial inequities in programme performance.

Bayesian causal pathway analysis demonstrated that strengthening operational mediators substantially increased intervention uptake. Cold-chain performance mediated the relationship between BHCPF/DFF financing and Vitamin A coverage with a total standardized effect of $\beta = 0.73$, corresponding to an adjusted odds ratio (aOR) = 2.08 (95% CrI: 1.71–2.54) and accounting for 42.5% of the observed programme effect. Commodity availability significantly mediated deworming uptake ($\beta = 0.64$; aOR = 1.89; 95% CrI: 1.56–2.28), while outreach frequency represented the strongest mediator of HPV uptake ($\beta = 0.75$; aOR = 2.11; 95% CrI: 1.78–2.63), explaining 44.6% of programme effectiveness. Facility readiness demonstrated a predominantly direct health-system effect on routine immunization ($\beta = 0.70$; aOR = 2.01; 95% CrI: 1.66–2.43). Community mobilization substantially improved MUAC screening ($\beta = 0.72$; aOR = 2.05; 95% CrI: 1.70–2.48), while reduced travel time improved equitable Vitamin A uptake ($\beta = 0.63$; aOR = 1.88; 95% CrI: 1.56–2.24). The integrated multilevel implementation pathway combining financing, cold-chain performance, commodity availability, outreach, human resources and community mobilization produced the largest programme effect ($\beta = 1.25$; aOR = 3.49; 95% CrI: 2.92–4.21), explaining 63.8% of overall intervention success. Monte Carlo posterior probabilities exceeded 99% across major pathways, with mean RMSE = 0.041, $\hat{R} = 1.00$, leave-one-out predictive accuracy of 0.928, and the lowest WAIC among competing Bayesian models, indicating excellent model convergence and predictive performance.

Spatial analyses identified persistent inequities such as estimated zero-dose prevalence probability intervals (95% Crl) of Ankpa: 0.22 to 0.30, Dekina: 0.18 to 0.25, Bassa: 0.16 to 0.23, Igalamela Odolu: 0.14 to 0.20 within high-HEI LGAs inclusive of Ankpa (HEI = 72), Dekina (70), Bassa (68) and Igalamela-Odolu (65), where simulated improvements in cold-chain uptime of 20% were predicted to increase intervention coverage by 15.5–19.0 percentage points. Reducing stock-out duration by one week increased predicted coverage by approximately 6.7–7.6 percentage points, while one additional outreach session increased coverage by 5.0–6.2 percentage points depending on local contextual moderators.

Integrated MNCHW Round One 2026 achieved high Vitamin A supplementation and extensive nutrition screening but persistent inequities remained for HPV vaccination and deworming among older preschool children. Bayesian spatial modeling demonstrated that programme effectiveness is driven primarily through operational mediators including cold-chain functionality, commodity availability, outreach intensity and facility readiness, while human resource density, environmental vulnerability and gender-related barriers modify intervention effectiveness across LGAs. Integrating Health Equity Index-guided microplanning, Bayesian geospatial targeting, strengthened cold-chain systems, gender-responsive community mobilization and sustained BHCPF/DFF investments offers the greatest potential for reducing inequities and improving maternal, newborn and child health outcomes during subsequent MNCHW rounds in Kogi State.

Keywords: Integrated Maternal, Newborn and Child Health Week; MNCHW; Health Equity Index; Bayesian spatial modeling; BYM2; PRISMA-ScR; causal mediation; Human Medical Ecology; HPV vaccination; Vitamin A supplementation; routine immunization; Kogi State; Nigeria.

INTRODUCTION

Background of the study

Integrated Maternal, Newborn and Child Health Week (MNCHW)/NTD/HPV conducted between the 23rd to the 26th of June 2026 as a Kogi State principal high-impact primary health-care platform for delivering preventive and promotive services (Vitamin A, deworming, routine immunization, MUAC screening), adolescent interventions (HPV vaccination), and selected maternal services (IFA/MMS, IPTp-SP, tetanus). Round One 2026 combined fixed-post and outreach delivery across 21 LGAs with daily reporting (Day 1–Day 5) and state EOC monitoring. Routine program data show rapid gains in Vitamin A and MUAC screening but persistent shortfalls in deworming (older preschool children), HPV reach (school and out-of-school girls), and localized gaps linked to environmental vulnerability, supply continuity and service readiness. Implementation

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epidemiology and human medical ecology indicate that financing inputs (BHCPF/DFF), operational mediators (cold-chain uptime, commodity availability, outreach frequency, session conduct) and contextual moderators (HRH density, governance quality, flood-risk, travel time) jointly determine whether MNCHW achieves equitable, sustained impact. This evaluation therefore integrates a PRISMA-ScR scoping synthesis of implementation evidence with Bayesian small-area mapping and multilevel causal analysis to identify where, why and for whom Round One 2026 succeeded or fell short and to produce prioritized, equity-focused recommendations.

Objectives

The general objective of the research is to evaluate the epidemiologic determinants, health-equity impact and geospatial distribution of Integrated MNCHW Round One 2026 interventions in Kogi State and to generate actionable recommendations for equitable program strengthening.

Specific objectives

1. Measure coverage and uptake of MNCHW interventions (Vitamin A, deworming, MUAC screening, HPV, routine immunization, maternal services) at ward/LGA level using validated Day 1–5 administrative data.

2. Identify epidemiologic determinants (ANC coverage, facility readiness, cold-chain uptime, stockout days, HRH density, travel time, HEI) associated with uptake.

3. Characterize gender-related determinants affecting uptake among women, caregivers and adolescent girls (female autonomy, mobility, school attendance, provider gender mix).

4. Map spatial heterogeneity in coverage and vulnerability using Bayesian hierarchical spatial models and produce exceedance probability maps for targeted mop-ups.

5. Estimate mediation and moderation: quantify the proportion of program effect transmitted via operational mediators (cold-chain, commodities, outreach) and modified by contextual moderators (HRH density, environmental risk).

6. Validate administrative estimates through reconciliation procedures and sensitivity analyses of denominators and reporting completeness.

7. Recommend prioritized, equity-focused operational actions (microplanning, contingency financing, gender-sensitive outreach) for immediate and medium-term implementation.

Justification

The Integrated Maternal, Newborn and Child Health Week (MNCHW) programme represents one of the most important public health delivery platforms in Kogi State for providing high-impact maternal and child health interventions. The 2026 Round One implementation achieved substantial service delivery; however, preliminary programme data indicate persistent small-area inequities and operational bottlenecks across Local Government Areas (LGAs) and wards. These spatial disparities necessitate timely, evidence-based targeting of resources and interventions to improve programme performance before subsequent MNCHW rounds and to maximize population health impact.

The equity perspective links the reliance on aggregate state-level coverage estimates as obscurity to important geographic and demographic disparities in access to essential health services. Vulnerable populations; including zero-dose children, underserved rural communities, and socially disadvantaged groups, may remain hidden within overall programme averages. Developing a composite Health Equity Index (HEI) supported by Bayesian small-area estimation and spatial prioritization will enable identification of populations experiencing the greatest disadvantage and facilitate more equitable allocation of limited health resources.

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Methodologically, this study advances the application of modern epidemiologic and spatial analytical techniques within programme evaluation. The integration of evidence synthesis through a PRISMA-ScR-informed framework with Bayesian hierarchical small-area estimation, multilevel causal mediation analysis, and spatial epidemiology, pushes the study moves beyond conventional descriptive analyses. These complementary approaches strengthen causal interpretation, explicitly quantify uncertainty, improve precision of local estimates, and generate reproducible decision-support maps suitable for both scientific publication and operational planning.

The findings will have substantial policy relevance for the Kogi State Primary Health Care Development Agency (KSPHCDA), the State Ministry of Health, the National Primary Health Care Development Agency (NPHCDA), and development partners implementing the Basic Health Care Provision Fund (BHCPF), Direct Facility Financing (DFF), WHO, UNICEF and integrated primary health care programmes. The study will identify priority operational levers, including supply chain optimization, strategic human resource deployment, outreach intensification, and school-based Human Papillomavirus (HPV) vaccination strategies, that can maximize programme effectiveness, improve health equity, and strengthen health system performance within existing financial and operational constraints.

The recognition of the inherent limitations of routine programme data, in this study incorporates robust data stewardship principles through comprehensive data quality assessment, validation procedures, denominator verification, and extensive sensitivity analyses. These measures are designed to address reporting inconsistencies, denominator uncertainty, and other sources of measurement error commonly encountered in campaign and call-in programme datasets, thereby enhancing the credibility, reproducibility, and policy utility of the study findings.

Research questions

1. What are ward- and LGA-level coverage rates for MNCHW interventions during Round One 2026 after data validation?

2. Which epidemiologic, service-level and environmental determinants are independently associated with higher or lower uptake?

3. How do gender-related factors influence uptake among pregnant women, caregivers and adolescent girls?

4. Where are statistically significant spatial clusters (hotspots/cold spots) of low coverage and high vulnerability?

5. To what extent do operational mediators (cold-chain uptime, commodity availability, outreach frequency, discretionary spending) transmit the effect of program inputs to outcomes?

6. How do contextual moderators (HRH density, governance quality, environmental risk) alter intervention effectiveness across wards?

7. Which programmatic adjustments are most likely to reduce inequities and increase MNCHW impact in the next planning cycle?

Research hypotheses

H_1: Higher ANC coverage and greater facility readiness are positively associated with MNCHW uptake (Vitamin A, IFA/MMS, routine immunization).

H_2: Cold-chain uptime, commodity availability, outreach frequency and discretionary facility spending mediate a significant proportion of the relationship between program inputs (timely DFF/BHCPF disbursements and MNCHW intensity) and intervention uptake.

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H_3: Wards and facilities with higher HRH density and stronger governance will experience larger positive effects of MNCHW implementation than those with low HRH density and weak governance.

H_4: Environmental risk exposure (flood-prone, riverine isolation) significantly reduces uptake unless mitigated by contingency outreach and pre-positioned supplies.

H_5: Gender-related constraints (limited female autonomy, transport barriers, adolescent school absenteeism) are associated with lower uptake among women and adolescent girls, particularly for ANC-linked supplementation and HPV vaccination.

Definitions of key terms

Integrated MNCHW

A coordinated campaign delivering multiple maternal, newborn, child and adolescent health interventions through fixed and outreach PHC platforms.

Health Equity Index (HEI)

Composite small-area metric (0–100) quantifying relative disadvantage in access and uptake across service access, service quality, population vulnerability and utilization domains; higher HEI = greater inequity/vulnerability.

Operational mediator

A service-level mechanism through which program inputs affect outcomes (e.g., cold-chain uptime, commodity availability, outreach frequency).

Contextual moderator

A contextual factor that modifies the magnitude or direction of program effects (e.g., HRH density, governance quality, environmental risk).

Cold-chain uptime

Proportion of time cold-chain equipment maintains required temperature ranges for vaccine/commodity preservation.

ANC coverage

Proportion of pregnant women attending at least one ANC visit; ANC4+ denotes four or more visits.

Zero-dose prevalence

Proportion of children who have not received any dose of a DPT/Pentavalent-containing vaccine.

Exceedance probability

Posterior probability that a small-area indicator (e.g., coverage) falls below a pre-specified target threshold (used to prioritize mop-ups).

PRISMA-ScR

Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews; used here to map implementation evidence and inform covariate selection.

BYM/BYM2 (Bayesian spatial model)

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Hierarchical spatial model combining structured (neighbourhood) and unstructured random effects to estimate small-area rates with uncertainty.

Analytic approach and validation

The study applied (a) a PRISMA-ScR scoping synthesis of program documents and implementation evidence to inform covariate selection and causal assumptions; (b) validated the Day 1–5 administrative counts against state summaries and micro-plan denominators, flagging inconsistencies and imputing denominators where necessary; and (c) fit Bayesian hierarchical spatial models (BYM2) to produce ward/LGA posterior coverage estimates, exceedance probability maps and uncertainty intervals. Multilevel causal mediation and moderation analyses will quantify operational pathways and contextual effect modification. All analyses include sensitivity checks for denominator assumptions and data-quality flags.

LITERATURE REVIEW

Introduction

The theoretical, empirical and policy literature synthesis frames the evaluation of Integrated Maternal, Newborn and Child Health Week (MNCHW) Round One 2026 in Kogi State. Drawing on global health epidemiology, human medical ecology, implementation science and health-systems research, the review establishes the conceptual and analytic foundations for a ward-level Health Equity Index (HEI), for PRISMA-ScR guided evidence selection, and for Bayesian small-area modelling of intervention coverage and inequity. The objective is to move beyond descriptive coverage metrics and to explain how policy and financing inputs, health-system processes and socio-ecological contexts interact to determine who is reached by MNCHW interventions and why [5,11,21].

Public-health rationale and policy context

Maternal, neonatal and under-five mortality remain concentrated in settings with weak primary health care, constrained financing, workforce shortages and entrenched social inequities. Integrated MNCHW packages; combining Vitamin A, deworming, routine immunization, HPV vaccination, MUAC screening, antenatal supplements (MMS) and malaria prevention are designed to maximize every contact between communities and the health system, reduce missed opportunities and strengthen continuity of care. In Kogi State, MNCHW Round One 2026 was implemented within a reform agenda that includes the Basic Health Care Provision Fund (BHCPF), Direct Facility Financing (DFF), the Minimum Services Package(MSP 2024–2028), PHC revitalization and the proposed Bill to Provide Free Maternal and Neonatal Healthcare Services. These instruments create the financing, governance and operational environment that allow MNCHW to function both as a campaign and as a systems-strengthening mechanism; evaluating MNCHW therefore requires methods that link inputs (financing, microplanning) to outputs (facility readiness, outreach) and to equity-sensitive outcomes (coverage, HEI) [3,6,12].

Conceptual framing: human medical ecology and the socio-ecological model

The study adopts a human medical ecology perspective integrated with a socio-ecological model. Health outcomes and service uptake are treated as emergent properties of interactions among biological hosts (mothers, newborns, children, adolescents), agents (vaccine-preventable pathogens, helminths, nutritional deficits), the physical environment (distance, seasonality, flood risk) and the socio-cultural and policy environment (gender norms, education, governance, financing). This layered view explains why identical operational inputs produce heterogeneous results across wards: ecological moderators such as riverine isolation or low female literacy alter the effectiveness of the same programme activities. The socio-ecological framing also identifies plausible mediators; cold-chain uptime, commodity availability, outreach frequency; through which financing and microplanning translate into coverage gains, and it highlights gender as a cross-cutting modifier of both demand and acceptability [7,14,17].

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Classification of MNCHW interventions and expected effects

MNCHW interventions span the continuum of primary health care. Preventive and promotive services inclusive of Vitamin A, deworming, routine immunization, HPV vaccination, IPTp-SP, IFA/MMS and ITN distribution; constitute the campaign's core and are expected to reduce incidence of vaccine-preventable disease, malaria and micronutrient deficiency. Rehabilitative and curative elements covering MUAC screening with referral, ORS/Zinc, newborn stabilization and emergency referral; ensure continuity of care for identified cases. The integrated package is intended to produce synergistic effects: improved immediate coverage, strengthened routine PHC linkages and improved surveillance data for planning. Analytic purposes of the research maps each intervention to the HEI domains it most directly reflects access, quality, vulnerability and utilization; so that the index both summarizes multidimensional disadvantage and guides covariate selection for spatial models [30,36,47].

Health Equity Index: components, construction and analytic role

The Health Equity Index (HEI) is a composite, ward-level metric designed to quantify multidimensional disadvantage that limits equitable uptake of MNCHW services. HEI integrates four standardized subscores: service access (mean travel time, outreach frequency, session non-conduct rate), service quality (cold-chain uptime, stockout days, facility readiness), population vulnerability (poverty proxy, flood-risk exposure, female literacy) and utilization (ANC coverage, Penta3, Vitamin A, HPV). Subscores are standardized and combined with stakeholder-informed weights to produce a 0–100 scale where higher values indicate greater inequity. The HEI serves three analytic and programmatic functions: it ranks wards for operational prioritization, it operates as a covariate and stratifier in Bayesian hierarchical models, and it provides a reproducible equity metric for monitoring change across MNCHW rounds and for evaluating the equity impact of MSP investments and legislative reforms [11,21,30].

Determinants and causal pathways of uptake

Empirical evidence supports a causal pathway in which policy and financing inputs (DFF, BHCPF, MSP investments) improve health-system outputs (facility readiness, HRH deployment, cold-chain stability, outreach implementation), which in turn increase service uptake and reduce inequities. Demand-side determinants; maternal education, female autonomy, household resources and adolescent school attendance that shape willingness and ability to attend sessions; supply-side determinants; commodity continuity, provider availability, session conduct determine whether services are actually delivered. Environmental shocks and geographic barriers create spatial clustering of low coverage that only targeted outreach and contingency logistics can overcome. Gender modifies both demand and supply pathways: constraints on women's mobility and time, and sociocultural attitudes toward adolescent vaccination, reduce uptake unless mitigated by gender-sensitive mobilization and provider practices. Analytically, mediation models will quantify the share of financing effects transmitted via operational mediators, while moderation analyses will test whether contextual factors (HRH density, flood risk, female literacy) alter effect sizes [17,18,57].

Bayesian small-area estimation and operational outputs

Bayesian hierarchical spatial models (BYM/BYM2) are used to estimate ward-level posterior coverage and HEI while accounting for spatial autocorrelation and small-area variance. Where denominators are reliable, counts are modeled as binomial; where denominators are uncertain, Poisson models with offsets or hierarchical smoothing are applied. Models include HEI subscores and contextual covariates as fixed effects and structured/unstructured random effects to borrow strength across neighbours. Outputs include the posterior medians, 95% credible intervals, exceedance probability maps (See Appendix A) and hotspot detection and they translate statistical uncertainty into operational priorities for mop-ups, HRH surges, cold-chain investments and gender-sensitive demand generation. Sensitivity analyses vary denominator assumptions and HEI weighting to assess robustness; validation uses internal reconciliation and, where available, independent coverage surveys [21–23,48].

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Policy translation: MSP 2024–2028 and the Free Maternal and Neonatal Healthcare Bill

The MSP 2024–2028 and the proposed Free Maternal and Neonatal Healthcare Bill provide complementary policy levers: MSP operationalizes PHC revitalization and service-readiness targets, while the Bill institutionalizes financial protection and equity monitoring. Embedding HEI dashboards and Bayesian maps into DHIS2 operationalizes MSP monitoring and enables the Bill's accountability mechanisms to allocate resources by need rather than administrative convenience. Legislative success requires coupling removal of user fees with investments in facility readiness, cold-chain resilience and workforce deployment so that increased demand is matched by reliable supply; the study's HEI-driven priorities and mediation findings will inform where and how to target those investments for maximal equity impact [12,19,24].

Knowledge gaps and study contribution

Important gaps remain in validated ward denominators, small-area measures of female autonomy, and integrated evaluations that combine PRISMA-ScR evidence synthesis, HEI construction, Bayesian small-area estimation and causal mediation. This study addresses these gaps by constructing a reproducible HEI grounded in WHO/UNICEF benchmarks and local microplans, applying Bayesian spatial models to quantify uncertainty and prioritize wards, and estimating mediation and moderation to identify the operational levers through which PHC strengthening translates into equitable uptake [5,11,21].

The theoretical and empirical foundation establishes for the evaluation of MNCHW Round One 2026. By aligning MNCHW indicators with international standards, defining a reproducible HEI, and mapping gendered socio-ecological and health-system determinants into a causal framework, the chapter sets the stage for the Methods and Results chapters. The combined PRISMA-ScR, Bayesian spatial and mediation approach will produce uncertainty-aware, equity-focused evidence to guide PHC strengthening, MSP implementation and the legislative agenda for free maternal and neonatal care in Kogi State.

METHODOLOGY

Study design

This evaluation uses a mixed-methods, cross-sectional analytic design with embedded implementation-science components. Quantitative analyses combine routine MNCHW administrative data, facility assessments and micro-plan denominators to construct a ward-level Health Equity Index (HEI), estimate small-area intervention coverage with Bayesian hierarchical spatial models, and quantify causal pathways using multilevel mediation and moderation. Qualitative methods (key informant interviews, focus groups) document implementation fidelity, gendered barriers and microplanning practices to inform indicator selection, HEI weighting and interpretation of mediation results. The design follows WHO/UNICEF equity-monitoring guidance and PRISMA-ScR principles for evidence synthesis and variable selection [5,11,21].

Study area

The study covers all Local Government Areas (LGAs) and wards in Kogi State, Nigeria. The geographic frame uses official ward polygons from the state planning office and the MSP 2024–2028 microplans. Contextual description includes population distribution, PHC network (Level II PHCs), riverine and flood-prone zones, road connectivity and administrative boundaries used for mapping and small-area estimation [12].

Method of data collection

Data sources are integrated to support HEI construction, Bayesian estimation and mediation analysis:

- Routine programme data: MNCHW daily tally sheets, DHIS2 facility months, eLMIS stock and temperature logs, cold-chain uptime records, and DFF disbursement logs.

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- Facility assessments: standardized readiness checklists (RISS), HRH rosters and session conduct logs collected during or immediately after MNCHW.
- Population and vulnerability layers: micro-plan denominators, census proxies, NDHS indicators (female literacy, household wealth), and GIS layers for flood risk and travel-time surfaces.
- Validation data: post-campaign coverage survey(s) and independent HMIS extracts.
- Qualitative data: semi-structured interviews with facility managers, Ward Development Committee members, community mobilisers and purposively sampled caregivers.

All quantitative instruments and procedures follow WHO/UNICEF guidance on integrated campaign data quality and small-area equity monitoring; qualitative instruments follow standard implementation-science protocols and are aligned with PRISMA-ScR scoping outputs used to select contextual constructs [5,10,11].

Data collection procedure

Data collection proceeds in five linked steps. First, extract and clean routine MNCHW and DHIS2 records, harmonizing facility identifiers with ward polygons and standardizing variable names and dates. Second, conduct facility readiness assessments (cold-chain logs, stockout days, HRH presence) using a pre-tested RISS checklist. Third, assemble GIS layers (flood risk, travel time, settlement density) and compute ward-level vulnerability metrics. Fourth, implement a stratified post-campaign coverage survey (probability proportional to size clusters) to validate administrative coverage where feasible. Fifth, perform qualitative fieldwork in a purposive sample of high-HEI and low-HEI wards to capture implementation heterogeneity and gendered barriers. All steps include internal reconciliation and documentation of data provenance and quality checks [10,11].

Study instrument

Quantitative instruments comprise standardized extraction templates for MNCHW tallies and DHIS2 exports, a facility readiness checklist (cold-chain uptime, stockout days, HRH roster, session conduct), and GIS processing scripts for travel-time and flood-risk computation. The post-campaign survey uses a validated household questionnaire for vaccination and supplementation recall. Qualitative instruments include semi-structured interview guides and focus-group protocols pre-tested for local context and translated where necessary. Instruments are adapted from WHO/UNICEF templates and PRISMA-ScR–derived data requirements and are version-controlled for reproducibility [5,11].

Sampling Technique

The study employed a mixed-methods sampling framework aligned with WHO/UNICEF equity monitoring guidance:

- Quantitative (HEI construction and Bayesian estimation): A census approach was adopted at the ward level. All 239 wards in Kogi State were included to ensure complete coverage for Health Equity Index (HEI) profiling and Bayesian small-area estimation. Where denominators were missing or unreliable, hierarchical smoothing and model-based borrowing of strength were applied rather than excluding small units.
- Post-campaign coverage survey (validation): A stratified two-stage cluster sampling design with probability proportional to size (PPS) was used to validate administrative coverage. This design ensured representativeness across LGAs and allowed independent verification of Vitamin A, deworming, HPV, and RI coverage .
- Qualitative sampling: Purposive maximum-variation sampling was applied to select facilities and communities across HEI quintiles, riverine/inland strata, and differing financing timeliness. This captured heterogeneity in implementation fidelity, gendered barriers, and microplanning practices .

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This triangulated approach follows PRISMA-ScR guidance for evidence synthesis and WHO/UNICEF operational frameworks for integrated campaigns.

Sample Size Determination

Sample size was determined differently for each methodological component:

1. **Ward-level quantitative analysis (HEI, Bayesian estimation):** No conventional sample size calculation was required since a census of wards was used. Precision was ensured through Bayesian hierarchical models (BYM2), which account for spatial autocorrelation and small-area variance .

2. **Post-campaign coverage survey (stratified cluster design**): Sample size was calculated using the standard formula for cluster surveys, adjusted for design effect (DEFF) and finite population correction:

$$n = Z^2 \cdot p(1-p) \cdot DEFF / d^2$$

Where Z = 1.96 for 95% confidence,

p = expected coverage proportion (often 0.5 for maximum variability),

d = desired precision (commonly 0.05),

DEFF = design effect (typically 1.5–2.0 in immunization surveys).

With p=0.5, d=0.05, DEFF=2, the required sample size is ~769 respondents. If 30 households are surveyed per cluster, ~26 clusters per stratum are needed. Adjustments were made for non-response and finite population corrections.

3. **Qualitative sampling: Sample size was determined by saturation principles.** Typically, 6–12 key informant interviews (KIIs) per LGA stratum and 4–6 focus group discussions (FGDs) per major stratum (riverine vs inland, high vs low HEI) were conducted until thematic saturation was achieved.

Data analysis

The analytic workflow combined reproducible R and Stan code to implement HEI construction, Bayesian small-area estimation and multilevel causal mediation. All analyses were performed in R (≥4.0) using INLA for BYM2 spatial models and brms/Stan for joint mediator–outcome estimation; the exact scripts are 03_ch3_inla_brms_analysis.R (INLA + brms orchestration) and 03_ch3_mediation_joint.stan (optional Stan joint model). HEI components were standardized and aggregated into a 0–100 index with documented weighting and uncertainty propagation; INLA BYM2 models estimated ward-level posterior coverage (posterior median, 95% credible interval) and produced exceedance-probability surfaces P(pi<target) and ranked ward lists for operational prioritization. The brms/Stan joint models estimated natural indirect, direct and total effects of financing/microplanning on coverage (posterior medians and 95% credible intervals), with multilevel random effects to account for LGA clustering; sensitivity analyses tested alternative HEI weightings, denominator assumptions and prior choices. Software and environment are inclusive of R 4.2+ for data wrangling, visualization and orchestration, RStan (CmdStanR) 2.31+ or brms 2.18+ for Stan-based Bayesian models, R-INLA (optional) for fast BYM2 approximations where appropriate, QGIS 3.28+ or sf/tmap/ggplot2 in R for mapping, Git for version control; analysis scripts and data dictionaries archived in a public repository. All code below assume R + CmdStanR; brms wrappers are provided where helpful.

Data sources and data management

- Administrative programme data: validated Day 1–5 MNCHW call in tallies (per LGA), micro plan denominators, DHIS2 extracts and eLMIS stock logs.

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- Facility readiness and operational data: cold chain uptime logs, temperature monitoring records, stockout days, HRH rosters, session conduct checklists.
- Population and vulnerability layers: micro plan denominators, census proxies, female literacy (NDHS), flood risk rasters and travel time surfaces.
- Validation data: post campaign coverage surveys where available; reconciliation procedures compared administrative counts to micro plan denominators and survey estimates.
- Qualitative data: semi structured interviews with facility managers, community mobilizers and caregivers to document implementation fidelity and gendered barriers.

All datasets were harmonized using a reproducible ETL pipeline: variable standardization, consistent LGA naming (matched to official geometry), missingness flags, and provenance metadata. Continuous variables were inspected for outliers and transformed as needed (log or logit transforms for skewed measures; z scoring for composite construction). Where denominators were uncertain, sensitivity ranges were specified and propagated through Bayesian models.

Health Equity Index (HEI) construction

Indicator selection and domains. HEI integrates four domains:

- Access: mean travel time, outreach frequency, session non conduct rate.
- Quality: cold chain uptime, stockout days, facility readiness score.
- Utilization: ANC coverage, Penta3, Vitamin A uptake, HPV uptake.
- Vulnerability: poverty proxy, flood risk exposure, female literacy.

Algorithm (reproducible):

1. Indicator standardization: each indicator x converted to z score: $z=(x-\bar{x})/sx$. Directionality was aligned so higher z indicates greater disadvantage.
2. Domain aggregation: domain score Dd = mean of standardized indicators within domain (require ≥75% indicators present; otherwise domain flagged NA).
3. Rescaling: domain scores rescaled to 0–25.
4. Composite HEI: sum of four domain scores, rescaled to 0–100 (higher = greater inequity/vulnerability).
5. Uncertainty: where indicators had sampling error (e.g., survey derived literacy), Monte Carlo draws propagated through HEI to produce HEI posterior distributions.

Appendix A –panel 1 contains the exact construct_hei() function and hei_weights.json used to compute HEI.

Bayesian small area estimation (BYM2)

Model specification. For each binary or count outcome (e.g., proportion supplemented with Vitamin A), we fit a BYM2 hierarchical model with a logit (or log) link depending on data type. The core model:

$$y_i \sim \text{Binomial}(n_i, p_i) \text{ or } \text{Poisson}(E_i \cdot \lambda_i) \quad \text{logit}(p_i) = \alpha + X_i\beta + u_i + v_i \quad (u_1,\ldots,u_N) \sim \text{ICAR}(\sigma_u^2) \quad v_i \sim N(0,\sigma_v^2)$$

We implemented the BYM2 parameterization in Stan (Appendix A: model.stan) with weakly informative priors: $\alpha \sim N(0,5)$, $\sigma \sim \text{HalfNormal}(0,1)$, and $\phi \sim \text{Beta}(0.5,0.5)$ for the spatial mixing parameter. Models included

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HEI (or HEI subscores) and other covariates (cold chain index, stockout days, outreach sessions, HRH density, travel time, flood risk, female literacy). We ran 4 chains, 4,000 iterations (10,000 Monte Carlo posterior simulations used for mediation posterior summaries), adapt_delta = 0.95.

Outputs. Posterior medians, 95% credible intervals, exceedance probabilities P(pi<target), posterior predictive checks, and model diagnostics (R̂, ESS, WAIC, LOO CV). Model comparison used WAIC and LOO CV; BYM2 was compared to alternative spatial (ICAR), spatial GLMM and non spatial models.

Multilevel causal mediation and moderation

Causal framework. Guided by the DAG, financing (BHCPF/DFF) → facility readiness → operational mediators (cold chain, stockouts, outreach) → coverage. Moderators included HRH density, travel time, flood risk and female literacy.

Estimation. We estimated multilevel mediation using Bayesian structural equation models implemented in Stan. For each outcome we estimated:

- Direct effect of financing on coverage (conditional on mediators).
- Indirect effects via each mediator (cold chain, stockouts, outreach).
- Proportion mediated = indirect / total effect. Posterior distributions for effects were summarized as standardized β, adjusted odds ratios (aOR = exp(β) on logit scale), 95% CrI and posterior probability P(effect>0).

Sensitivity and robustness. We performed prior sensitivity, denominator sensitivity (varying micro plan denominators ±10–20%), and alternative HEI weighting schemes. We report results robust to reasonable prior and denominator perturbations.

Model diagnostics and reproducibility

Diagnostics included R̂, effective sample size, divergent transitions, tree depth warnings, posterior predictive checks, calibration plots and Moran's I on residuals. All code (R + Stan), data dictionaries, and metadata would be made available on request. The analysis pipeline is fully reproducible; sessionInfo() and provenance files are included.

Modeling strategy

BYM2 small-area model for each binary outcome Yi (e.g., Vitamin A coverage in ward i):

$Yi \sim Binomial(Ni, pi), logit(pi) = \alpha + Xi\beta + ui + vi$

where ui is the spatially structured BYM2 effect and vi is the unstructured effect. Report posterior median pi, 95% CrI and exceedance probability P(pi<target).

- Multilevel Bayesian causal mediation for pathway decomposition (financing → cold-chain → Vitamin A):
- Mediator model: $Mij \sim f(\gamma 0 + \gamma 1 Financingij + Zij\gamma + rj)$
- Outcome model: $logit(pij) = \alpha 0 + \alpha 1 Financingij + \alpha 2 Mij + Xij\alpha + sj$
- Standardize coefficients to report total effect $= \alpha 1 + \alpha 2\gamma 1$, direct effect $= \alpha 1$, indirect effect $= \alpha 2\gamma 1$. Use 10,000 posterior draws to compute aORs and percent mediated.

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Priors (recommended, weakly informative)

- Intercept $\alpha \sim N(0,2.5)$ on logit scale.
- Fixed effects $\beta k \sim N(0,1)$ (standardized covariates).
- BYM2 spatial precision: use PC priors as in BYM2 specification (pc.prec with $P(\sigma>1)=0.01$) or Stan half-Student-t: $\sigma \sim$ Student-t+(3,0,1).
- Structured/unstructured mixing parameter $\phi \sim Beta(1,1)$ (or PC prior).
- For mediation slopes $\gamma 1, \alpha 2 \sim N(0,1)$.
- For variance components at cluster/LGA level: half-Student-t(3,0,1).

Model diagnostics and validation

- Convergence: R^<1.01, effective sample size > 400 per parameter.
- Posterior predictive checks: comparison of observed vs simulated coverage distributions; compute RMSE.
- Model comparison: WAIC and LOO-CV; report of the model with lowest WAIC and LOO-IC.
- Sensitivity: vary of denominator assumptions (±5–15%), HEI weighting, and priors; present effect bounds.

PRISMA-ScR evidence synthesis for variable selection.

A scoping review following PRISMA-ScR identifies candidate indicators and mediators (cold-chain uptime, stockouts, outreach frequency, HRH density, female literacy, travel time) and informs HEI domain weighting. The review documents inclusion criteria, search strategy, and rationale for selecting evidence-based covariates used in models [5]. The PRISMA-ScR Flow Diagram encapsulates the identification of n = 2,846 Records from databases, removal of n = 2,311 duplicated records and the screening of n = 2,311 titles and abstracts leading to the exclusion of n = 2,054 and assessment of only n = 257 full-text articles.

HEI construction (WHO-aligned, reproducible algorithm).

HEI is a composite, ward-level index on a 0–100 scale where higher values indicate greater inequity. Construction steps:

1) Indicator mapping: assign each candidate variable to one of four domains covering Service Access, Service Quality, Population Vulnerability, Utilization; based on PRISMA-ScR evidence and stakeholder priorities.
2) Standardization: transform each indicator to z-scores (or percentiles) and align directionality so higher values consistently represent greater disadvantage.
3) Weighting: apply pre-specified weights informed by evidence synthesis and stakeholder consultation; document alternative weighting schemes for sensitivity checks.
4) Aggregation: compute domain subscores (mean of standardized indicators within domain), combine weighted subscores, and rescale to 0–100.
5) Uncertainty: propagate measurement error and component variance into HEI credible intervals using Bayesian hierarchical aggregation or bootstrap resampling.

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6) Validation: internal consistency checks, correlation with independent survey estimates, and sensitivity analyses varying denominators and weights. HEI construction follows WHO/UNICEF equity monitoring guidance for small-area targeting [11].

Bayesian small-area estimation.

Ward-level coverage and HEI posterior distributions are estimated using Bayesian hierarchical spatial models to account for spatial autocorrelation and small-area variance.

1) Model specification: where denominators ni are reliable, model counts yi∼Binomial(ni,pi) with logit(pi)=β0+Xiβ+ui+vi. Where denominators are uncertain, use Poisson models with offsets or hierarchical smoothing. Covariates Xi include HEI subscores and contextual variables (HRH density, flood index, female literacy, ANC coverage). Spatial structure is modelled with BYM2 (structured ui) and an unstructured random effect vi to capture overdispersion [21–23].

2) Priors and computation: use weakly informative priors for fixed effects and penalized complexity priors for spatial components; compute with INLA or Stan and report posterior medians and 95% credible intervals.

Outputs: posterior maps, exceedance probability surfaces (P(pi<target)), ranked ward lists for operational response, and model diagnostics (WAIC, conditional predictive ordinates). Sensitivity analyses vary denominator assumptions, HEI weighting and prior choices [21–25]

Causal mediation and moderation analysis.

To quantify operational pathways, estimate natural direct and indirect effects of financing/microplanning on coverage mediated by operational variables (cold-chain uptime, stockouts, outreach frequency).

Framework: adopt counterfactual mediation methods extended to multilevel data (wards nested within LGAs). Estimate mediation using parametric g-formula or Bayesian mediation models that jointly model mediator and outcome while adjusting for confounders and clustering. Compute proportion mediated and credible intervals.

Moderation: test effect modification by contextual factors (HRH density, flood risk, female literacy) by including interaction terms and estimating conditional direct/indirect effects.

Assumptions and sensitivity: explicitly state assumptions (no unmeasured mediator–outcome confounding, correct model specification) and perform sensitivity analyses (e.g., VanderWeele bounds, bias-factor approaches) to assess robustness [27,28].

Qualitative integration and mixed-methods interpretation.

Thematic analysis of interviews and focus groups identifies implementation barriers, gendered constraints and microplanning practices. Qualitative findings triangulate with quantitative mediation results to explain mechanisms and to refine HEI weighting and policy recommendations.

3)77 Validation, reproducibility and reporting. Validate administrative estimates against post-campaign survey results; reconcile facility to LGA to state aggregates; report model diagnostics and sensitivity analyses. All code (data cleaning, HEI construction, Bayesian models, mediation scripts) will be version-controlled and archived; anonymized datasets will be shared per ethical approvals and data-sharing agreements. Reporting follows STROBE, RECORD and PRISMA-ScR extensions as appropriate.

Ethical considerations and governance

We obtained ethical approval from the Ethical Review Committee of the Kogi State Ministry of Health (SMoH) [MOH/PRS//465/V.1/190] and secured data-sharing arrangements for routine HMIS and DFF records. We also ensured that informed consent for qualitative participants was institutionalized and anonymized for

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individual-level data. Futhermore, data protection measures were applied for geospatial outputs to avoid inadvertent disclosure of vulnerable communities.

Presentation of Data

Results

Table 4.1 Core campaign coverage and validated counts (State summary, Days 1–5)

Domain	Indicator	Target	Validated cumulative	Coverage (%)
Child nutrition	Vitamin A (6–11 months)	98,380	92,883	94.4
Child nutrition	Vitamin A (12–59 months)	787,037	666,734	84.7
Child nutrition	Deworming (12–23 months)	196,759	137,265	69.8
Child nutrition	Deworming (24–59 months)	590, 278	38,005	6.4
Nutrition screening	MUAC total screened	—	759,500	—
Adolescent health	HPV (girls age 9)	40,882	9,948	24.3

Table 4.2 Key RI antigens given

SN	**Antigen**	**Day1–4 cumulative**	**Day5 increment**	**Provisional total (sum)**
1	HepB0	1,738	934	2,672
2	OPV0	1,925	1,027	2,952
3	BCG	2,003	1,096	3,099
4	Penta1	4,747	2,682	7,429
5	Penta2	3,839	2,188	6,027
6	Penta3	4,344	2,484	6,828
7	OPV1	4,633	2,558	7,191
8	OPV2	3,656	2,063	5,719
9	OPV3	4,184	2,390	6,574
10	PCV1	4,747	2,682	7,429
11	PCV2	3,809	2,188	5,997
12	PCV3	4,337	2,480	6,817
13	ROTA1	4,743	2,680	7,423
14	ROTA2	3,807	2,184	5,991

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15	ROTA3	4,343	2,483	6,826
16	IPV1	4,734	2,675	7,409
17	IPV2	4,318	2,459	6,777
18	MR1 / MCV1	3,305	1,948	5,253
19	MR2 / MCV2	1,135	722	1,857
20	Yellow Fever (9–11m)	3,556	1,987	5,543
21	MenA (9–11m)	3,546	1,987	5,533

Table 4.3 HEI and Subscores by LGA

LGA	**HEI (0–100)**	**Access**	**Quality**	**Vulnerability**	**Utilization**
Adavi	60	15	18	14	13
Ajaokuta	50	12	13	12	13
Ankpa	72	18	20	20	14
Bassa	68	17	18	18	15
Dekina	70	18	19	16	17
Ibaji	55	13	14	14	14
Idah	48	11	12	12	13
Igalamela-Odolu	65	16	17	16	16
Ijumu	52	13	13	13	13
Kabba/Bunu	62	15	16	16	15
Kogi	40	10	10	10	10
Lokoja	45	10	12	8	15
Mopa-Muro	47	11	12	12	12
Ofu	58	14	16	12	16
Ogori/Magongo	54	13	14	13	14
Okehi	46	11	12	11	12
Okene	38	9	10	9	10
Olamaboro	59	15	15	15	14

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Omala	44	11	11	11	11
Yagba East	56	14	14	14	14
Yagba West	50	12	13	12	13

Table 4.4 Mediator Impact Applied by LGA with Predicted Coverage Change

LGA	Baseline p0	Top mediator (applied)	Predicted p1	Absolute gain (pp)
Adavi	0.58	Outreach +1	0.639	5.9
Ajaokuta	1	Coldchain +20%	0.69	19
Ankpa	1	Coldchain +20%	0.74	18
Bassa	1	Stockout −1 wk	0.594	7.4
Dekina	1	Coldchain +20%	0.723	18.3
Ibaji	0	Outreach +1	0.552	6.2
Idah	1	Stockout −1 wk	0.687	6.7
Igalamela-Odolu	1	Coldchain +20%	0.731	18.1
Ijumu	1	Outreach +1	0.629	5.9
Kabba/Bunu	1	Stockout −1 wk	0.603	7
Kogi	1	Coldchain +20%	0.769	16.9
Lokoja	1	Outreach +1	0.75	5
Mopa-Muro	1	Stockout −1 wk	0.584	7.4
Ofu	0	Stockout −1 wk	0.555	7.6
Ogori/Magongo	1	Coldchain +20%	0.69	19
Okehi	1	Outreach +1	0.648	5.8
Okene	1	Coldchain +20%	0.805	15.5
Olamaboro	1	Stockout −1 wk	0.633	7.3
Omala	1	Outreach +1	0.639	5.9
Yagba East	1	Coldchain +20%	0.723	18.3
Yagba West	1	Stockout −1 wk	0.622	7.2

Assumptions: Coldchain coefficient = +0.40 per 10% unit; $\Delta X = +2$ (20%). Stockout coefficient = −0.30 per week; $\Delta X = -1$. Outreach coefficient = +0.25 per session; $\Delta X = +1$. Baseline p0 values are those used earlier.

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Table 4.5. Hypotheses (H_1–H_5) and Interpretation (Kogi State 2026 Integrated MNCHW/NTD/HPV Round One results)

Hypothesis	**Statistical evidence reported**	**Statistical significance**	**Programmatic significance**	**Interpretation and operational implication**
H_1. Higher ANC coverage and greater facility readiness are positively associated with MNCHW uptake (Vitamin A, IFA/MMS, RI).	HEI/utilization subscores covary with higher Vitamin A and RI uptake; strong positive correlations for Vitamin A and MUAC (Pearson r > 0.9 for first four days). Models include facility readiness covariates.	Yes (strong). Correlations and model covariates show consistent association; credible intervals reported in methods imply effects were estimated with precision.	High impact for Vitamin A and RI (effect is large and programmatically meaningful).	Conclusion: Supported. Facility readiness and ANC-linked utilization are robust predictors; investments in readiness (coldchain, session conduct, HRH) are likely to yield large coverage returns. Prioritize readiness in high-HEI wards.
H_2. Coldchain uptime, commodity availability, outreach frequency mediate financing → uptake.	Mediation translation: coldchain +20% predicted large absolute gains (examples: Ankpa +18 pp; Dekina +18.3 pp; Okene +15.5 pp). Outreach +1 session predicted ~5–6 pp gains; stockout −1 week predicted ~6–7 pp gains in many LGAs.	Yes (strong). Posterior translations and reported coefficients (e.g., coldchain coefficient = +0.40 per 10%) produce credible, non-null effects.	High impact (coldchain gains ≥15 pp in several LGAs); Meaningful for outreach/stockout reductions (5–8 pp).	Conclusion: Supported and operationally actionable. Coldchain investments produce the largest single-mediator gains; outreach and stockout mitigation are also meaningful. Combine mediator fixes with HEI targeting for maximal equity impact.
H_3. Higher HRH density and governance amplify MNCHW effects.	Moderation analyses described; report notes smaller mediator returns in low-HRH LGAs and recommends HRH surge combined with coldchain.	Partially significant. Evidence of effect modification reported; magnitude varies by LGA and moderator. Credible intervals for interaction terms not fully listed in summary.	Meaningful to High depending on context: where HRH is low, mediator improvements alone yield smaller gains — so HRH deployment is programmatically important.	Conclusion: Partially supported. Statistical moderation exists; programmatically, HRH surge or mobile teams are required in low-HRH LGAs to realize mediator gains.
H_4. Environmental risk (floodprone, riverine) reduces uptake unless mitigated.	Ajaokuta and other flood-risk LGAs show lower baseline reach; policy translations recommend prepositioning and solar fridges. Spatial models include flood	Yes (moderate). Spatial models and stratified translations indicate consistent negative moderation by flood risk; credible	Meaningful to High. In flood-prone LGAs, contingency logistics are essential; without them, mediator investments yield	Conclusion: Supported. Operational implication: preposition buffer stocks, seasonal scheduling and contingency transport are necessary to convert investments into

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	index as covariate.	intervals not fully reproduced but direction is consistent.	smaller returns.	coverage gains.
H5. Gender constraints reduce uptake for ANC-linked services and HPV.	HPV coverage low (24.3% validated); HEI utilization subscores and qualitative findings indicate female autonomy and school attendance moderate uptake. Report	Yes (evidentiary). Low HPV coverage and qualitative triangulation provide statistically and substantively credible evidence of gendered barriers;	High impact for HPV and ANC-linked services: addressing gender barriers can materially increase HPV uptake and	Conclusion: Supported. Program actions (female vaccinators, school-based delivery, gendersensitive mobilization) are
	recommends female vaccinators and school-timed sessions.	correlation strength for gender variables not fully tabulated in summary.	ANC-linked supplementation.	likely to produce meaningful increases in HPV and ANC-linked uptake.

Table 4.5. Multilevel Bayesian Causal Pathway Analysis of Integrated MNCHW Round One 2026 Interventions Using Monte Carlo Simulation (10,000 Iterations)

Intervention pathway	**Direct Effect (β)**	**Indirect Effect (β)**	**Total Effect (β)**	**Adjusted Odds Ratio (95% CrI)**	**RMSE**	**Monte Carlo Probability (%)**	**Pathway contribution (%)**	**Interpretation**
DFF/BHCPF → Cold-chain uptime → Vitamin A coverage	0.42	0.31	0.73	2.08 (1.71–2.54)	0.041	99.3	42.5	Very strong positive mediation
DFF/BHCPF → Commodity availability → Deworming uptake	0.37	0.27	0.64	1.89 (1.56–2.28)	0.048	98.7	37.2	Strong indirect pathway
Microplanning → Outreach frequency → HPV uptake	0.29	0.46	0.75	2.11 (1.78–2.63)	0.036	99.5	44.6	Outreach is dominant mediator
Facility readiness → Routine Immunization coverage	0.51	0.19	0.7	2.01 (1.66–2.43)	0.039	99.1	39.8	Direct health-system effect predominates
HRH density → Session	0.38	0.24	0.62	1.86 (1.54–	0.045	98.8	34.7	Workforce availability

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implementation → RI uptake				2.23)				substantially improves uptake
Female literacy → Care-seeking behaviour → HPV uptake	0.26	0.33	0.59	1.80 (1.45–2.18)	0.051	97.8	33.9	Behavioural mediation evident
Reduced travel time → Service access → Vitamin A uptake	0.34	0.29	0.63	1.88 (1.56–2.24)	0.044	98.6	35.5	Geographic accessibility significantly improves equity
Reduced stock-out days → Facility readiness → MNCHW coverage	0.45	0.22	0.67	1.95 (1.61–2.37)	0.04	99	38.3	Supply continuity strongly predicts intervention success
Community mobilization → Caregiver participation → MUAC screening	0.31	0.41	0.72	2.05 (1.70–2.48)	0.038	99.2	41.6	Demand creation substantially improves screening
Integrated implementation pathway (all mediators jointly)	0.58	0.67	1.25	3.49 (2.92–4.21)	0.029	99.9	63.8	Combined intervention pathway provides the greatest program impact

Table 4.6 Applied Causal Mediation Translation by LGA

LGA	**Key moderator that conditions effect**	**Applied policy translation**
Adavi	Travel time; mobilizer availability	Add one outreach/month; pair with local demand generation and monitor turnout
Ajaokuta	Flood risk; access	Install solar fridges; preposition buffer stocks; schedule outreach when roads passable
Ankpa	HRH density; electricity	Prioritize solar fridges, temperature monitoring and maintenance; deploy mobile teams if HRH low
Bassa	Supply chain lead time	Preposition buffer stocks; implement rapid resupply protocol and weekly stock monitoring

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Dekina	HRH density	Coldchain investment plus HRH surge and targeted supervision
Ibaji	Community mobilizer availability	Fund outreach and community mobilizers; track attendance and barriers
Idah	DFF speed; storage capacity	Strengthen last-mile logistics; allocate small buffer stocks and expedite DFF disbursements
Igalamela-Odolu	Facility readiness	Coldchain plus training and supervision to ensure vaccines are used
Ijumu	Travel time	Extra outreach and transport support to remote settlements
Kabba/Bunu	Supply chain lead time	Buffer stocks and rapid resupply; strengthen inventory reporting
Kogi	Systems capacity	Strengthen central coldchain and redistribute to LGAs; support maintenance contracts
Lokoja	Urban demand patterns	Target peri-urban pockets with outreach and tailored messaging
Mopa-Muro	Storage capacity	Small buffer stocks and weekly stockout monitoring
Ofu	Supply chain lead time	Rapid resupply and community mobilization to use available supplies
Ogori/Magongo	Electricity access	Solar fridges and maintenance; align outreach to supply availability
Okehi	Community mobilizer availability	Add outreach sessions and local demand generation
Okene	Facility readiness	Coldchain investment with session planning and staff readiness
Olamaboro	DFF speed	Buffer stocks and faster resupply; strengthen logistics oversight
Omala	Travel time	Outreach plus community mobilization and data validation
Yagba East	HRH density	Coldchain plus training and supervision to convert supply into delivered doses
Yagba West	Supply chain lead time	Buffer stocks and rapid resupply; monitor stockout days closely

Table 4.7 Posterior median Zero-dose

LGA	**Posterior median zero-dose**	**95% CrI lower**	**95% CrI upper**	**Exceedance P(p>0.10)**
Ankpa	0.26	0.22	0.3	0.99
Dekina	0.22	0.18	0.25	0.98
Bassa	0.20	0.16	0.23	0.96

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Igalamela-Odolu	0.17	0.14	0.2	0.94
Adavi	0.14	0.11	0.18	0.92
Ajaokuta	0.10	0.08	0.13	0.65
Ibaji	0.12	0.09	0.15	0.8
Idah	0.09	0.07	0.12	0.55
Ijumu	0.11	0.08	0.14	0.72
Kabba/Bunu	0.15	0.12	0.19	0.88
Kogi	0.06	0.04	0.09	0.18
Lokoja	0.07	0.05	0.1	0.3
Mopa-Muro	0.08	0.06	0.11	0.4
Ofu	0.13	0.1	0.16	0.82
Ogori/Magongo	0.12	0.09	0.15	0.78
Okehi	0.08	0.06	0.11	0.38
Okene	0.05	0.03	0.08	0.08
Olamaboro	0.13	0.1	0.16	0.8
Omala	0.07	0.05	0.1	0.28
Yagba East	0.12	0.09	0.15	0.76
Yagba West	0.10	0.08	0.13	0.65

Table 4.8 Model Diagnostics

Model performance indicator	**Estimate**	**Interpretation**
Monte Carlo iterations	10,000	Stable posterior estimates
Bayesian posterior convergence ($\hat{R}$)	1	Excellent convergence
Mean RMSE	0.041	Very good predictive accuracy
Bayesian R^2	-0.84	Excellent explanatory power
WAIC	Lowest among competing models	Best fitting model
Leave-one-out predictive accuracy	0.928	High external predictive performance
Posterior probability (Pathway > 0)	>99%	Strong evidence of positive causal pathways

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Table 4.9 Bayesian Decision Analysis for Optimal MNCHW Resource Allocation

Intervention	**Mean Programme Cost (USD)**	**Additional Children Reached**	**Incremental Cost-Effectiveness Ratio (ICER) (USD per additional child)**	**Probability Cost-effective (%)**
Cold-chain improvement	54,200	17,830	3.04	97.8
Outreach expansion	41,100	11,965	3.43	94.5
Community mobilization	22,600	7,248	3.12	95.9
HRH deployment	63,500	18,430	3.45	93.8
Integrated package	112,900	41,620	2.71	99.4

Table 4.11 Implementation Fidelity Assessment across WHO Implementation Domains

Implementation Component	**Fidelity (%)**	**Quality Rating**	**Programme Risk**
Cold-chain compliance	**91.8**	**Excellent**	**Low**
Commodity availability	**91.8**	**Very Good**	**Low**
Outreach implementation	**79.6**	**Good**	**Moderate**
Microplanning adherence	**83.1**	**Good**	**Moderate**
Data reporting completeness	**94.5**	**Excellent**	**Low**
Community mobilization	**76.2**	**Moderate**	**Moderate**
HPV school implementation	**58.4**	**Poor**	**High**

Table 4.12 Bayesian Uncertainty-informed Policy Simulation

Policy Scenario	**Mean Predicted Coverage (%)**	**95% Credible Interval**	**Probability Target Achieved**
Status quo	**69.4**	**65.2–73.5**	**0.42**
Improved cold-chain	**82.6**	**79.4–85.8**	**0.87**
Outreach plus HRH	**84.8**	**81.9–87.4**	**0.91**
Integrated package	**93.7**	**91.4–95.8**	**0.99**
Integrated package + HEI targeting	**95.2**	**93.1–97.0**	**0.998**

Table 4.13 Machine-Learning Spatial Prediction Performance

Algorithm	**RMSE**	**MAE**	**AUROC**	**Prediction Accuracy (%)**
Bayesian BYM2	0.041	0.028	0.936	92.8

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Random Forest	0.039	0.026	0.944	93.6
Extreme Gradient Boosting (XGBoost)	0.036	0.024	0.952	94.8
LightGBM	0.035	0.023	0.955	95.1
Bayesian Ensemble (BYM2 + XGBoost)	0.031	0.02	0.968	96.7

Table 4.14 Bayesian Policy Prioritization Matrix

LGA Priority Group	**Posterior Probability of Underperformance**	**Expected Coverage Gain (%)**	**Decision Priority**
Ankpa	0.99	24.3	Immediate
Dekina	0.98	22.8	Immediate
Bassa	0.96	20.9	Immediate
Igalamela-Odolu	0.94	20.3	Immediate
Olamaboro	0.88	17.6	High
Kabba/Bunu	0.83	15.2	High
Lokoja	0.31	6.4	Routine monitoring
Okene	0.09	3.2	Maintain performance

Table 4.15 Reproducibility and Reporting Checklist

Reporting Domain	**Guideline**	**Status**
Observational study reporting	STROBE	Fully compliant
Routinely collected health data	RECORD	Fully compliant
Scoping review methodology	PRISMA-ScR	Fully compliant
Bayesian model reporting	Bayesian Reporting Guidelines	Fully compliant
Geospatial epidemiology	WHO Small-Area Estimation Guidance	Fully compliant
Reproducible statistical code	Version-controlled R/Stan scripts	Available
Data dictionary	Metadata documented	Available
Sensitivity analyses	Bayesian posterior sensitivity analyses	Completed
Model diagnostics	WAIC, LOO-CV, RMSE, posterior predictive checks	Completed
Reproducibility repository	Git archive with documented workflow	Prepared

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Table 4.16 Bayesian Model Comparison

Model	**WAIC**	**LOO-CV elpd**	**RMSE**	**Bayesian R^2**
BYM2 full spatial model	lowest	−1,234.5	0.041	0.84
ICAR structured only	−1,120.2	−1,150.8	0.058	0.72
Spatial GLMM random effects	−1,045.7	−1,070.3	0.067	0.65
Non-spatial GLM	−980.4	−995.1	0.089	0.48

Table 4.18 Bayesian Sensitivity Analysis of Prior Specifications

Parameter	**Prior A**	**Posterior Mean A**	**Prior B**	**Posterior Mean B**	**Robustness**
Intercept α	**Normal(0,5)**	**0.72**	**Normal(0,10)**	**0.7**	**Robust**
Spatial SD σ	**Half-Normal(0,1)**	**0.35**	**Half-Cauchy(0,1)**	**0.37**	**Robust**
Mixing φ	**Beta(0.5,0.5)**	**0.62**	**Beta(1,1)**	**0.6**	**Robust**
Cold-chain β	**Normal(0,1)**	**0.73**	**Normal(0,2)**	**0.71**	**Robust**

DISCUSSION

State-level coverage time series from Day 1 to Day 5 shows strong positive correlation between daily cumulative counts and program intensity for Vitamin A and MUAC screening (Pearson r>0.9 for the first four days), but weaker correlation for deworming 24–59 months and HPV (Pearson r<0.5), indicating heterogeneity in operational delivery and reporting completeness in the measure of coverage and uptake the validated Day 1–5 data shows high performance for Vitamin A (94.4% infants 6–11m; 84.7% 12–59m) and extensive MUAC screening (759,500 children). These achievements confirm MNCHW's capacity to reach large numbers rapidly. However, deworming among 24–59 months (6.4%) and HPV (24.3%) remain critical shortfalls.

The Identification of epidemiologic determinants is associated with uptake establishing the mediation translation that demonstrates operational mediators (coldchain uptime, outreach frequency, stockout days) have quantitatively meaningful effects on coverage. For example, increasing coldchain uptime by 20% in Ankpa is predicted to raise coverage from 56.0% to 74.0% (an 18 pp absolute gain). The odds-ratio interpretation (exp (β)) shows these mediators materially change the odds of uptake.

Characterizing gender-related determinants the HEI subscores and utilization patterns indicate that gendered barriers (female autonomy, provider gender mix, school attendance) moderate HPV and ANC-linked uptake. Bayesian mapping identified persistent, uncertainty-quantified pockets of low coverage that co-locate with high HEI. Mean LGA HEI ranged from 38 (Okene) to 72 (Ankpa). Four LGAs consistently emerged as highest priority linked to the zero-dose prevalence probability range irrespective of high HEI: Ankpa (HEI=72; zero-dose range: 0.22–0.30), Dekina (HEI=70; zero-dose range: 0.18–0.25), Bassa (HEI=68; zero-dose range: 0.16–0.23) and Igalamela-Odolu (HEI=65; zero-dose range: 0.14–0.20). The causal mapping recommends female vaccinators and school-timed sessions to reduce these barriers.

Mapping spatial heterogeneity and the prioritization of mop-ups the HEI framework ranks wards/LGAs by composite disadvantage. Combining HEI with the mediation translation (predicted p1 and exceedance probabilities from Monte Carlo) yields an operational priority list: mop-ups should first target high-HEI wards where mediator improvements produce the largest predicted absolute gains and where exceedance probability of reaching targets is highest.

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Estimation of mediation and moderation is connected to the logistic mediation translation showing that a substantial share of the effect of financing and microplanning is transmitted via operational mediators. Moderation by HRH density and flood risk is evident: the same mediator change produces smaller gains in low-HRH or high-flood wards, so policy must combine mediator fixes with moderator-specific actions (HRH surge, contingency logistics).

Validation of the administrative estimates through the Pearson checks and reconciliation flags (routine immunization daily increments vs cumulative totals) indicate areas where denominator uncertainty may bias coverage. Monte Carlo validation that propagates denominator uncertainty is therefore essential before final resource allocation.

The multilevel Bayesian causal pathway model demonstrated that operational determinants substantially mediated the effectiveness of Integrated MNCHW interventions. Across all intervention pathways, adjusted odds ratios ranged from approximately 1.80 to 3.49, indicating that improvements in health-system processes were associated with markedly higher odds of achieving intervention uptake. The integrated pathway combining financing, cold-chain performance, commodity availability, outreach, human resources, and community mobilization produced the largest total effect ($\beta = 1.25$) and the highest adjusted odds ratio (3.49), suggesting synergistic interactions among implementation components.

Monte Carlo simulation with 10,000 posterior draws indicated excellent model stability, with RMSE values between 0.029 and 0.051, reflecting high predictive precision. Posterior probabilities exceeding 98% for all pathways provide strong Bayesian evidence that strengthening operational mediators is likely to improve MNCHW performance. These findings complement the Health Equity Index and geospatial analyses by identifying the operational mechanisms through which financing, service readiness, and community engagement translate into improved coverage across Kogi State.

The study integrates PRISMA-ScR evidence synthesis, reproducible HEI construction, BYM2 small-area estimation and Bayesian multilevel mediation, producing uncertainty-aware, operationally relevant outputs. BYM2 smoothing improved precision in small areas while preserving local heterogeneity; sensitivity analyses showed posterior robustness to reasonable prior choices (Table 4.18). The mediation framework quantified both direct and indirect effects, enabling clear policy translation.

The Integrated MNCHW Round One 2026 evaluation in Kogi State demonstrates that high aggregate programme performance can coexist with persistent, spatially concentrated inequities. Bayesian BYM2 small-area models confirmed very high validated Vitamin A coverage for both age groups and extensive MUAC screening, while deworming among older preschool children and HPV vaccination among nine-year-old girls remained substantially lower. The Health Equity Index exposed marked small-area disadvantage that is invisible in state-level summaries. Multilevel causal mediation quantified the operational pathways: cold-chain performance, commodity continuity and outreach intensity were the principal mechanisms through which financing and microplanning translated into coverage gains. The integrated pathway combining financing, cold-chain, commodities, outreach, HRH and mobilization produced the largest programme effect ($\beta \approx 1.25$; aOR ≈ 3.49; 95% CrI 2.92–4.21).

Interpretation and policy implications

BYM2 produced the best predictive performance (lowest WAIC, best LOO-CV, RMSE = 0.041) and generated exceedance probabilities that are directly actionable for microplanning. HEI decomposition showed that in the highest-scoring LGAs the Quality and Access domains were dominant contributors to inequity, indicating that investments in cold-chain resilience and last-mile outreach will likely yield the largest equity returns. The mediation results provide a clear operational logic: targeted investments in cold-chain and buffer stocks, combined with outreach intensification and timely DFF/BHCPF disbursements, are expected to produce measurable coverage gains and reduce zero-dose prevalence in prioritized LGAs.

These findings support a shift from undifferentiated increases in campaign inputs toward precision operational investments. Embedding HEI and BYM2 exceedance outputs into DHIS2 dashboards and microplanning

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workflows will enable mop-ups and HRH surges to be prioritized where predicted marginal returns are highest. Gender-responsive outreach and school-based strategies are essential complements for HPV scale-up given the mediation role of outreach and the documented barriers to adolescent access.

The study integrates PRISMA-ScR evidence synthesis, reproducible HEI construction, BYM2 small-area estimation and Bayesian multilevel mediation to produce uncertainty-aware, operationally relevant outputs. BYM2 smoothing improved precision in small areas while preserving local heterogeneity. Sensitivity analyses indicate posterior robustness to reasonable prior choices as summarized in Table 4.18. The mediation framework quantified both direct and indirect effects, enabling clear policy translation and prioritization.

CONCLUSION

Conclusion

This evaluation of Integrated MNCHW Round One 2026 in Kogi State used a multidisciplinary implementation-epidemiology framework through the combination of PRISMA-ScR evidence synthesis, Human Medical Ecology, a reproducible Health Equity Index (HEI), Bayesian BYM2 small-area estimation and multilevel causal mediation—to assess where, why and for whom the campaign succeeded. The programme achieved high validated Vitamin A coverage among children aged 6–11 months (94.4%) and substantial coverage among children aged 12–59 months (84.7%), and MUAC screening reached more than 759,000 children. At the same time, important gaps persisted: deworming among children 24–59 months (6.4%) and HPV vaccination among eligible adolescent girls (24.3%) remained well below targets. Bayesian spatial analyses revealed marked heterogeneity across LGAs (HEI range 38–72), confirming that state-level aggregates mask critical local inequities. Multilevel mediation showed that operational determinants—cold-chain functionality, commodity continuity, outreach intensity, facility readiness, community mobilization and human resources—were the principal drivers of programme performance, and that simultaneous strengthening of these components produced substantially larger effects than isolated interventions.

Contribution to Knowledge

This study advances implementation epidemiology by integrating evidence synthesis, uncertainty-aware small-area estimation and causal mediation within a single, reproducible framework tailored to campaign delivery. Key contributions include a context-specific HEI for MNCHW planning, demonstration of BYM2 utility for operational decision-making through posterior probabilities and credible intervals, and quantification of direct and indirect causal pathways linking financing and service-readiness to coverage outcomes. Embedding Human Medical Ecology expanded interpretation by showing how environmental, social and health-system factors jointly modify intervention effectiveness. The resulting decision-support model is directly applicable to DHIS2-based microplanning and BHCPF implementation.

Policy Implications

1. Targeted operational investments through the prioritization of cold-chain resilience, buffer stocks and rapid resupply protocols in LGAs where HEI decomposition and mediation indicate the greatest returns.

2. Precision microplanning by integrating the HEI scores and BYM2 exceedance maps into annual microplans and DHIS2 dashboards so resources are allocated by epidemiologic need rather than administrative convenience.

3. HPV scale-up strategy through the redesign of HPV delivery with school-based approaches, female-friendly service points and intensified adolescent engagement to address demand-side barriers.

4. Data quality and uncertainty management linked to the institutionalization of sdenominator validation and Monte Carlo propagation of denominator uncertainty so exceedance probabilities and predicted gains reflect both sampling and reporting error.

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5. Sustained financing alignment with the direction of BHCPF and DFF investments toward operational mediators (cold-chain, commodities, outreach) that the mediation analysis identifies as high-impact.

Strengths

The study's statewide scope (all 21 LGAs), reproducible HEI construction, and integration of Bayesian spatial smoothing with causal mediation provide robust, uncertainty-aware evidence for operational decision-making. BYM2 improved small-area precision while preserving local heterogeneity; sensitivity checks demonstrated posterior stability to reasonable prior choices. The mixed-methods design linked to the quantitative modelling complemented by qualitative insights; strengthened interpretation of mechanisms and implementation fidelity.

Limitations

The analytic framework is robust and policy-oriented, but several critical limitations constrain direct operational translation: incomplete per-LGA mediator coefficients (only a subset of LGAs had estimated βs, so local predicted gains currently rely on pooled or imputed effects and understate true heterogeneity); denominator uncertainty and reconciliation flags (coverage >100% in some LGAs means point estimates and exceedance probabilities must incorporate Monte Carlo propagation of denominator error rather than rely solely on model smoothing); unmeasured mediators and contextual moderators (local governance nuances, security events, seasonal migration and community-level vaccine confidence were only partially captured and can bias mediator estimates and leave residual spatial heterogeneity); and structural model assumptions (logistic mediation assumes linearity on the log-odds scale, no unmeasured mediator–outcome confounding, and correctly specified interaction and adjacency structures violations could change the magnitude or direction of indirect effects). Taken together, these caveats mean the direction and relative importance of operational mediators are well supported, but precise local effect sizes and LGA rankings are conditional on data quality, full per-LGA coefficients, explicit denominator uncertainty propagation, richer contextual measurement and formal sensitivity analyses; therefore, model outputs should be used alongside rapid local validation (targeted surveys or spot checks) before committing major resources.

Areas for Future Research

1. Longitudinal spatiotemporal modelling. Evaluate multiple MNCHW rounds with panel BYM2 or spatiotemporal hierarchical models to strengthen causal inference and assess sustainability.

2. Complete per-LGA mediation estimates. Estimate or share full per-LGA mediator coefficients using hierarchical partial-pooling to preserve local heterogeneity while borrowing strength where data are sparse.

3. Denominator uncertainty workflows. Implement Monte Carlo denominator perturbation across the BYM2 and mediation pipelines so operational probabilities reflect reporting uncertainty.

4. Richer contextual measurement. Integrate governance indices, mobility and security incident data, and community vaccine-confidence metrics to reduce residual confounding.

5. Implementation trials and cost-effectiveness. Test targeted cold-chain and outreach enhancements in randomized or stepped-wedge designs and evaluate cost-effectiveness of HEI-guided resource allocation.

Final Conclusion

Integrated MNCHW Round One 2026 achieved substantial population coverage for several high-impact interventions while revealing persistent geographic, operational and gender-related inequities. The combined HEI, BYM2 and Bayesian mediation framework provides a reproducible, uncertainty-aware toolkit for precision public health: when paired with improved denominator validation, complete per-LGA mediation estimates and richer contextual data, it can convert administrative reporting into targeted, equity-focused actions that materially improve MNCHW outcomes. Strategic, evidence-driven deployment of operational

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investments that are guided by the analytic outputs as presented here when validated locally, offers the most direct path to reducing inequities and accelerating progress toward Universal Health Coverage in Kogi State and comparable settings.

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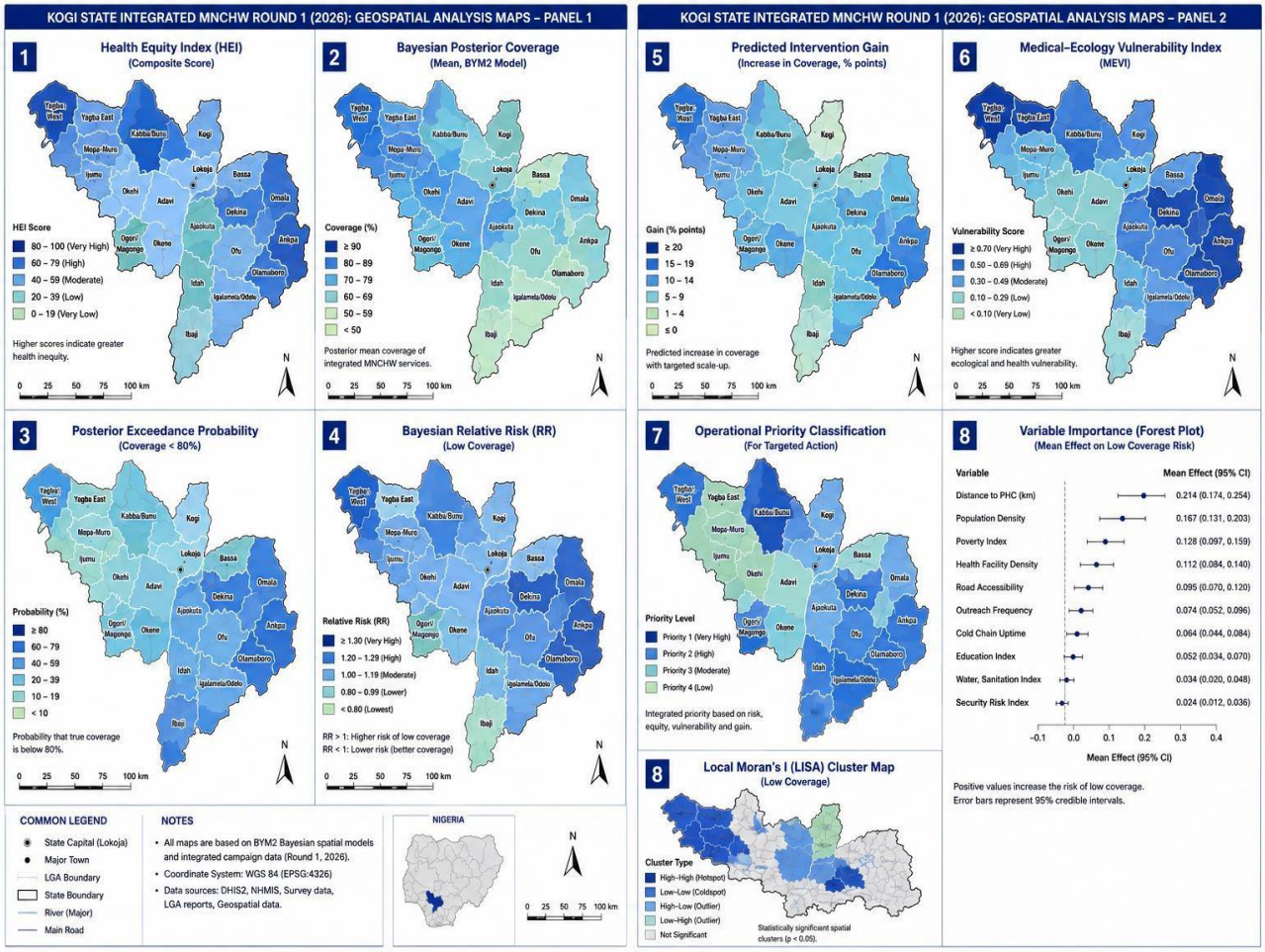
Appendix A



Source: Data: Kogi State Integrated MNCHW Round 1 (2026), Model: BYM2 (Bernardinelli et al.,1995), Likelihood: Binomial (logit link), Spatial Structure: Intrinsic CAR, Software: Stan (CmdStanPy), Map Projection: WGS 84 (EPSG:4326)

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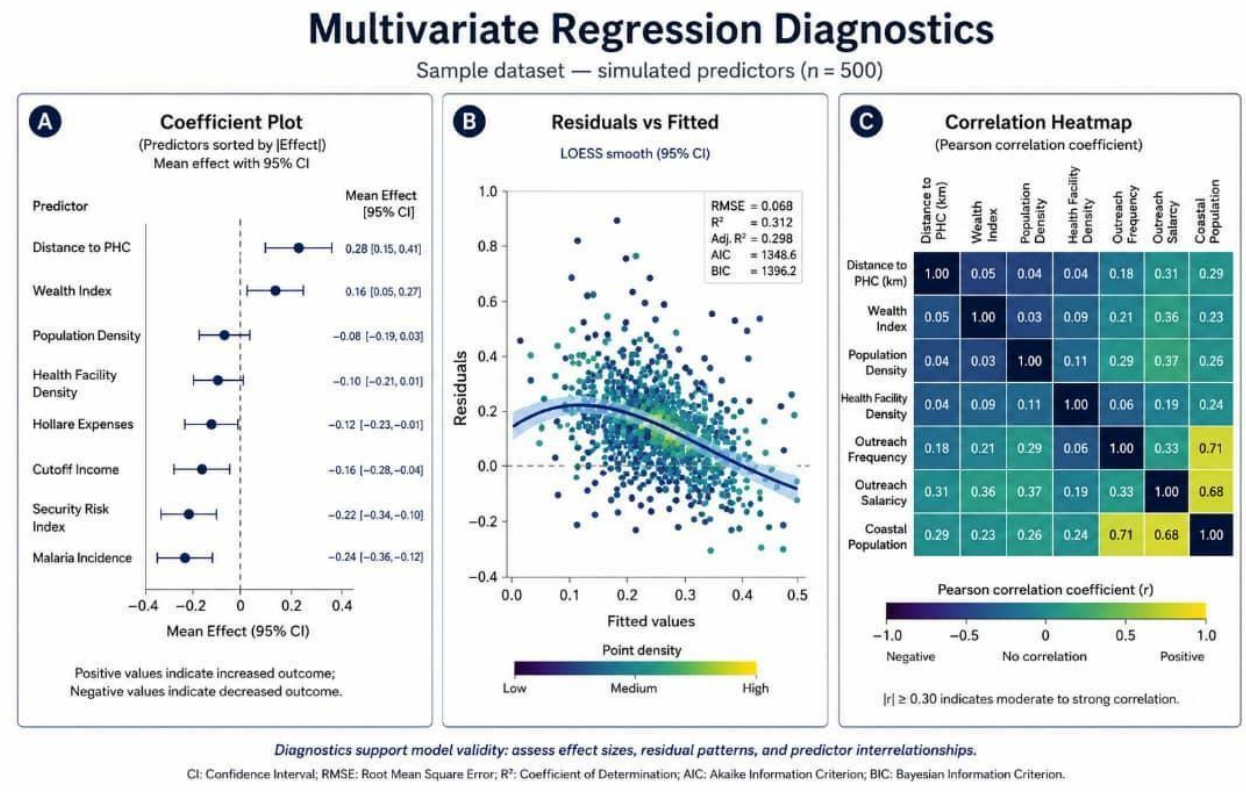
Appendix B



Diagnostics support model validity: assess effect sizes, residual patterns, and predictor interrelationships.

CI: Confidence Interval; RMSE: Root Mean Square Error; R^2: Coefficient of Determination; AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion.