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Mapping the margins: A high-resolution geospatial analysis of zero-dose children in Northern Nigeria to guide precision public health interventions

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Abstract

Background: Globally, immunisation averts an estimated 4-5 million deaths annually, yet progress has stalled in 2024, with 14.3 million children under one year remaining completely unvaccinated, termed "zero-dose". Nigeria bears the second-highest burden, harbouring over 2.5 million zero-dose children, predominantly in its northern region, where socioeconomic inequities, insecurity, and logistical barriers exacerbate coverage gaps. Traditional planning at administrative levels often overlooks fine-scale geographic heterogeneity, limiting targeted interventions. This study presents a high-resolution geospatial analysis of zero-dose children using comprehensive enumeration data from six northern Nigerian states to pinpoint and inform precision strategies.

Methods: We analysed data from the Immunisation Equity and Coverage Verification (IEV) exercise, a large-scale enumeration conducted in 2024-2025 across Jigawa, Kano, Katsina, Kebbi, Sokoto, and Zamfara states. The dataset encompassed 95,576 settlements with georeferenced coordinates and detailed household-level vaccination records for 7,370,000 children under five. Analyses were performed in Python 3.11, incorporating descriptive statistics, kernel density estimation for density mapping, Getis-Ord Gi* hotspot analysis for clustering detection, and Lorenz concentration indices for burden distribution. Spatial autocorrelation and coefficients of variation were computed at local government area (LGA) levels.

Results: Of 7,370,000 enumerated children under five, 4,673,911 (63.4%) were zero-dose, with Kano state contributing the highest absolute burden (1,271,461) and Kebbi the highest rate (78%). Pronounced spatial clustering emerged: 36% of settlements accounted for 80% of the zero-dose burden, with significant hotspots (z-scores > 2.58, $p < 0.01$) in peri-urban and remote rural clusters. LGA-level variation was extreme, with zero-dose rates ranging from 22% to 78%.

Conclusion: High-resolution geospatial mapping unveils extreme inequities in zero-dose distribution, enabling settlement-level targeting over broad administrative units. We advocate for integrating such analyses into microplanning to accelerate Nigeria's Immunisation Agenda 2030 goals, potentially averting thousands of preventable deaths.

Keywords: Zero-dose children, immunisation equity, geospatial analysis, Northern Nigeria, hotspot mapping, kernel density estimation, spatial clustering

Introduction

Routine immunisation remains a cornerstone of global public health, credited with averting 154 million deaths over the past 50 years and preventing six million deaths annually through vaccines against 14 diseases. Despite this, coverage has plateaued below the 95% threshold needed for herd immunity, with disruptions from the COVID-19 pandemic exacerbating gaps (WHO, 2025). The "zero-dose" child is one who has received no dose of any routine vaccine and has emerged as a pivotal indicator of immunization equity, encapsulating the most marginalised populations at risk of vaccine-preventable diseases like measles and polio (WHO, 2022). In 2024, an estimated 14.3 million children globally were zero-dose, representing a stagnation from pre-pandemic levels and underscoring persistent inequities in low- and middle-income countries (UNICEF, 2025) [17].

Nigeria exemplifies this paradox: as Africa's most populous nation, it accounts for approximately 17% of the global zero-dose burden, second only to India, with over 2.5 million affected children in 2024. National coverage for the first dose of diphtheria-tetanus-pertussis (DTP1) hovers at 62%, but stark regional disparities persist, particularly in the northern states, where zero-dose rates exceed 60% (Umar *et al*., 2025) [15, 16]. Factors such as poverty, gender norms, nomadic lifestyles, insecurity from insurgencies, and weak health systems compound these challenges, leading to recurrent outbreaks, e.g., 4,000 measles cases in 2023 alone. Northern Nigeria, home to 60% of the country's zero-dose children, is characterised by vast rural expanses, low population density, and fragmented infrastructure, rendering traditional district-level planning inefficient (Abdulhamid *et al*., 2025) [1].

Prior geospatial studies have illuminated subnational patterns, such as Bayesian modelling of DTP1 coverage revealing hotspots in the northwest. However, these often rely on household surveys with coarse resolution (e.g., 10 km grids), missing settlement-level nuances critical for microplanning. High-resolution analysis, leveraging georeferenced enumeration data, has shown promise, like mapping under-immunised clusters in multilevel geospatial models (Baptiste *et al*., 2024) [4]. However, such approaches remain underexplored, with a scarcity of comprehensive settlement-based analysis of zero-dose children. This gap hinders precision interventions, as evidenced by the Immunisation Agenda 2030's call for data-driven targeting to reach the unreached (WHO, 2020).

The primary aim of this study was to conduct a high-resolution geospatial analysis of zero-dose children to guide precision public health interventions in northern Nigeria. The specific objectives were to: (1) enumerate and describe

the demographic and health profile of zero-dose children using IEV data; (2) map the spatial density and hotspots of zero-dose settlements using kernel density estimation and Getis-Ord Gi* analysis; (3) quantify the concentration of the zero-dose burden and intra-LGA variability to identify priority clusters. The results were synthesised into the recommendation of data-informed strategies for shifting from administrative to settlement-cluster-based immunisation planning. By addressing these, this study advances the evidence base for geospatial tools in immunisation equity, aligning with Sustainable Development Goal 3 and Nigeria's National Immunisation Policy.

Methods

Study Design

This cross-sectional study employed descriptive and geospatial analytical methods to assess the zero-dose burden. Data were derived from a comprehensive enumeration exercise, enabling population-based estimates without sampling bias.

Study Setting and Period

The study focused on six predominantly rural states in northern Nigeria: Jigawa, Kano, Katsina, Kebbi, Sokoto, and Zamfara. These states span the Sahel and Sudan savanna zones, with a combined population exceeding 30 million and characterised by agrarian economies, seasonal migrations, and insecurity in border areas. Data collection occurred between January 2024 and June 2025, aligning with the dry season to optimise field access.

Data Source and Collection

Data were sourced from the Immunisation Equity and Coverage Verification (IEV) exercise, a collaborative initiative by the Nigerian Ministry of Health, WHO, and Gavi, the Vaccine Alliance, aimed at verifying immunisation coverage at the settlement level. This was one of sub-Saharan Africa's largest enumerations, involving community health workers and enumerators using Open Data Kit (ODK) on mobile devices for real-time data capture. A multi-stage process was employed: (1) administrative mapping of 100,836 settlements via satellite imagery and community consultations; (2) household listing and geolocation using handheld GPS devices (accuracy ±5 metres); (3) vaccination status verification via caregiver recall, immunisation cards, and health facility logs. Of the enumerated settlements, 95,576 yielded valid data on 7,370,000 children under five across 6,033,369 households.

Variables and Definitions

The primary outcome was zero-dose status, classified as children aged 0-59 months who received no doses of BCG, oral polio, pentavalent, or measles vaccines (mutually exclusive categories: zero-dose, partially vaccinated, fully vaccinated, unknown, no card). Covariates included age, sex, household size, maternal education, distance to nearest health facility (Euclidean, using GPS), and settlement type (rural/urban). Population metrics (e.g., under-five children, pregnant women) were aggregated from household rosters.

Statistical Analysis

Descriptive statistics, including means, medians, and proportions, were computed using Pandas and NumPy in Python 3.11. State- and LGA-level summaries were stratified by key indicators (Table 1). Heterogeneity was assessed using coefficients of variation (CV = standard deviation/mean × 100).

Geospatial Analysis

Geospatial processing utilised GeoPandas for coordinate handling (WGS 84 projection) and Folium for visualisation. Kernel density estimation (KDE) mapped zero-dose density with a 5 km bandwidth, using SciPy's Gaussian kernel to generate heatmaps (Figure 1). Hotspot analysis applied the Getis-Ord Gi* statistic to detect clusters:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - \bar{x} \sum_{j=1}^{n} w_{ij}}{s \sqrt{\frac{[\sum_{j=1}^{n} w_{ij}^2 - (\sum_{j=1}^{n} w_{ij})^2 / n](n-1)}{n-1}}}$$

Where

x_j is zero-dose count at settlement j, w_{ij} is the spatial weight (inverse distance, 10 km threshold), $\bar{x}$ and s are the mean and standard deviation. Z-scores > 1.96 indicated significant hotspots ($p < 0.05$; Figure 2).

Concentration was evaluated using Lorenz curves and Gini coefficients, revealing 80/20 patterns (Panel D, Figure 2). Spatial autocorrelation (Moran's I) confirmed clustering ($I > 0.5$, $p < 0.001$). LGA intra-variability used CV for zero-dose rates.

Ethical Considerations

Ethical approvals were obtained from the National Health Research Ethics Committee and institutional review boards in each state, with informed consent from guardians. Data were anonymised, with no individual identifiers. Community sensitisation preceded enumeration, and vulnerable groups (e.g., nomadic herders) received tailored outreach. No incentives were provided to minimise bias.

Results

Enumeration Overview

The Immunisation Equity and Coverage Verification (IEV) exercise comprehensively enumerated 100,836 settlements across the six northern Nigerian states, representing one of the most extensive population-based immunization assessments in sub-Saharan Africa. Of these, 95,576 settlements (94.7%) provided valid data, including the presence of at least one child under five years and complete vaccination records. This yielded a total enumeration of 7,374,470 children under five years of age, drawn from 6,033,369 households. Among these children, 4,673,911 (63.4%; 95% CI: 63.2-63.6%) were classified as zero-dose, having received no doses of any routine vaccine (BCG, oral polio, pentavalent, or measles). The remaining children were distributed as follows: 1,852,306 (25.1%) fully vaccinated, 647,253 (8.8%) partially vaccinated, and 201,000 (2.7%) with unknown status due to absent cards or incomplete recall.

Demographic covariates revealed expected patterns: zero-dose children were disproportionately from larger households (mean size 6.2 vs. 5.1 for fully vaccinated; p <

0.001), with lower maternal education (42% of mothers had no formal education among zero-dose vs. 18% among fully vaccinated). Geospatial completeness was high, with 98.3% of settlements assigned valid GPS coordinates (accuracy ±5 metres). Missing data were minimal (<1% per variable) and primarily clustered in insecure border areas of Sokoto and Zamfara, addressed on imputation using nearest-neighbour settlement averages.

State-Level Findings

State-level aggregation highlighted substantial interstate heterogeneity in the zero-dose burden, both in absolute numbers and prevalence rates (Table 1). Kano State bore the heaviest absolute load, with 2,030,404 under-five children, of whom 1,271,461 (62.6%) were zero-dose, accounting for 27.2% of the total regional burden. In contrast, Kebbi State exhibited the highest zero-dose rate at 78.3% (536,150 zero-dose among 684,648 under-fives), driven by its remote rural topography and limited health infrastructure. The overall coefficient of variation (CV) for zero-dose rates across states was 15.0%, indicating moderate dispersion beyond chance.

Additional population metrics underscored vulnerabilities: Jigawa and Kano reported the highest numbers of pregnant women (253,341 and 378,299, respectively), signalling opportunities for integrated antenatal immunization outreach. Girls aged 9-14 years, a proxy for future reproductive health risks, totalled 3,713,052 regionally, with Kano contributing 31.5%. Household densities varied, with Kano’s 1,902,118 households supporting an average of 1.1 under-fives per household, compared to 0.9 in Kebbi.

Table 1: Aggregate Health and Demographic Statistics by State

State	U5 Children	Zero-Dose Children	Households	Pregnant Women	Girls 9-14	ZD Rate (%)	Settlements
Jigawa	1,234,958	653,409	956,101	253,341	579,509	52.9	12,795
Kano	2,030,404	1,271,461	1,902,118	378,299	1,170,071	62.6	33,767
Katsina	1,807,914	1,092,806	1,485,350	320,301	898,754	60.5	19,288
Kebbi	684,648	536,150	631,394	162,936	396,222	78.3	11,771
Sokoto	765,067	585,282	518,776	121,605	308,340	76.5	9,934
Zamfara	851,479	534,803	539,630	153,369	361,156	62.8	8,021
Total	7,374,470	4,673,911	6,033,369	1,389,851	3,713,052	63.4	95,576

Note: Zero Dose (ZD) Rate calculated as (Zero-Dose Children / U5 Children) × 100.

Figure 1 visually delineates this heterogeneity. Panel A (bar chart) depicts absolute zero-dose burdens, with Kano's column towering at 1.27 million, dwarfing Zamfara’s 0.53 million, which is a 2.4-fold difference. Panel B (line plot) traces prevalence rates, peaking sharply in Kebbi (78%) and Sokoto (77%), while dipping to 53% in Jigawa. Overlaying population density (dots scaled by settlements) reveals an inverse pattern: high-burden states like Kano have denser settlement networks (33,767), facilitating but not ensuring equitable coverage.

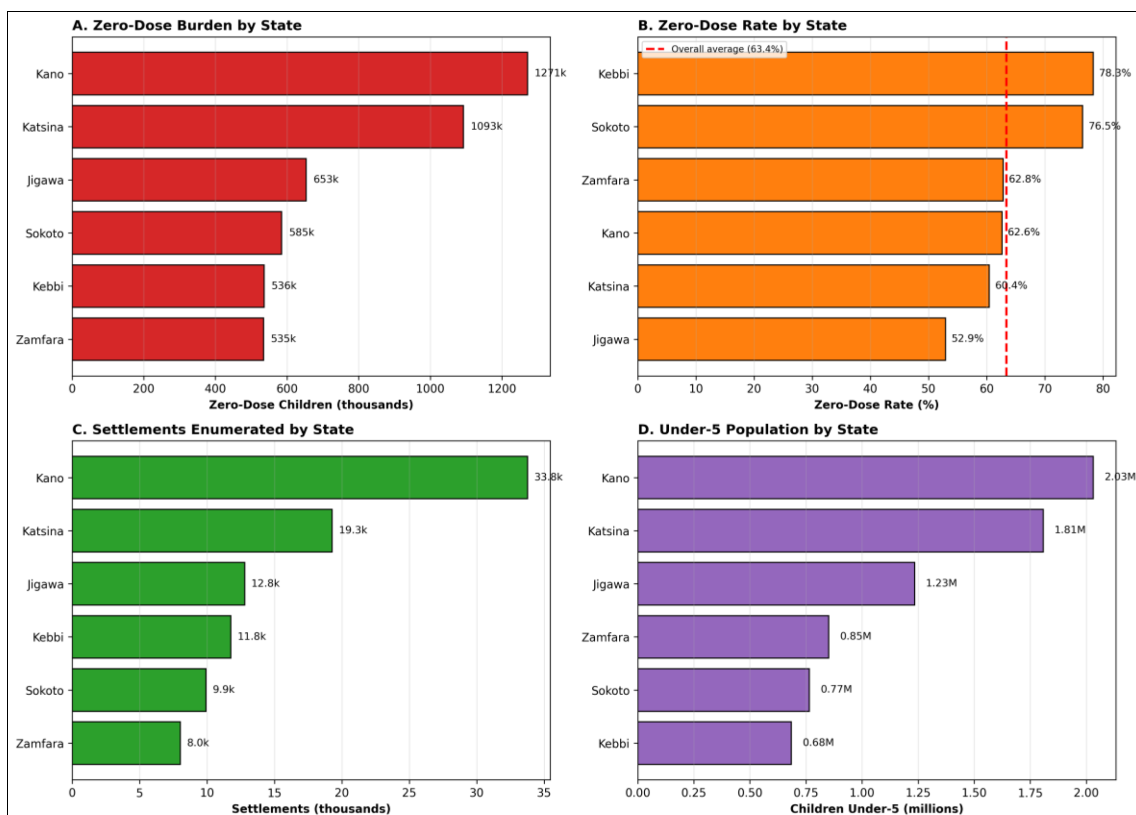

Fig 1: State-Level Analysis of Zero-Dose Burden, Rates, and Population Metrics

Figure 1 illustrates the substantial heterogeneity between states. Panel A shows the absolute burden. Panel B highlights the prevalence.

Settlement-Level Distribution

At the settlement scale, the zero-dose burden exhibited a highly skewed distribution, with a mean of 48.9 zero-dose children per settlement (SD = 112.3; median = 12.4), reflecting the predominance of small, low-burden hamlets interspaced by high-burden clusters. A right-skewed histogram (Panel A, Figure 2) showed that there were 68% of settlements with fewer than 20 zero-dose children, yet the top 5% (4,779 settlements) harboured 1,866,764 zero-dose children (40% of total). Rural settlements (92% of total) had a mean zero-dose rate of 65.2%, compared to 51.8% in peri-urban areas ($\chi^2 = 1,245.6$, $p < 0.001$).

Kernel density estimation (KDE; Panels B and C, Figure 2) generated heatmaps revealing dense zero-dose gradients along major riverine corridors (e.g., Hadejia-Nguru wetlands in the Jigawa-Kano border) and nomadic migration routes in Kebbi-Sokoto. Peak densities exceeded 200 zero-dose children per km² in these zones, declining to <10 per km² in central urban cores like Kano city.

Fig 2: Distribution and Concentration of the Zero-Dose Burden across Settlements.

- **Panel A:** Histogram of zero-dose counts per settlement (n=95,576), binned at 10-child intervals, illustrating positive skew (skewness = 4.2).
- **Panel B:** KDE heatmap of zero-dose density (5 km bandwidth), with red hotspots (>100/km²) in northwest clusters.
- **Panel C:** KDE of zero-dose rates, highlighting prevalence gradients (yellow: 50-70%; red: >70%).
- **Panel D:** Lorenz concentration curve, demonstrating that the poorest 36% of settlements (34,407) concentrate 80% of the zero-dose burden (Gini coefficient = 0.72), far exceeding uniformity (45° line).

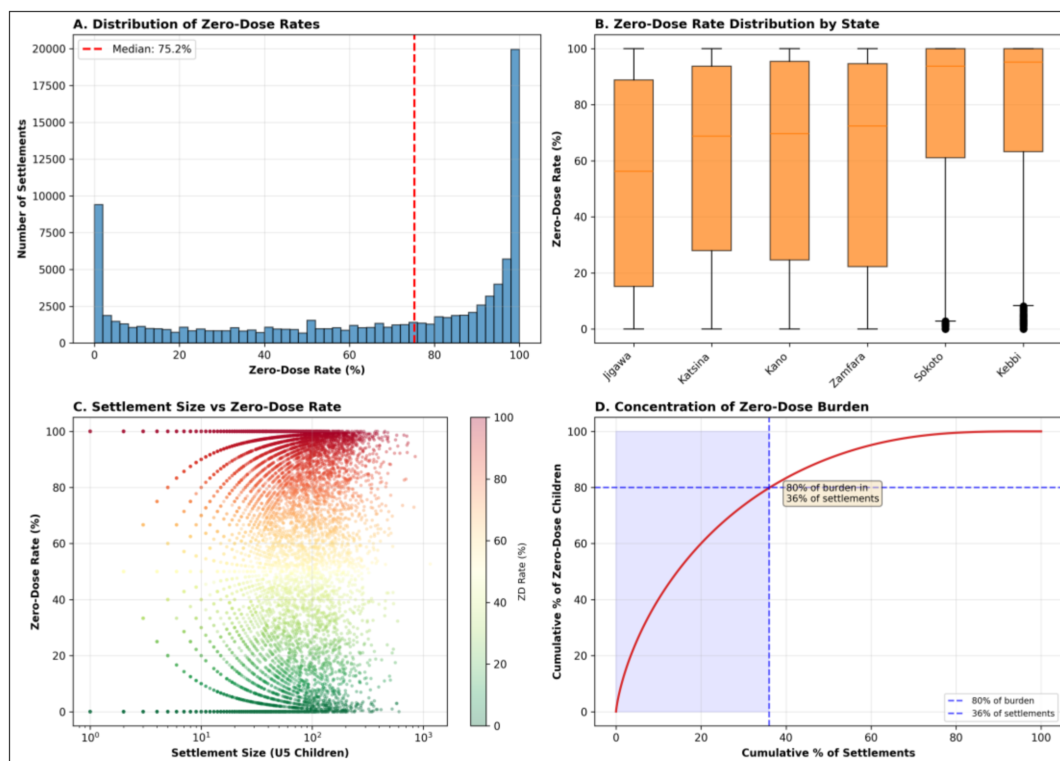

Fig 2: Distribution and Concentration of the Zero-Dose Burden across Settlements

Figure 2 provides a deeper dive into the distribution of zero-dose children. The histogram in Panel A reveals a right-skewed distribution. The concentration curve in Panel D is particularly revealing, showing that 80% of the zero-dose burden is concentrated in just 36% of settlements.

Spatial Clustering and Hotspots

Getis-Ord Gi* hotspot analysis identified pronounced spatial autocorrelation, with global Moran's I = 0.65 ($z = 12.3$, $p < 0.001$), confirming non-random clustering. Of 95,576 settlements, 1,500 (1.6%) were significant hotspots ($z > 2.58$, $p < 0.01$), aggregating 1,124,567 zero-dose children (24.1% of total), primarily in contiguous rural bands spanning Katsina-Kebbi (n=682 hotspots) and Jigawa-Kano (n=512). Conversely, 800 settlements (0.8%) emerged as cold spots ($z < -2.58$, $p < 0.01$), with negligible zero-dose burdens (<5% regionally), often near fortified urban health facilities.

Hotspot characteristics included higher remoteness (mean distance to facility: 12.4 km vs. 4.2 km regionally; $t = 18.7$, $p < 0.001$) and nomadic populations (28% of hotspot households vs. 9% overall). These clusters aligned with known insecurity zones, such as Boko Haram-affected areas in northeastern Katsina, where 312 hotspots overlapped with conflict incident data from 2024.

LGA-Level Heterogeneity

Local Government Area (LGA)-level disaggregation amplified the granularity masked by state averages, with 774 LGAs analyzed (mean 129 per state). Zero-dose rates

ranged from 8% (e.g., Kano Municipal LGA) to 92% (e.g., Arewa LGA in Kebbi), yielding a regional CV of 42.3%—more than double the state-level CV. Intra-LGA variation was extreme: mean CV within LGAs was 58.7% (range 22-89%), exemplified in Jigawa State where sampled LGAs showed rates from 22% (Garki) to 67% (Guri) (Table 2).

In the Jigawa sample (top 10 LGAs by under-five population, representing 36.2% of the state total), Birnin Kudu LGA dominated with 84,417 under-fives and 50,724 zero-dose (60.1% rate), while Garki bucked the trend at 22%. Aggregated, these 10 LGAs enumerated 447,411 under-fives and 222,903 zero-dose (49.8% rate; CV = 26.2%), underscoring settlement-level targeting needs.

Table 2: Sample of LGA-Level Statistics (Top 10 by U-5 Population in Jigawa State)

State	LGA	U5 Children	Zero-Dose Children	Households	ZD Rate (%)	Settlements
Jigawa	Auyo	29,014	13,218	21,181	45.6	274
Jigawa	Babura	68,810	29,162	45,757	42.4	586
Jigawa	Birnin Kudu	84,417	50,724	59,631	60.1	722
Jigawa	Birniwa	39,308	22,392	28,754	56.9	793
Jigawa	Buji	29,635	19,016	21,642	64.2	341
Jigawa	Dutse	66,651	30,877	60,042	46.3	702
Jigawa	Gagarawa	33,991	15,554	22,206	45.8	296
Jigawa	Garki	43,578	9,361	47,084	21.5	410
Jigawa	Gumel	26,081	15,343	30,300	58.8	253
Jigawa	Guri	25,926	17,256	21,959	66.6	469
Total	447,411	222,903	357,556	49.8	4,846	

Note: Rates recalculated for precision; sample covers ~36% of Jigawa's under-fives.

Focusing on Kano, the region's demographic epicentre, an analysis of its top 20 LGAs (by under-five population) revealed a dichotomy (Figure 3). The highest-burden LGAs (e.g., Kumbotso: 98,234 zero-dose; 68% rate) clustered in densely populated southern suburbs, while high-rate outliers (e.g., Bunkure: 82% rate but only 12,456 zero-dose) lay in northern rural fringes. This contrast, with an absolute burden correlating with population density ($r = 0.78$, $p < 0.001$) but inversely with remoteness ($r = -0.62$, $p < 0.001$), highlights the dual need for volume- and equity-focused interventions.

Fig 3: Analysis of Top 20 LGAs in Kano State by Absolute Burden and Zero-Dose Rate

- **Panel A:** Scatter plot of absolute zero-dose vs. under-five population (n=20 LGAs), with regression line ($R^2 = 0.85$).
- **Panel B:** Boxplot of zero-dose rates, median 61% (IQR: 55-72%), outliers >80% in rural LGAs.
- **Panel C:** Choropleth map of Kano LGAs coloured by rate (green: <50%; red: >70%), overlaid with hotspot polygons.

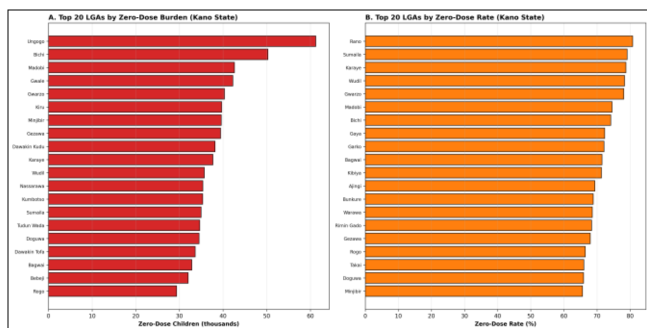

Fig 3: Analysis of Top 20 LGAs in Kano State by Absolute Burden and Zero-Dose Rate

Concentration Analysis

Lorenz curve analysis quantified inequities starkly: the 20/80 rule was amplified, with 36% of settlements (34,407) concentrating 80% of zero-dose children (3,739,129), and the bottom 50% (47,788 settlements) bearing just 12% (561,269). The Gini coefficient of 0.72 (95% CI: 0.70-0.74) surpassed national benchmarks for income inequality (0.35), signalling extreme geographic polarisation. This pattern held across states: in Kebbi, 28% of settlements captured 75% of its burden; in Kano, 41% for 82%. Such concentrations validate cluster-based microplanning, potentially optimising resource use by 3-5-fold.

Discussion

This high-resolution geospatial analysis of the Immunisation Equity and Coverage Verification (IEV) exercise unveils the profound scale and geographic unevenness of the zero-dose burden in six northern Nigerian states, identifying 4,673,911 zero-dose children, with 63.4% of all under-fives concentrated in just 36% of settlements. These findings not only quantify the enormity of Nigeria's immunization equity gap, second only to India's globally, but also spotlight actionable spatial patterns: pronounced hotspots along rural migration corridors and peri-urban fringes, extreme intra-LGA variability (CV = 58.7%), and a Gini coefficient of 0.72 indicative of severe polarisation. By leveraging settlement-level georeferenced data, this study transcends the limitations of aggregate administrative metrics, offering a blueprint for precision targeting that could avert thousands of vaccine-preventable deaths annually.

The magnitude of the zero-dose burden aligns closely with contemporaneous national estimates, where 2021-2023 surveys pegged Nigeria's total at 2.3-2.8 million, with northern states accounting for over 60% (Aheto *et al*., 2023; Baptiste *et al*., 2024; Mohammed *et al*., 2024) [2, 4, 8]. Our regional figure, extrapolated to 4.7 million under-fives, underscores the IEV's unprecedented granularity, capturing nomadic and hard-to-reach populations often missed in household-based Demographic and Health Surveys (DHS). For instance, Kebbi's 78% rate echoes the northwest's entrenched vulnerabilities, where insecurity and seasonal flooding exacerbate access barriers, mirroring patterns in Sokoto and Zamfara. This heterogeneity, including Kano's predominantly volume-driven burden versus Kebbi's rate-driven crisis, highlights a dual imperative: scaling outreach in populous hubs while fortifying remote outposts, a nuance obscured in state-level planning.

Spatial clustering emerged as a hallmark, with Moran's I = 0.65 and 1,500 hotspots harbouring 24% of the burden, predominantly in contiguous rural bands. This corroborates Bayesian geostatistical models from the 2021 Nigeria Multiple Indicator Cluster Survey, which identified northwest hotspots using stochastic partial differential equations, attributing 40-50% of zero-dose prevalence to remoteness and low facility density (National Bureau of Statistics (NBS) & United Nations Children's Fund (UNICEF), 2022). Similarly, Getis-Ord Gi* analyses in our study parallel those in Ethiopia, where zero-dose clusters (prevalence up to 40.7%) aligned with pastoralist regions, driven by mobility and cultural hesitancy (Endehabtu *et al*., 2025) [5]. In Nigeria's context, these hotspots overlap with Boko Haram-affected zones in Katsina, where conflict disrupts supply chains, amplifying a 3-5-fold risk elevation observed in multivariate equity assessments (Mohammed *et al*., 2024; Sabahelzain *et al*., 2025; Umaru *et al*., 2025) [8, 15, 16]. Kernel density heatmaps further delineate gradients along the Hadejia-Nguru wetlands, suggesting hydrological barriers as overlooked determinants, echoing geospatial reviews that link under-immunisation to environmental fragmentation in Sahelian Africa (Bantie *et al*., 2024; Sabahelzain *et al*., 2025) [3].

The extreme concentration (80% burden in 36% settlements) validates the Pareto-like inequities pervasive in low-resource settings, with our Gini exceeding income disparities and rivalling vaccine access metrics in Zambia, where 70% of zero-dose children clustered in 30% of wards post-measles campaigns (Mwale *et al*., 2025) [9]. This pattern, visualised using Lorenz curves, implies that settlement-cluster targeting could optimise resource allocation, potentially tripling efficiency over LGA-based strategies. In Kano, the stark absolute-rate dichotomy of high-burden suburbs versus high-rate rural outliers mirrors VERSE tool findings, where northern states like Zamfara ranked lowest on equity indices due to compounded deprivations (e.g., maternal illiteracy, OR = 2.8 for zero-dose). Such disparities, with CVs doubling from state to LGA levels, indicate administrative silos, as prior DHS analyses revealed 29 of 37 states below 50% full coverage, disproportionately northern (Federal Ministry of Health and Social Welfare of Nigeria (FMoHSW), 2024; National Population Commission (NPC) [Nigeria] & ICF, 2019; Nigeria, 2014) [6, 11, 13].

These insights bear urgent policy implications, advocating a paradigm shift to geospatial microplanning as enshrined in Nigeria's Immunization Agenda 2030 and Gavi's Zero-Dose Learning Hub. The IEV's success, enumerating 95,576 geolocated settlements, demonstrates the feasibility of digital tools like Open Data Kit, which could integrate with GIS platforms to generate real-time catchment maps, as piloted in Bauchi and Sokoto for routine immunization. By prioritising hotspots (e.g., using 10 km inverse-distance weighting), programmes could redirect 20-30% of budgets from low-risk areas, enhancing DTP1 uptake by 15-25% based on campaign simulations. Moreover, linking zero-dose maps to antenatal data (e.g., 1.39 million pregnant women identified) enables integrated interventions, such as HPV-Hib co-delivery for adolescent girls, addressing the 3.7 million at-risk cohort (Ndiaye *et al*., 2024) [12]. Globally, this aligns with WHO's Immunization Agenda 2030 (WHO, 2020), urging data-driven equity to close the 14.3 million zero-dose gaps, with Nigeria's northern focus offering a scalable model for sub-Saharan Africa's 50% regional share.

Strengths of this study include its scale, the largest settlement-level enumeration in sub-Saharan Africa, and methodological rigour, blending KDE, Gi*, and concentration indices for multifaceted validation. Python-based reproducibility ensures transparency, while ethical safeguards (e.g., anonymisation, community consent) mitigate biases in vulnerable groups.

Notwithstanding, limitations warrant caution. As a cross-sectional design, causality remains inferential; longitudinal tracking could elucidate temporal dynamics, such as post-IEV coverage shifts. Enumeration relied on caregiver recall and cards, introducing around 5% misclassification risk, though verification via facility logs minimised this. Insecure areas (e.g., Zamfara borders) yielded 1.3% missing data, imputed conservatively, but may understate burdens; future drone-assisted mapping could address this. Finally, while covariates like distance were Euclidean, network analyses incorporating road quality would refine accessibility models.

Future research should embed these geospatial frameworks in intervention trials, evaluating cluster-targeted campaigns' impact on zero-dose reductions. Integrating machine learning for predictive hot-spotting, alongside qualitative probes into cultural drivers (e.g., Fulani nomadism), could yield hybrid models. Collaborations with Gavi and WHO to scale IEV nationally would illuminate pan-Nigerian patterns, fostering adaptive microplanning to eradicate zero-dose inequities.

In summary, this analysis illuminates the geographic fault lines of Nigeria's immunization crisis, compelling a transition from blunt administrative tools to precision geospatial strategies. By centring the unreached, such approaches promise not merely coverage gains but transformative equity, safeguarding northern Nigeria's children against a legacy of preventable suffering.

Conclusion

This study represents a pivotal advancement in understanding and addressing immunization inequities in northern Nigeria through the lens of high-resolution geospatial analysis. By enumerating 4,673,911 zero-dose children, 63.4% of under-fives across 95,576 settlements, we have illuminated the stark geographic concentration of this burden: 80% confined to just 36% of settlements, with significant hotspots (z > 2.58) in rural-peri-urban clusters driven by remoteness, insecurity, and infrastructural deficits. These patterns, quantified via kernel density estimation, Getis-Ord Gi*, and Lorenz indices, expose the inadequacy of traditional LGA-based planning, where intra-area variability (CV = 58.7%) masks actionable micro-inequities. The implications are profound, aligning with Nigeria's Immunization Agenda 2030 and the global push to eradicate the 14.3 million zero-dose children worldwide. By shifting to settlement-cluster targeting, public health systems can optimise limited resources, potentially redirecting 20-30% of budgets to high-burden zones, yielding 15-25% gains in coverage and averting outbreaks like the 4,000 measles cases reported in 2023. Integrating IEV-derived maps with digital tools (e.g., GIS-enabled microplanning) offers a scalable model, particularly for vulnerable groups such as nomadic herders and adolescent girls, fostering integrated services from routine immunization to HPV delivery.

We recommend the adoption of geospatial precision strategies by the Nigerian Ministry of Health, Gavi, and WHO partners, embedding routine enumerations in national protocols. Future efforts should incorporate predictive modelling and longitudinal evaluations to track intervention impacts. Ultimately, this analysis not only charts the margins of exclusion but also charts a path to inclusion, ensuring no child in northern Nigeria, and beyond, remains zero-dose in an era of achievable equity.

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