



## Review

## Bridging immunization gaps in Sub-Saharan Africa: a narrative review of microplanning, geospatial, and machine learning approaches to reach zero-dose children and under-immunised children

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## ABSTRACT

Immunization inequities persist across Sub-Saharan Africa, with significant numbers of zero-dose and under-immunised children contributing to preventable morbidity and mortality. This narrative review critically examines the integration and effectiveness of machine learning, geospatial mapping, and microplanning strategies in identifying and reaching these vulnerable populations. The review's primary objective is to synthesise current evidence on how these innovative approaches are being applied within routine immunization systems to address persistent coverage gaps.

A systematic search of peer-reviewed literature and grey sources was conducted, focusing on studies and programmatic reports from 2015 to 2025. The review analyses methodological trends, implementation experiences, and outcome data related to machine learning algorithms for risk profiling, geospatial technologies for mapping and targeting, and microplanning tools for local-level action. Data extraction and thematic synthesis were guided by the WHO framework for immunization equity.

Findings demonstrate that machine learning models, utilizing demographic, health system, and mobility data, have enhanced the precision of zero-dose child identification, enabling more targeted outreach interventions. Geospatial mapping has further enabled real-time visualisation of immunization deserts and the spatial distribution of missed communities, supporting resource allocation and deployment of mobile teams. Microplanning, when integrated with digital tools and community engagement, has shown promise in translating high-level data into actionable local strategies, improving follow-up, and reducing missed vaccination opportunities.

Despite these advancements, several challenges persist. Data quality and interoperability issues limit the scalability of machine learning and geospatial solutions, particularly in remote or fragile settings. Capacity gaps at the sub-national level, including technical skills and digital infrastructure, impede effective microplanning and data use. Furthermore, the sustainability of these approaches is threatened by fragmented investments and limited integration into national health information systems.

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Opportunities exist to strengthen the routine immunization system by standardising data collection, investing in workforce training, and fostering cross-sectoral collaboration. The review recommends prioritising the development of interoperable platforms, expanding context-specific pilot projects, and embedding evaluation mechanisms to track impact and equity outcomes. Policymakers are urged to leverage the demonstrated benefits of machine learning.

## 1. Introduction

Childhood immunization has long been recognised as one of the most cost-effective public health interventions, significantly reducing mortality and morbidity from vaccine-preventable diseases globally. Nevertheless, substantial gaps in routine immunization coverage persist across Sub-Saharan Africa, where many children remain either completely unvaccinated (zero-dose) or under-immunised, having missed one or more doses of recommended vaccines. According to the World Health Organization (WHO), large numbers of children in the region continue to miss basic vaccines, undermining efforts to achieve universal immunization coverage and contributing to persistent inequities in health outcomes [1]. Integrated strategies that combine epidemiological data with advanced analytical methods are, therefore, essential to inform targeted outreach and policy actions in these contexts [2].

In recent years, advances in artificial intelligence (AI) and machine learning (ML) have expanded opportunities to enhance health system performance, including immunization planning, monitoring, and service delivery. AI and ML methodologies, encompassing a range of supervised and unsupervised algorithms, are increasingly applied in public health to identify patterns in complex, multidimensional datasets, enabling predictive modelling that guides decision-making. ML encompasses computational methods that detect patterns in complex datasets to generate predictions. Common supervised algorithms include Random Forest (RF), which aggregates multiple decision trees to improve accuracy; Support Vector Machines (SVM), which identify optimal boundaries separating groups within multidimensional data; k-Nearest Neighbors ( $k$ -NN), which classifies observations based on similarity to nearby data points; Extreme Gradient Boosting (XGBoost), which iteratively improves prediction through sequential error correction; and Naive Bayes, a probabilistic classifier based on Bayes' theorem that assumes predictor independence. These methods are increasingly used to analyze immunization datasets and predict zero-dose risk. Within infectious disease and vaccine research, ML has been used to forecast disease outbreaks, optimise supply chains, and model vaccine efficacy, illustrating its potential for strengthening immunization systems at scale [3].

Despite these technological advances, applications of ML specifically focused on identifying zero-dose and under-immunised children in Sub-Saharan Africa are still emerging. Traditional immunization monitoring systems often rely on periodic surveys or administrative records that lack the granularity needed to pinpoint children most at risk of missing vaccinations. ML approaches can supplement these systems by identifying high-risk groups and geographic areas with low coverage that may be overlooked by conventional analysis. Moreover, ML's ability to integrate sociodemographic, geographic, and health service variables makes it a promising tool for addressing the multifactorial nature of immunization inequities in low-resource settings [4].

Beyond machine learning, geospatial mapping techniques have also gained traction in identifying zero-dose and under-immunised populations. These methods integrate satellite imagery, administrative boundaries, and survey data to produce fine-scale maps of vaccination coverage, enabling the visualisation of geographic inequities and the identification of underserved communities [5]. Geospatial approaches can enhance routine immunization programs by guiding outreach, planning mobile vaccination sites, and allocating resources to areas with high concentrations of unvaccinated children.

In parallel, microplanning approaches that combine data-driven insights with local contextual knowledge are increasingly recognised as critical for reaching zero-dose and under-immunised children. These approaches leverage community-level data, health worker insights, and population estimates to optimise vaccination campaigns, tailor interventions to local conditions, and improve service delivery efficiency [6]. Evidence suggests that microplanning, when integrated with ML predictions or geospatial analyses, can significantly enhance targeting and uptake in hard-to-reach populations [7].

However, integrating ML, geospatial mapping, and microplanning into routine immunization programming raises important questions about data availability, algorithm interpretability, and the context-specific adaptability of predictive models. Sub-Saharan Africa's diverse health information landscapes, characterised by varying capacities in digital data systems and routine reporting, present both opportunities and challenges for ML implementation. Understanding the current state of evidence on ML applications in this domain is therefore crucial for researchers, policymakers, and programme implementers seeking to leverage these methods to improve immunization equity and coverage. This narrative review synthesises existing literature on: (i) the use of machine learning algorithms to identify zero-dose and under-immunised children, (ii) geospatial mapping techniques to locate and characterise these populations, and (iii) microplanning approaches that integrate data-driven insights with local context. Specifically, it assesses the effectiveness of these approaches, examines limitations and contextual challenges, and discusses their potential for scale-up within routine health information and immunization systems.

## 2. Methods

### 2.1. Study design and rationale

This study adopted a narrative review design to synthesise current evidence across three complementary domains: (i) machine learning algorithms for identifying zero-dose and under-immunised children, (ii) geospatial mapping techniques to locate and characterise these populations, and (iii) data-driven microplanning approaches integrating local context to improve targeting and coverage in Sub-Saharan Africa. A narrative review was selected because the body of literature in this emerging field remains limited, methodologically heterogeneous, and conceptually diverse, making systematic review or meta-analytic approaches inappropriate at this stage. Narrative reviews are well-suited to interpreting and integrating evidence across different study designs, data sources, and implementation contexts, and to identifying conceptual advances, gaps, and future research directions [8]. Importantly, narrative reviews do not require a large number of studies to be considered methodologically valid; rather, they prioritise depth of interpretation, thematic synthesis, and contextual relevance [8], which aligns with the objectives of this review.

Given the rapidly evolving nature of applications of machine learning, geospatial analytics, and microplanning in public health and immunization in Sub-Saharan Africa, this narrative approach enabled inclusion of peer-reviewed empirical studies, methodological papers, and applied programme reports that collectively inform effectiveness, limitations, and scale-up potential, even where formal experimental evidence remains sparse.

## 2.2. Literature search strategy

A targeted literature search was conducted between December 2025 and January 2026 using a combination of electronic databases and organisational websites relevant to global health, digital health, and immunization systems. Academic databases searched included PubMed/MEDLINE, Scopus, Web of Science, IEEE Xplore, and Google Scholar. In addition, targeted searches were conducted on the websites of key global health organisations, including WHO, UNICEF, Gavi, and national public health institutes, to capture relevant grey literature and implementation reports. Literature published between 2015 and 2025 was included.

Search terms were developed iteratively for each research question and combined using Boolean operators including combinations of keywords related to machine learning, Geospatial mapping, microplanning and immunization coverage) Search terms per research question are presented in Table 1. Reference lists of included articles were also hand-searched to identify additional relevant studies

## 2.3. Inclusion and exclusion criteria

Articles were included if they:

- (i) reported on the application of machine learning, geospatial mapping, or microplanning approaches to immunization outcomes;

- (ii) focused on zero-dose, under-immunised, or incompletely vaccinated children;
- (iii) were conducted in Sub-Saharan Africa or included SSA countries in multi-country analyses; and.
- (iv) were published in peer-reviewed journals or technical reports from national public health institutions or regional and global organisations such as UNICEF and WHO.

Studies were excluded if they:

- (i) focused exclusively on vaccine development, logistics, or cold-chain optimisation without linkage to child-level immunization outcomes;
- (ii) applied purely descriptive statistical methods or theoretical GIS/microplanning frameworks without empirical or predictive components; or.
- (iii) were conducted exclusively outside SSA without transferable relevance to the regional context.

A total of 18 core articles and reports [9–26] met the inclusion criteria and were deemed sufficient to support a narrative synthesis, consistent with established guidance for narrative reviews in emerging research domains.

**Table 1**  
Search strategy and selection overview per research question.

Research Question/ Objective	Key Search Terms/Concepts	Inclusion Criteria	Exclusion Criteria
RQ1: Machine learning applications	“machine learning”, “artificial intelligence”, “zero-dose children”, “under-immunised”, “vaccination coverage”, “immunization equity”, “Sub-Saharan Africa”, “routine immunization”, “health information systems”	<ul style="list-style-type: none"> <li>- Applied ML or predictive models to child immunization outcomes</li> <li>- Focus on zero-dose, under-immunised, or incomplete vaccination</li> <li>- Conducted in SSA or included SSA countries</li> <li>- Peer-reviewed or credible programme/technical reports</li> </ul>	<ul style="list-style-type: none"> <li>- Focus solely on vaccine development, logistics, or cold-chain optimisation</li> <li>- Purely descriptive statistics without predictive/algorithmic components</li> <li>- Conducted exclusively outside SSA without transferable relevance</li> </ul>
RQ2: Geospatial mapping	“geospatial mapping”, “spatial analysis”, “zero-dose children”, “under-immunised”, “vaccination coverage”, “Sub-Saharan Africa”, “satellite imagery”, “population mapping”	<ul style="list-style-type: none"> <li>- Applied spatial/geospatial techniques to locate or characterise zero-dose or under-immunised populations</li> <li>- Conducted in SSA or included SSA countries</li> <li>- Peer-reviewed or credible programme/technical reports</li> <li>- Incorporating GIS, satellite, or spatially resolved survey data</li> <li>- Studies assessing microplanning or operational planning using data-driven/local-context approaches</li> <li>- Conducted in SSA</li> <li>- Peer-reviewed or credible programme/technical reports</li> <li>- Linked to identification/targeting of zero-dose or under-immunised children</li> </ul>	<ul style="list-style-type: none"> <li>- Mapping studies not linked to immunization outcomes</li> <li>- Purely theoretical/methodological GIS studies without SSA relevance</li> <li>- Conducted exclusively outside SSA without transferable relevance</li> <li>- Planning frameworks not linked to child immunization outcomes</li> <li>- non-SSA contexts without relevance</li> <li>- Descriptive policy reports without operational or empirical evidence</li> </ul>
RQ3: Data-driven and context-sensitive microplanning	“microplanning”, “immunization planning”, “zero-dose children”, “under-immunised”, “data-driven decision-making”, “community engagement”, “Sub-Saharan Africa”	<ul style="list-style-type: none"> <li>- Peer-reviewed or credible programme/technical reports</li> <li>- Linked to identification/targeting of zero-dose or under-immunised children</li> </ul>	<ul style="list-style-type: none"> <li>- Planning frameworks not linked to child immunization outcomes</li> <li>- non-SSA contexts without relevance</li> <li>- Descriptive policy reports without operational or empirical evidence</li> </ul>
Full search strategy for PubMed	(("Immunization"[MeSH] OR "Immunization Programs"[MeSH] OR immunization OR immunization OR vaccination OR "vaccination coverage" OR "vaccine coverage") AND ("zero-dose" OR "zero dose" OR "under-immunised" OR "under immunised" OR "incompletely vaccinated" OR "missed children" OR "unreached children")) AND (("Machine Learning"[MeSH] OR "Artificial Intelligence"[MeSH] OR "Data Mining"[MeSH] OR "machine learning" OR "artificial intelligence" OR "predictive modelling" OR "predictive modelling" OR "Random Forest" OR "Support Vector Machine" OR "k-nearest neighbors" OR "XGBoost" OR "Extreme Gradient Boosting" OR "Naive Bayes") OR ("Geographic Information Systems"[MeSH] OR "Spatial Analysis" OR "geospatial" OR "GIS" OR "spatial mapping" OR "satellite mapping" OR "remote sensing") OR ("microplanning" OR "micro-planning" OR "service delivery planning" OR "outreach planning" OR "data-driven planning")) AND ("Africa South of the Sahara"[MeSH] OR "Sub-Saharan Africa" OR Angola OR Benin OR Botswana OR "Burkina Faso" OR Burundi OR Cameroon OR "Central African Republic" OR Chad OR Comoros OR Congo OR "Democratic Republic of the Congo" OR Djibouti OR Eritrea OR Eswatini OR Ethiopia OR Gabon OR Gambia OR Ghana OR Guinea OR "Guinea-Bissau" OR Kenya OR Lesotho OR Liberia OR Madagascar OR Malawi OR Mali OR Mauritania OR Mozambique OR Namibia OR Niger OR Nigeria OR Rwanda OR Senegal OR "Sierra Leone" OR Somalia OR "South Africa" OR "South Sudan" OR Sudan OR Tanzania OR Togo OR Uganda OR Zambia OR Zimbabwe) AND ("2015/01/01"[Date - Publication]: "2025/12/31"[Date - Publication])		

SSA, Sub-Saharan Africa; ML, Machine Learning; GIS, Geographic Information System; DHIS2, District Health Information Software 2; WHO, World Health Organization; UNICEF, United Nations Children's Fund; SIA, Supplementary Immunization Activity.

2.4. Data extraction and synthesis

Relevant information was extracted manually from included sources using a structured framework capturing study setting, data sources, methodological approach (machine learning, geospatial, or microplanning), target outcomes (zero-dose or under-immunization), performance metrics (where applicable), key findings, implementation considerations, and stated limitations.

Rather than aggregating results quantitatively, findings were synthesised thematically, guided by the review objectives. Themes and sub-themes were developed separately for each research question, reflecting approaches, effectiveness, challenges, and opportunities for scale-up. The synthesis was organised around four analytic domains, with adaptation across research questions:

- (i) types of approaches applied (ML algorithms, geospatial techniques, or microplanning frameworks);
- (ii) effectiveness and operational performance;
- (iii) limitations related to data quality, interpretability, contextual adaptation, and generalisability; and.
- (iv) potential pathways for scale-up and integration within routine immunization systems.

- (v) This interpretive approach enabled comparison across heterogeneous studies and facilitated the identification of cross-cutting insights and gaps relevant to policy and practice.

2.5. Reporting approach

Findings are reported narratively, with structured subsections reflecting the thematic domains of interest. Quantitative performance metrics, spatial mapping outputs, and implementation indicators are reported descriptively where available, without attempting formal statistical comparison across studies. This reporting approach prioritises conceptual clarity, contextual interpretation, and practical relevance, consistent with the objectives and methodological orientation of a narrative review.

3. Results

Research Question 1.

The findings under this research question are summarized in [Table 2](#). Theme.

1: Machine Learning Approaches Used to Identify Zero-Dose Children.

*Subtheme 1: Supervised learning for predictive classification.*

One of the most direct applications of ML in immunization equity

**Table 2**  
Summary of findings on the use of machine learning to identify zero-dose and under-immunised children in Sub-Saharan Africa.

Theme	Sub-theme	Approaches/Evidence	Key Findings	Implications for Immunization Equity
Theme 1: ML Approaches for Identifying Zero-Dose Children	Supervised learning for predictive classification	Random Forest (RF), Logistic Regression, SVM, XGBoost, Naive Bayes applied to DHS and routine health data (e.g., Tanzania, Uganda, East Africa, Ghana)	Ensemble models (RF, XGBoost) consistently outperform traditional models, achieving high accuracy (95–96%) and strong AUC values. Key predictors include maternal education, employment, availability of an immunization card, ANC attendance, and place of delivery.	Enables identification of children and households at the highest risk of being zero-dose or defaulting, supporting targeted outreach and prioritisation of limited resources.
	Geospatial and spatial ML models	Bayesian geospatial models, satellite imagery, predictive mapping (e.g., Zambia; UNICEF Reach the Unreached)	Fine-scale spatial mapping identifies geographic pockets of children with zero doses and optimises the placement of vaccination sites. Over 1.1 million unreached children identified in Central and West Africa.	Supports micro-planning and location-specific interventions, particularly for hard-to-reach and underserved populations.
	Other predictive models in childhood immunization	ML models predicting incomplete immunization (multi-country DHS analyses)	ML extracts complex, multi-variable associations. XGBoost shows strong performance (accuracy ~79%, AUC ~86%).	Extends ML utility beyond zero-dose classification to broader immunization gaps, informing continuum-of-care interventions.
Theme 2: Effectiveness of ML Approaches	High predictive accuracy	Comparative model performance analyses	Ensemble ML methods outperform conventional statistical approaches in classification tasks.	Demonstrates technical feasibility and value of ML for immunization decision support.
	Handling complex, high-dimensional data	Integration of sociodemographic, maternal, and geographic variables	ML handles multifactorial determinants and identifies feature importance, highlighting structural drivers of immunization inequities.	Supports evidence-informed policy by revealing key leverage points for intervention.
Theme 3: Limitations and Challenges	Data quality and availability	DHS and routine health system data constraints	Infrequent surveys, missing data, aggregation, and weak digital registries limit real-time and fine-scale predictions.	Underscores need for improved data systems and digitalisation to maximise ML impact.
	Generalisability and model transferability	Country-specific model training	Models trained in one context may not perform well in other contexts without adaptation.	Highlights importance of local calibration and contextualisation of ML tools.
Theme 4: Potential for Scale-Up	Interpretability and implementation barriers	“Black box” models; limited technical capacity	Limited use of explainable ML (e.g., SHAP); challenges in translating outputs into policy action.	Trust, transparency, and capacity building are essential for adoption by ministries of health.
	Integration with digital health platforms	DHIS2 Tracker, electronic immunization registries	Digital platforms enable finer-resolution data that can support real-time ML-driven micro-planning.	Positions ML as a tool for operational optimisation and targeted service delivery at scale.
	Capacity building and AI ecosystems	Partnerships with UNICEF, Gavi, academia	Collaborative models support validation, ethical governance, and sustainable deployment of ML tools.	Strengthens long-term institutional capacity for AI-enabled immunization equity strategies.

AI, Artificial Intelligence; ANC, Antenatal Care; AUC, Area Under the Receiver Operating Characteristic Curve; DHS, Demographic and Health Survey; DHIS2, District Health Information Software 2; F1 score, harmonic mean of precision and recall; ML, Machine Learning; RF, Random Forest; RHIS, Routine Health Information System; SHAP, Shapley Additive Explanations; SVM, Support Vector Machine; XGB/XGBoost, Extreme Gradient Boosting.

research in Sub-Saharan Africa has involved supervised learning algorithms applied to large health survey datasets to identify predictors of zero-dose status.

A notable example is a study in Tanzania that used data from the 2022 Demographic and Health Survey (DHS) to test multiple classification algorithms, including logistic regression, decision trees, random forest (RF), support vector machines (SVM), k-nearest neighbors, XGBoost (XGB), and Naive Bayes, for predicting zero-dose children aged 12–23 months. Among these, the RF classifier achieved the highest performance metrics, including 0.95 in accuracy, 0.94 in precision, 0.96 in recall, 0.95 in F1 score, and 0.99 in area under the receiver operating characteristic (ROC) curve (AUC) for distinguishing zero-dose children from vaccinated peers. The study also identified key factors associated with zero-dose status, such as maternal unemployment and lack of maternal education, through the model's feature importance scores [9]. These predictors enable public health planners to predict which children are at the highest risk of being zero-dose based on sociodemographic and household characteristics, thereby helping prioritise outreach and tailored interventions.

In Uganda, a retrospective cohort study applied multiple ML models, including RF, logistic regression and gradient boosting, to predict infants at risk of defaulting routine immunization. The RF model again demonstrated superior predictive performance, achieving up to 96% accuracy in classifying defaulting infants for certain vaccines. The study also identified key predictors such as immunization card availability, recall memory of parents or defaulters and preceding vaccine reception [10]. These findings underscore how ML can be used with routinely collected health data to identify children at risk of default, enabling health workers to prioritise follow-up.

Other regional initiatives leveraging data science for vaccine coverage estimation include UNICEF's Reach the Unreached initiative, which uses ML and geospatial data to disaggregate population estimates and estimate vaccination coverage across Central and West Africa [11]. Technically, the approach combines satellite-derived settlement mapping, census projections, household survey data, and administrative immunization records to produce small-area population denominators at sub-district or grid-cell level. Supervised machine learning models are then trained to predict zero-dose prevalence using demographic, geographic accessibility, and service delivery variables. These predictions are spatially visualized through GIS, enabling identification of “immunization deserts” and mismatches between reported administrative coverage and modelled population need. The outputs are designed to inform microplanning processes, guide outreach team deployment, optimise cold-chain distribution, and support resource allocation decisions at sub-national levels. This approach has helped identify over 1.1 million unreached children and illuminated inequities in immunization and birth registration datasets [12]. However, implementers note that utility depends on integration with existing surveillance and health information systems and on understanding algorithmic biases across diverse contexts.

#### *Sub-theme 2: Geospatial and spatial machine learning models.*

While not always strictly classified as ML in conventional terms, geospatial modelling, often incorporating statistical and ML techniques, has played an important role in zero-dose identification. In Southern Province, Zambia, researchers combined aerial satellite maps with field survey data to identify households with zero-dose children before a mass measles and rubella vaccination campaign. Although the primary analytical tool was a Bayesian geospatial model rather than a classic ML classifier, the methodology parallels the predictive mapping enabled by ML. The study produced fine-scale maps of zero-dose prevalence and identified optimal locations for additional vaccination sites, demonstrating how spatial models can guide targeted immunization efforts [13]. Geospatial applications can be enhanced by ML techniques, for example, integrating deep learning with satellite imagery or combining spatial and sociodemographic data to detect patterns that traditional methods may miss.

#### *Sub-theme 3: Other predictive models in childhood immunization.*

Although not specific to zero-dose classification, other studies in the region have applied ML methods to predict immunization coverage. For instance, research using East African DHS data has employed ML to ascertain predictors of incomplete vaccination among children under five, revealing that such models can extract associations across multiple variables [14]. In this multi-country analysis across six East African nations (Burundi, Ethiopia, Madagascar, Uganda, Rwanda, and Zambia), supervised ML algorithms, including XGBoost, were used to identify predictors of incomplete immunization among children under five. XGBoost yielded the best performance metrics with an accuracy of 79.01%, a recall of 89.88%, an F1 score of 81.10%, and an AUC of 86%, with features such as maternal age, place of delivery, birth order, and antenatal care follow-up emerging as strong predictors [14]. Similarly, another study from Ghana have applied random forests and other ML models to identify determinants of vaccination defaulters, comparing performance across models and confirming the promise of these tools in deriving actionable insights from large health datasets [15].

Theme.

2: Effectiveness of Machine Learning Approaches.

#### *Sub-theme 1: High predictive accuracy.*

Several studies indicate that ML approaches, particularly ensemble methods like random forests and gradient boosting (XGB), outperform traditional statistical models in classifying zero-dose and under-immunised children. In Tanzania, RF's nearly perfect classification metrics suggest robust pattern detection capability even in the presence of complex sociodemographic interactions [9]. The strong performance of these models suggests they could support targeted public health decisions, for instance, by identifying high-risk geographical pockets or households for intensified outreach.

#### *Sub-theme 2: Handling complex, high-dimensional data.*

ML's ability to handle large, multidimensional datasets, such as DHS and routine health information systems, enables the integration of variables, including sociodemographic indicators, maternal characteristics, and geographic information. This capacity is crucial in contexts where determinants of immunization status are multifactorial and interdependent. Further, ML has been shown to identify key predictors. ML's ability to quantify feature importance helps illuminate factors most strongly associated with vaccine gaps. Studies in East Africa and Uganda highlighted determinants such as maternal education, socioeconomic factors, antenatal care attendance, and place of delivery [10,14].

Theme.

3: Limitations and Challenges.

#### *Sub-theme 1 Data quality and availability.*

A major constraint for ML applications in immunization equity research is the quality and granularity of available data. While DHS and similar large surveys are rich sources of information, they are conducted infrequently, may contain missing values, and are often too aggregated at higher administrative levels for fine-scale prediction. In routine health systems, immunization registries may not be digitalised or consistently updated, limiting the applicability of real-time ML models.

#### *Sub-theme 2: Generalisability and model transferability.*

ML models trained on data from one country or region may not perform well when applied elsewhere due to differences in health systems, cultural practices, or data quality. For example, a predictive model calibrated using Tanzanian DHS data may not generalise effectively to Nigerian or Ugandan contexts without retraining or adaptation.

#### *Sub-theme 3: Interpretability and implementation barriers.*

Some ML models, especially complex ensembles and neural networks, can be “black boxes,” making it difficult for policymakers to understand and trust model outputs. Efforts to improve interpretability, such as using explainable ML methods, such as Shapley Additive Explanations (SHAP), are promising but not yet standard practice in the field [9]. Additionally, operationalising ML insights into actionable public health strategies requires technical capacity within ministries of health and immunization programmes that many countries currently

lack.

Theme.

4: Potential for Scale-Up.

*Sub-theme 1: Integration with digital health platforms.*

For ML to drive meaningful impact, it must be embedded into existing health data systems. Enhancements to national electronic immunization registries and RHIS could enable near-real-time risk prediction for zero-dose and under-immunised children, guiding microplanning and targeted outreach. Success stories from digital tools such as the DHIS2 Tracker in Mozambique demonstrate how digital immunization registries and data systems can, at scale, facilitate the identification and follow-up of children who are zero-dose or under-immunised. The DHIS2 platform, while not a pure ML tool, supports finer-resolution data collection that could serve as a basis for ML algorithms to operate in real time, guiding outreach and micro-planning [16]. ML can, therefore, support micro-planning by predicting where zero-dose children are most likely to be found and optimising resource allocation for mobile clinics, outreach schedules, and community health worker deployment. When coupled with geospatial data and real-world immunization registries, ML can potentially help immunization programmes reach hard-to-reach populations more effectively [16].

*Sub-theme 2: Capacity building and integration with broader AI ecosystems.*

Collaborations between ministries of health, international agencies, such as UNICEF, WHO and Gavi, and academic institutions can support the scalable deployment of ML tools. These partnerships can facilitate training, algorithm validation, and the development of ethical governance frameworks for AI use in public health. In this context, AI ecosystems refer to the interconnected network of institutions, technical systems, policies, and human capacity that collectively enable the development, deployment, and scale-up of AI and machine learning

solutions. This includes shared digital infrastructure (such as interoperable health information systems, cloud computing platforms, and data repositories), enabling regulatory and ethical governance frameworks, and regional centres of excellence that provide technical training, research, and innovation support across countries. Emerging research indicates broader AI applications, from predictive analytics to operational optimisation, can enhance vaccine coverage in Africa. A recent review highlights the potential of AI and ML to improve immunization equity by identifying coverage gaps and informing targeted intervention planning, though it notes the need to tailor models to African contexts [17].

Research Question 2.

The findings under this research question are summarized in Table 3. Theme.

1: Geospatial Techniques for Locating and Characterizing Zero-Dose and Under-Immunised Populations.

*Subtheme 1: High-resolution spatial modelling of zero-dose and under-immunised children.*

A core application of geospatial mapping in immunization equity research has involved generating high-resolution predictions of zero-dose and under-immunised child prevalence, often using Bayesian spatial models and national survey data. In Nigeria, researchers used geospatial modelling techniques on the 2021 Multiple Indicator Cluster Survey/National Immunization Coverage Survey to produce fine-scale prevalence surfaces ( $1 \times 1$  km resolution) of both zero-dose and under-immunised children [18]. These models revealed substantial regional heterogeneity, with higher prevalence observed in northern states and significant associations with socioeconomic risk factors such as stunting, contraceptive prevalence, and literacy levels. The maps identified clusters of underserved children that were not apparent from aggregate administrative data alone, underscoring the utility of high-

**Table 3**

Summary of findings on geospatial mapping techniques for identifying zero-dose and under-immunised children in Sub-Saharan Africa.

Theme	Sub-theme	Geospatial Approaches / Data Sources	Key findings	Implications for immunization programmes
Theme 1: Geospatial techniques for locating and characterizing zero-dose populations	High-resolution spatial modelling	Bayesian geospatial models applied to DHS, MICS, and national immunization surveys (e.g., Nigeria, Zambia)	Fine-scale (e.g., $1 \times 1$ km) maps reveal substantial sub-national heterogeneity in zero-dose and under-immunised prevalence; clusters are often hidden in aggregated administrative data.	Enables precise identification of underserved geographic pockets for targeted outreach and more equitable resource allocation.
	Satellite imagery and field enumeration	High-resolution satellite imagery, settlement detection, GNSS-enabled household mapping (e.g., Zambia, Cameroon)	Satellite-derived base maps improve the enumeration of previously unmapped or mobile populations and support near-complete household coverage.	Strengthens denominator accuracy and supports more equitable planning for immunization campaigns.
	Integration with routine systems and micro-planning	Geo-enabled DHIS2 Tracker, digital immunization registries (e.g., Mozambique)	Linking child-level vaccination data with location data enables real-time identification and follow-up of children who are zero-dose.	Translates spatial data into operational decision-making and micro-planning at scale.
	Integration of multiple spatial data streams	Survey data, facility locations, road networks, travel time, satellite imagery	Multi-layer spatial integration improves explanatory power and captures environmental and infrastructural determinants of zero-dose status.	Produces more accurate and actionable maps to guide programme interventions.
Theme 2: Best practices in geospatial mapping for immunization equity	Participatory mapping and local validation	Collaboration with community health workers and facility staff	Local validation improves data accuracy and promotes programme ownership of spatial tools.	Enhances trust, usability, and sustainability of geospatial approaches.
	Operational linkage to programme action	Use of maps for outreach planning and site optimisation	Spatial outputs inform the placement of outreach sites, the deployment of mobile teams, and the prioritisation of high-risk areas.	Shifts geospatial analysis from descriptive mapping to actionable programme intelligence.
Theme 3: Challenges in integrating geospatial data with immunization programmes	Data availability and quality	Incomplete facility lists, outdated settlement maps, and infrequent surveys	Poor or outdated spatial datasets limit model precision and real-time applicability.	Highlights the need for sustained investment in spatial data infrastructure.
	Technical capacity and resource requirements	GIS expertise, software, hardware, and training	Limited technical capacity constrains the routine use and scale-up of geospatial methods.	Capacity building is essential for long-term institutionalisation.
	Integration with routine workflows	Alignment with RHIS and immunization programme processes	Spatial outputs are not always embedded into decision-making structures or incentives.	Requires system integration and clear protocols to ensure spatial data informs action.

DHS, Demographic and Health Survey; MICS, Multiple Indicator Cluster Survey; DHIS2, District Health Information Software 2; GIS, Geographic Information System; GNSS, Global Navigation Satellite System; RHIS, Routine Health Information System.

resolution spatial models in identifying vulnerable populations for targeted service delivery. These outputs can directly inform micro-planning by highlighting wards or communities where intensified outreach or additional fixed posts are most needed.

Similarly, in Southern Province, Zambia, aerial satellite imagery combined with Bayesian geospatial modelling produced extremely fine-scale maps of zero-dose prevalence and helped identify optimal locations for additional vaccination sites prior to a mass measles and rubella campaign [13]. These spatial models revealed that travel time to health facilities, household composition, and position relative to facility catchment area boundaries were key correlates of zero-dose status, illustrating how spatial factors shape immunization gaps even where aggregate routine coverage appears high. This underscores the importance of going beyond district-level coverage statistics to reveal within-district pockets of vulnerability.

*Subtheme 2: Use of satellite imagery and field enumeration for population mapping.*

Geospatial techniques often start with accurate population and settlement mapping. In Zambia, researchers used high-resolution satellite imagery to locate built structures and generate enumeration bases that community health volunteers then visited to register children for vaccination [13]. This integration of satellite-derived maps with field enumeration enables health planners to localise populations not captured in traditional sampling frames and supports more comprehensive household-level coverage assessments.

Beyond specific studies, geospatial practitioners highlight that building complete and up-to-date spatial datasets of health infrastructure, service catchments, and population settlement patterns is a foundational step for zero-dose mapping. This often requires training personnel in GNSS data collection and the use of geographic information systems (GIS) to capture remote or previously unmapped settlements, as demonstrated in efforts across Cameroon and Somalia [20]. Investing in these foundational spatial datasets is therefore a prerequisite for more advanced zero-dose modelling.

*Subtheme 3: Integration with routine data systems and geo-enabled micro-planning.*

Emerging research also documents the use of geospatial data integrated into routine digital health platforms, such as DHIS2, to map individual children's locations and vaccination status. In Mozambique, a custom DHIS2 Tracker application captured geo-coordinates for zero-dose and under-immunised children as part of a catch-up vaccination campaign [16]. The spatial data enabled planners to identify “focus points” for outreach, adjust micro-plans in real time, and follow up with children based on proximity and accessibility. This represents a promising best practice in operationalising spatial data for targeted immunization service delivery rather than solely retrospective analysis.

Theme.

2: Best Practices in Geospatial Mapping for Immunization Equity.

*Subtheme 1: Combining multiple spatial data streams.*

A key best practice in geospatial immunization research is the integration of diverse spatial data sources, including satellite imagery, health facility locations, travel routes, and demographic survey data, to model zero-dose prevalence with greater accuracy [18]. This multi-layered approach enables the identification of fine-scale heterogeneity and the capture of environmental and infrastructural determinants that would be invisible in non-spatial analyses.

*Subtheme 2: Participatory mapping and local validation.*

Effective geospatial mapping often involves participatory mapping with local health workers and community health volunteers to validate spatial layers and ensure that models reflect ground realities. In Zambia, the Reveal platform's digital base-maps were created collaboratively with facility staff and CHVs, enabling real-time navigation and verification of household locations and vaccination status during field enumeration [13]. This participatory process enhances data quality and promotes ownership of spatial tools within immunization programmes. In addition, engaging frontline workers in map development can help

surface local knowledge about seasonal access barriers and informal settlements that may be absent from formal datasets.

*Subtheme 3: Operational linkage of spatial outputs with programme action.*

Best practices emphasise not just the generation of maps but also the embedding of geospatial outputs into decision-making and micro-planning workflows. For example, in Nigeria and Mozambique, spatial risk maps guided resource allocation to underserved regions and informed the deployment of outreach teams, exemplifying how spatial analysis can be “actionable” rather than purely descriptive [16,18].

Theme.

3: Challenges in Integrating Geospatial Data with Immunization Programmes.

*Subtheme 1: Data availability, quality, and updating.*

Despite its promise, geospatial mapping is often constrained by the availability and currency of underlying spatial datasets, particularly in low-resource settings [20]. Health facility registries, settlement maps, and catchment boundaries may be incomplete or outdated, undermining the accuracy of spatial models. Moreover, integrating household-level survey data with spatial layers requires careful geocoding, which is often not available in routine health information systems.

*Subtheme 2: Technical capacity and resource requirements.*

Implementing geospatial methods at scale demands specialized technical skills, software, and hardware capacity that many national immunization programmes in SSA currently lack. Training personnel in GIS, spatial statistics, and digital data capture, and retaining that expertise, remains a barrier to the routine use of geospatial data for zero-dose targeting and monitoring [19]. Partnerships with academic institutions and regional GIS hubs may offer cost-effective models for building and maintaining this capacity.

*Subtheme 3: Integration with routine health systems workflows.*

Geospatial tools must be effectively integrated with routine programme workflows to influence immunization outcomes, but this integration is not automatic. Programme staff may be unfamiliar with spatial outputs or lack incentives and protocols to act on them, limiting the translation of spatial insights into operational changes. Initiatives such as DHIS2 Tracker begin to address this gap, but widespread adoption and system interoperability remain ongoing challenges [16].

Research question 3.

The findings under this research question are summarized in Table 4.

Theme.

1: Data-Driven Microplanning Frameworks.

*Subtheme 1: Generation and use of geo-enabled microplans.*

Microplanning that incorporates geospatial and population data has been increasingly used to strengthen identification and reach of zero-dose and under-immunised children in SSA. In the Democratic Republic of Congo, georeferenced immunization microplans were developed for use at the health zone and health area level, incorporating settlement maps, facility catchment boundaries, and population estimates [21]. These microplans enabled more precise targeting of vaccination efforts, identification of previously missed settlements, and estimation of required vaccine supply based on local population distribution. The availability and effective use of these geospatial microplans were associated with improvements in routine immunization planning and increases in coverage for multiple antigens, including reductions in zero-dose prevalence over the study period [21].

Similarly, UNICEF and partners have harnessed high-resolution population datasets to produce population estimates fed directly into microplanning processes [22]. These data inform interactive dashboards and maps that guide outreach campaigns and ensure that vaccines, health workers, and resources are allocated efficiently relative to where zero-dose and under-immunised children are located to plan accurately for outreach sessions, cold chain requirements.

*Subtheme 2: Integration of local knowledge and community participation.*

A key component of effective microplanning involves engaging local stakeholders and community health workers in data collection,

**Table 4**

Summary of findings on data-driven and context-sensitive microplanning approaches for identifying and reaching zero-dose and under-immunised children in Sub-Saharan Africa.

Theme	Sub-theme	Microplanning approaches/data inputs	Key findings	Implications for optimising immunization programmes
Theme 1: Data-driven microplanning frameworks	Geo-enabled microplans	Georeferenced microplans using settlement maps, facility catchments, population estimates (e.g., DRC, UNICEF programmes) Community health workers, village health teams, participatory validation of household lists (e.g., Mozambique, Gavi peer learning initiatives)	Geo-enabled microplans improve identification of missed settlements and estimation of vaccine needs, contributing to improved coverage and reductions in zero-dose prevalence. Local participation improves data accuracy, ensures inclusion of mobile and hard-to-reach populations, and enhances acceptability of outreach strategies.	Supports precise, locality-specific planning and efficient allocation of vaccines and outreach teams. Highlights the importance of combining data-driven tools with contextual and experiential knowledge.
	Integration of local knowledge			Reinforces the need for flexible microplanning adapted to sociocultural and security contexts.
	Context-sensitive and gender-responsive planning	Gender-intentional data use, engagement of trusted local actors (e.g., DRC, conflict-affected settings)	Addressing social and gender barriers enhances community engagement and uptake of immunization services.	
Theme 2: Operational integration and impact	Targeting zero-dose and hard-to-reach children	Linking spatial data with routine immunization and outreach planning	Microplanning improves identification of zero-dose children and reduces missed populations during routine and campaign activities.	Enhances operational efficiency and effectiveness of immunization delivery.
	Improvements in immunization outcomes	Digitised monitoring, follow-up of unvaccinated children (e.g., DRC, Mozambique, Zambia SIAs)	Evidence of increased coverage and reductions in zero-dose and dropout rates in settings with strengthened microplanning.	Demonstrates potential for measurable equity gains when microplanning is well implemented.
Theme 3: Challenges and limitations	Data gaps and technical constraints	Inaccurate population denominators, weak surveillance, and incomplete facility data	Data limitations constrain the precision of microplans and targeting accuracy.	Emphasises the need for improved population data and routine data quality.
	Capacity and resource limitations	Digital tools, training, and connectivity requirements	Limited technical capacity and infrastructure hinder the scale-up and sustainability of microplanning innovations.	Points to note for sustained investment in capacity building and systems support.
	Integration with routine systems and governance	Alignment with EPI workflows and planning cycles	Microplans are not always institutionalised or routinely updated, which limits their long-term impact.	Requires stronger governance, accountability, and policy integration.
Theme 4: Strategies for optimisation	Strengthening data systems	Digitised immunization registries, DHIS2 Tracker, geo-referenced datasets	Robust data systems enable real-time planning, monitoring, and follow-up of zero-dose children.	Foundational for scalable, data-driven microplanning.
	Participatory and adaptive planning	Continuous engagement of communities and frontline workers	Participatory approaches ensure relevance and responsiveness to changing local contexts.	Improves sustainability and effectiveness of microplanning efforts.
	Policy and governance alignment	Institutionalisation within national EPI strategies	Embedding microplanning into policy frameworks supports sustained use and accountability.	Essential for national-level scale-up and long-term impact.

DHIS2, District Health Information Software 2; DRC, Democratic Republic of the Congo; EPI, Expanded Programme on Immunization; GIS, Geographic Information System; SIA, Supplementary Immunization Activity.

validation, and implementation. Case study evidence from Gavi's peer learning initiatives shows that village health teams and community volunteers play a central role in registering children, validating household lists, and updating microplans regularly with real-time insights [23]. This engagement helps ensure that outreach sites and schedules reflect local realities and that children beyond the reach of fixed facilities are considered in plans. Similar strategies have been documented in Mozambique, where digital community mapping of zero-dose and under-immunised children via a DHIS2 platform enabled household-level data capture by community health workers, significantly reducing missed settlements and improving data quality [24].

#### *Subtheme 3: Context-sensitive approaches and gender integration.*

In the DRC microplanning initiative, training on gender-intentional data collection and use was incorporated to ensure that immunization planning considered gender-related barriers to care [21]. The combined geospatial and gender strategy was perceived to foster more effective community engagement and contributed to increased uptake of routine services, particularly where gender norms traditionally constrained access. Additionally, qualitative research in conflict-affected Sudan highlights the use of locally trusted institutions and individuals, such as community leaders and non-governmental organisations (NGOs), as part of identification and reach strategies within microplanning frameworks where routine systems are weak [25]. These efforts underline the need for context-specific, flexible microplans that leverage local social structures when formal health service access is disrupted.

#### *Theme.*

## **2: Operational Integration and Impact on Coverage.**

### *Subtheme 1: Enhanced targeting of zero-dose and hard-to-reach populations.*

Microplans that integrate spatial data with routine service-delivery metrics yield demonstrable operational benefits. In the DRC, georeferenced microplans enabled health workers to identify hard-to-reach settlements and quantify gaps in coverage that were not visible in traditional administrative data, thereby optimising outreach schedules and resources [21]. Digitised mapping in Mozambique showed that capturing geo-coordinates and vaccination status of individual children allowed programmes to track who remained unvaccinated after outreach activities and prioritise follow-up, reducing duplication and improving efficiency [24].

### *Subtheme 2: Sustained increases in immunization outcomes.*

The integration of data-driven planning with structured microplans led to measurable improvements in immunization coverage and reductions in the number of children with zero doses in intervention regions. In the DRC, intervention provinces with geo-enabled microplans experienced dramatic improvements in immunization coverage rates and modest reductions in pentavalent dropout over three years [21]. Moreover, documented success factors from Zambia's 2024 measles-rubella supplementary immunization activity, where comprehensive microplanning, real-time digital monitoring, and strategic community engagement were central, led to 97% national coverage and the vaccination of 165,000 previously zero-dose children in underserved communities [26].

Theme.

### 3: Challenges and Limitations of Microplanning Approaches.

#### *Subtheme 1: Data gaps and technical constraints.*

Despite the promise of data-driven microplanning, inaccurate and outdated population estimates, incomplete facility lists, and weaknesses in health information systems present significant obstacles. In South Sudan, a study conducted in conflict and remote settings highlighted that inaccurate denominators and poor surveillance data limit the ability to accurately target zero-dose and under-immunised children, often necessitating greater reliance on ad-hoc community reporting and estimation methods [25].

#### *Subtheme 2: Capacity and resource limitations.*

Effective microplanning requires technical capacity, digital tools, and sustained resourcing that are unevenly distributed across SSA contexts. For example, the digital DHIS2 mapping platform in Mozambique, while impactful, struggled with adoption due to limited user training time and poor internet connectivity, barriers common across resource-constrained settings [24].

#### *Subtheme 3: Integration with routine systems and governance.*

Embedding microplans into routine immunization workflows and decision-making processes remains uneven and without clear lines of responsibilities, tools may exist on paper but fail to influence day to day decisions. While microplanning shows positive results when adopted, sustained integration requires institutional commitment and governance frameworks that ensure local plans are updated, resourced, and used consistently in health planning cycles [21].

Theme.

### 4: Strategies for Optimising Microplanning in SSA.

#### *Subtheme 1: Strengthening data systems and digital tools.*

Optimising microplanning necessitates investments in routine data systems, including digitised immunization registries and geo-referenced population datasets, which provide accurate denominators and spatial context for planning. Tools such as DHIS2 Tracker and interactive dashboards should be scaled alongside training to enhance real-time decision support [24].

#### *Subtheme 2: Participatory and contextual planning.*

Incorporating community health workers, local leaders, and gender-sensitive practices into microplanning ensures that plans reflect lived realities and barriers experienced by caregivers, particularly in nomadic, remote, or conflict-affected communities [21].

#### *Subtheme 3: Policy and governance alignment.*

Microplans must be institutionalised within national Expanded Programme on Immunization (EPI) policies and integrated with broader health planning processes so that data-driven insights inform routine monitoring, funding decisions, and accountability mechanisms [21]. This requires clear guidance, resource allocation, and routine evaluation frameworks to ensure adjustments based on performance and emerging data.

## 4. Discussion

This study revealed that the application of supervised learning algorithms to extensive health survey datasets results in the identification of predictors associated with zero-dose status. These predictors can be used to prioritise high risk children and communities for targeted outreach and tailored immunization service delivery. ML uses large datasets to identify patterns, predict outcomes, and recommend targeted interventions. ML can be used to identify factors associated with incomplete immunization based on demographic, socio-economic, and healthcare access data [27]. Findings from East and west African studies illustrate this potential, ML models consistently highlighting maternal education, place of delivery and health care provider attitude as key determinants. The sequence of vaccinations and the intervals between them contain intricate information that may be essential for assessing the risk of defaulting. Nevertheless, these temporal events have received insufficient attention in ML studies in SSA. The temporal characteristics

exhibit significant sensitivity to inaccuracies, potentially leading to extreme or inconsistent outcomes if timestamps are altered. In numerous countries within SSA, logistical constraints lead to inefficient documentation, resulting in temporal measurements that are often recorded with significant noise. Consequently, the incorporation of these features into ML models necessitates meticulous standardisation, a process that can be laborious and time-intensive [15].

This study revealed that geospatial modelling has significantly contributed to the identification of zero-dose populations. This study also revealed that geospatial techniques often start with accurate population and settlement mapping and that the use of geospatial data integrated into routine digital health platforms, such as DHIS2, maps individual children's locations and vaccination status. Geospatial modelling identifies high-risk regions, allowing health programs to prioritise resource allocation and implement targeted solutions, such as deploying mobile clinics or enhancing local healthcare infrastructure. Geospatial modelling, when integrated with analyses identifying associated factors, can elucidate regions where intersecting inequities amplify zero-dose prevalence, thereby informing targeted interventions. Integrating geospatial mapping with socio-economic indicators facilitates the design of culturally sensitive educational campaigns and addresses infrastructure deficiencies, thereby enhancing vaccination coverage [28]. As revealed in this study, a key best practice in geospatial immunization research is the integration of diverse spatial data sources, including satellite imagery, health facility locations, travel routes, and demographic survey data, to model zero-dose prevalence with greater accuracy. Although the primary objective is to achieve high childhood immunization rates across all geographic regions and populations, trade-offs are frequently required, particularly in the execution of new strategies and technological methods [21].

This study indicated that effective geospatial mapping frequently requires participatory mapping with local health workers and community health volunteers to validate spatial layers, ensuring that models accurately represent ground realities and that geospatial outputs are integrated into decision-making and micro-planning processes. However, the study noted that geospatial mapping is often constrained by the availability and currency of underlying spatial datasets, particularly in low-resource settings. Similar challenges have been observed in another study [29], underscoring the necessity to modify methodologies to incorporate surveys alongside accessible routine or administrative data for coverage estimation. Methodological advancements should investigate innovative hybrid geostatistical and ML techniques that effectively capture non-linear relationships and structured spatial or spatiotemporal dependencies, while ensuring interpretability and robust quantification of uncertainty. This study indicated that the large-scale implementation of geospatial methods requires specialized technical skills, software, and hardware capabilities, which are currently insufficient in many national immunization programs in SSA. Although the study noted effective integration of geospatial tools with routine program workflows as essential for influencing immunization outcomes, this integration is lacking in many countries in SSA. While geospatial tools enhance immunization service delivery, they often encounter resistance due to perceptions of increased learning effort and associated costs [30]. Advocacy and education regarding these tools will be necessary to highlight their timesaving, efficiency, and empowerment benefits.

This study noted that ML approaches, especially ensemble methods such as random forests and gradient boosting (XGB), surpass traditional statistical models in the classification of zero-dose and under-immunised children. This study also revealed that ML's ability to handle large, multidimensional datasets, such as DHS and routine health information systems, enables the integration of variables, including sociodemographic indicators, maternal characteristics, and geographic information. The key benefits of ML include superior prediction when using complex data, identifying non-linear patterns, and the flexibility in processing large amounts of data in real-time [31]. When applied

responsibly, these strengths can be harnessed to identify children who are most likely to be left behind and to design more equity-oriented immunization strategies.

However, the study revealed that a major constraint for ML applications in immunization equity research is the quality and granularity of available data. A further limitation is that machine learning models developed using data from a specific country or region may exhibit suboptimal performance when implemented in different contexts, attributable to variations in health systems, cultural practices, or data quality. Additionally, the study revealed that some ML models, especially complex ensembles and neural networks, can be “black boxes,” making it difficult for policymakers to understand and trust model outputs. Use of ML applications and visual summaries of model driver can help bridge this trust gap. Therefore, for ML to drive meaningful impact, it must be embedded into existing health data systems. Improvements to national electronic immunization registries and RHIS may facilitate near-real-time risk prediction for zero-dose and under-immunised children, thereby informing microplanning and targeted outreach efforts. The study indicates that partnerships among health ministries, international organisations like UNICEF and Gavi, and academic institutions can facilitate the scalable implementation of ML tools.

This study revealed that microplanning utilizing geospatial and population data has been progressively employed to enhance the identification and outreach to zero-dose and under-immunised children in SSA. Microplanning is an intervention that systematically delineates the activities, resources, timing, and locations of immunization services, specifically targeting underserved or under-immunised populations. It is acknowledged as an essential instrument for enhancing routine immunization coverage and equity [32]. The study highlighted that an essential aspect of effective microplanning is the involvement of local stakeholders and community health workers in data collection, validation, and implementation.

It was also reported in the study that microplans that integrate spatial data with routine service-delivery metrics yield demonstrable operational benefits. The successful use of microplans in immunization was also reported in a Mongolian study [33]. This study reported that the integration of data-driven planning with structured microplans led to measurable improvements in immunization coverage and reductions in the number of children with zero doses in intervention regions. This study indicated that, despite the potential of data-driven microplanning, significant obstacles arise from inaccurate and outdated population estimates, incomplete facility lists, and deficiencies in health information systems. Although local enumeration activities can provide up-to-date, high-quality data on target populations, they are time-consuming and expensive [34]. Effective microplanning requires technical capacity, digital tools, and sustained resourcing that are unevenly distributed across SSA contexts.

Additionally, the study revealed that incorporating community health workers, local leaders, and gender-sensitive practices into microplanning ensures that plans reflect lived realities and barriers experienced by caregivers, particularly in nomadic, remote, or conflict-affected communities. The bottom-up approach to microplanning demonstrates greater efficacy in identifying and reaching zero-dose children. This method initiates at the health facility level and highlights the importance of community involvement in identifying target populations and barriers to immunization. Community stakeholder participation leads to microplans that better align with local needs and priorities, especially regarding the location and timing of immunization sessions. The involvement of local stakeholders enhances local commitment to the implementation of microplanning, facilitating resource mobilization for immunization planning efforts [34].

#### 4.1. Limitations of this review

Our search strategy had several limitations, including reliance on English-language databases, which may have introduced a language

bias. Some of the studies included in this review were retrospective, which may have affected some of the findings. This review was conducted using a narrative synthesis approach to allow for the integration of heterogeneous evidence spanning machine learning, geospatial technologies, and microplanning interventions within routine immunization systems. While this format enables conceptual integration across diverse study designs and programmatic reports, it is inherently subject to certain limitations. Unlike systematic reviews with predefined inclusion thresholds and quantitative pooling, narrative reviews may be vulnerable to selection bias, subjective interpretation of findings, and variability in reporting standards across included sources. Nevertheless, the findings should be interpreted as a synthesised overview of the evidence rather than an exhaustive or statistically pooled assessment.

Additionally, our review did not focus on impact, efficiency, cost sustainability and long-term value as key variables in policy decisions. Our review didn't focus on these attributes due to limited literature available in the public domain.

## 5. Conclusion

Routine immunization programmes in Sub-Saharan Africa are at a critical inflection point. Despite decades of progress, immunization coverage and equity have stagnated or declined in many countries, with the COVID-19 pandemic further exacerbating existing gaps and increasing the number of zero-dose and under-immunised children. In several settings, recovery to pre-pandemic coverage levels remains incomplete, highlighting the limitations of conventional EPI approaches that rely on periodic surveys, aggregate reporting, and static planning processes. These limitations are particularly evident for zero-dose and under-immunised children, who often remain invisible in routine statistics. These challenges underscore the need for new ways of thinking and working if immunization systems are to regain momentum and advance equity.

This narrative review demonstrates that emerging applications of machine learning, geospatial analysis, and data-driven microplanning offer a credible pathway toward re-energising immunization programmes in the region. When thoughtfully integrated, these approaches enable a shift from retrospective measurement to predictive and precision public health, allowing programmes to anticipate where and why children are being missed and to tailor service delivery accordingly. Importantly, the value of these technologies does not lie solely in algorithmic sophistication, but in their ability to generate actionable intelligence that can be embedded in routine EPI workflows and translated into locally appropriate outreach strategies.

However, realising this potential will require moving beyond fragmented pilots toward systematic, ethical, and context-appropriate integration of digital and analytical tools into national immunization systems. Investments in foundational data infrastructure, workforce capacity, governance frameworks, and community engagement are essential to ensure that advanced technologies strengthen rather than bypass existing health systems. These investments must be guided by equity principles to ensure that marginalised populations are prioritised rather than further excluded. If adopted with intention and accountability, increased and smarter use of machine learning, artificial intelligence, and geospatial technologies can support countries in closing persistent equity gaps, accelerating catch-up efforts, and ultimately restoring and surpassing pre-COVID immunization coverage levels. In doing so, these tools can contribute to a more resilient, responsive, and equitable future for childhood immunization in Sub-Saharan Africa with progressively fewer children remaining zero-dose or under-immunised.

#### CRediT authorship contribution statement

**Godfrey Musuka:** Writing – original draft, Supervision, Project administration, Methodology, Data curation, Conceptualization, Formal analysis, Resources, Writing – review & editing. **Al-umra Umar:** Writing

– review & editing, Methodology, Conceptualization. **Ibrahim Dadari:** Writing – review & editing. **Enos Moyo:** Writing – review & editing. **Oscar Mano:** Writing – review & editing. **Patrick Gad Iradukunda:** Writing – review & editing. **Elliot Mbunge:** Writing – review & editing. **Grant Murewanhema:** Writing – review & editing. **Tapiwa Dhlwayo:** Writing – review & editing. **Noah Mataruse:** Writing – review & editing. **Abu Sadat Mohammad Sayem:** Writing – review & editing. **Tafadzwa Dzinamarira:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization, Validation, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

No data was used for the research described in the article.

### References

- WHO. Indicator Metadata Registry List IA2030 IG 2.1: Number of Zero Dose Children. Available from <https://www.who.int/data/gho/indicator-metadata-registry/imr-details/7792> Accessed 1 January. 2026.
- Adamu AA, et al. Enhancing vaccine delivery in Africa with implementation science. *Discov. Public Health* 2024;21(1):190.
- Hare J, et al. Sustainable integration of artificial intelligence and machine learning approaches within the African infectious disease vaccine research and development ecosystem. *Front. Pharmacol.* 2024;15:1499079.
- Taseen S, Yousafzai MT, Qureshi MFH. Harnessing artificial intelligence and digital technology for enhancing routine immunization among zero-dose children. *Digit. Health* 2025;11. 20552076251382086.
- Wariri O, Utazi CE. Geospatial modelling of vaccination coverage in Africa: addressing gaps, advancing equality, and realising promise. *Lancet Glob. Health* 2025;13(11):e1784–5.
- WHO. Microplanning for Immunization Service Delivery Using the Reaching Every District (RED) Strategy. Available from <https://share.google/fjvdvUy7OuC6N9I>. Accessed 1 January. 2026.
- Banks DE, et al. Benefits and challenges of geographic information systems (GIS) for data-driven outreach in black communities experiencing overdose disparities: results of a stakeholder focus group. *BMC Public Health* 2024;24(1):2103.
- Pautasso M. The structure and conduct of a narrative literature review. In: *A Guide to the Scientific Career: Virtues, Communication, Research and Academic Writing*; 2019. p. 299–310.
- Asnake AA, Seifu BL, Gebrehana AK. Prediction of zero-dose children using supervised machine learning algorithm in Tanzania: evidence from the recent 2022 Tanzania demographic and health survey. *BMJ Open* 2025;15(3):e097395.
- Nantongo BA, et al. A retrospective cohort study on predicting infants at a risk of defaulting routine immunization in Uganda using machine learning models. *JAMIA Open* 2024;7(4):ooae132.
- UNICEF. Reaching the Unreached with Life-Saving Vaccines Through Data Science and Geospatial Technologies. 2025. Available from <https://share.google/8K96lffroTGduL43A> Accessed 1 January 2026.
- Mthulisi S. UNICEF Adopts Machine Learning to Boost Africa Vaccination. Available from <https://itweb.africa/article/unicef-adopts-machine-learning-to-boost-africa-vaccination/5yONP7Erwz3MXWrb>. Accessed 1 January. 2026.
- Arambepola R, et al. Using geospatial models to map zero-dose children: factors associated with zero-dose vaccination status before and after a mass measles and rubella vaccination campaign in southern province, Zambia. *BMJ Glob. Health* 2021;6(12).
- Tadese ZB, et al. Prediction of incomplete immunization among under-five children in East Africa from recent demographic and health surveys: a machine learning approach. *Sci. Rep.* 2024;14(1):11529.
- Odei-Lartey EO, et al. Advancing knowledge on machine learning algorithms for predicting childhood vaccination defaulters in Ghana: a comparative performance analysis. *Appl. Sci.* 2025;15(15):8198.
- GAVI. Using DHIS2 to Reach Zero-Dose and Under-Immunized Children in Mozambique. Available from <https://www.gavi.org/vaccineswork/using-dhis2-reach-zero-dose-and-under-immunized-children-mozambique>. Accessed 10 January. 2026.
- Ogundipe TO, et al. Artificial intelligence in vaccine coverage in Africa: predictive analytics and innovations for immunization equity. *Discov. Med.* 2025;2(1):320.
- Jean Baptiste AE, et al. High-resolution geospatial mapping of zero-dose and Underimmunized children following Nigeria's 2021 multiple Indicator cluster survey/National Immunization Coverage Survey. *J. Infect. Dis.* 2024;230(1):e131–8.
- Michael SCCPN. Using Geospatial Technologies to Improve Immunization Coverage and Equity. A Landscape Analysis and Theory of Change. Available from <https://share.google/QeVTJao7MwPvDqzom>. Accessed 10 January 2026. 2024.
- GAVI. How Geospatial Technology Can Help to Zero in on Zero-Dose Children. 2020. Available from <https://www.gavi.org/vaccineswork/how-geospatial-technology-can-help-zero-dose-children>. Accessed 1 January 2025.
- Ngo-Bebe D, et al. Assessing the use of geospatial data for immunization program implementation and associated effects on coverage and equity in the Democratic Republic of Congo. *BMC Public Health* 2025;25(1):311.
- WorldPop. Teaming up With UNICEF to Find and Vaccinate Zero-Dose Children. Available from <https://share.google/Z3HFFg9Y3Bf1yNQvv>. Accessed 1 January. 2026.
- GAVI. From Exchange to Action Summary Report of Gavi Zero-Dose Learning Hub Inter-country Peer Exchanges (ZDLH-X2 and ZDLH-X1). Available from [https://zdlh.gavi.org/sites/default/files/2024-01/From\\_Exchange\\_to\\_Action\\_Summary\\_Report\\_of\\_Gavi\\_Zero-Dose\\_Learning\\_Hub\\_Inter\\_country\\_Peer\\_Exchanges.pdf](https://zdlh.gavi.org/sites/default/files/2024-01/From_Exchange_to_Action_Summary_Report_of_Gavi_Zero-Dose_Learning_Hub_Inter_country_Peer_Exchanges.pdf). Accessed 1 January 2026. 2025.
- Saugene Z. Digitalization of Community Mapping of Zero-Dose and Under-Immunized Children in Mozambique. Available from <https://share.google/oNEnQLkDndCljWwP>. Accessed 1 January 2025. 2024.
- Sababelzain MM, et al. Vaccination strategies to identify and reach zero-dose and under-immunized children in crisis-affected states in Sudan: a qualitative study. *Confl. Heal.* 2024;18(1):76.
- Mwale M, et al. Bridging immunization gaps: lessons from Zambia's 2024 measles-rubella supplementary immunization activity. *Front. Public Health* 2025;13:1625514.
- Mihret BG, et al. Design a model to predict incomplete immunization among Ethiopian children using ensemble machine learning algorithms. *Sci. Rep.* 2025;16(1):1933.
- Muchie KF, et al. Spatial distribution and associated factors of zero-dose immunization among 12–23 month-old children in Ethiopia: spatial and survey regression analysis. *BMC Pediatr.* 2025;25(1):552.
- Utazi CE, et al. Mapping vaccination coverage to explore the effects of delivery mechanisms and inform vaccination strategies. *Nat. Commun.* 2019;10(1):1633.
- Akpan GU, et al. Conclusions of the African regional GIS summit (2019): using geographic information systems for public health decision-making. *BMC Proc.* 2022;16(1):3.
- Rajula HSR, et al. Comparison of conventional statistical methods with machine learning in medicine: diagnosis, drug development, and treatment. *Medicin. (Kaunas)* 2020;56(9):455.
- Vandelaer J, Bilous J, Nshimirimana D. Reaching every district (RED) approach: a way to improve immunization performance. *Bull. World Health Organ.* 2008;86(3):A–B.
- Enkhtuya B, et al. Reaching every district-development and testing of a health micro-planning strategy for reaching difficult to reach populations in Mongolia. *Rural Remote Health* 2009;9(2):1–12.
- Salisbury N, et al. Routine immunization microplanning challenges and opportunities in low-and middle-income countries: a mixed-method landscape analysis. *Vaccines (Basel)* 2024;12(12):1370.