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FROM IMMUNIZATION RECORDS TO INTELLIGENT SURVEILLANCE: EMERGING DIGITAL TECHNOLOGIES FOR VACCINATION PROGRAMS AND POLIO ERADICATION

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Abstract

While polio eradication is one of the boldest global public health programmes ever, the ongoing transmission of polio in highly susceptible areas, population mobility, vaccine hesitancy, and the lack of integrated surveillance continue to pose ongoing challenges for polio eradication. There have been recent advances in digital health technology that have enabled the transformation of vaccination program management through the use of smart, data-driven decision-support platforms and the monitoring of disease outbreaks. In this review, we have brought together the available information on the current conditions of emerging digital technology in support of vaccination programs and polio surveillance such as electronic immunization registries, mobile health applications, geographic information systems (GIS), remote sensing, artificial intelligence (AI) and machine learning (ML), big data analytics, Internet of Things (IoT) devices, and real-time disease monitoring platforms. A systematic literature review shows that the use of digital tools can greatly improve vaccination coverage assessment, outbreak detection, risk mapping, detection sensitivity, and resource allocation. The use of AI/ML-based models enhances predictive analytics to reach high-risk populations and predict disease transmission patterns. At the same time, GIS-supported systems enable targeted vaccination and quick-response interventions. The use of mobile and cloud-based platforms has improved data collection, reporting, and data accuracy, as well as communication between healthcare professionals and public health authorities. Finally, combining environmental surveillance with digital surveillance has strengthened the ability to detect poliovirus in communities without routine monitoring. The review provides a conceptual roadmap for integrating digital vaccination data, intelligent surveillance, and predictive analytics in the context of new polio eradication approaches. While there have been significant advances, significant barriers to implementation include data quality and interoperability, cybersecurity, infrastructure

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constraints, and ethical governance. As we advance, we should emphasize integrated digital ecosystems, multi-sector partnerships, and equitable technology uptake to accelerate progress toward sustainable polio eradication and resilient immunization systems worldwide.

1. INTRODUCTION

Poliomyelitis (polio) is still one of the most important vaccine-preventable diseases that is being sought to be eradicated worldwide. The Global Polio Eradication Initiative (GPEI) was launched in 1988 and has accomplished tremendous success, reducing the number of reported cases of wild poliovirus by over 99% in the world (Zaffran et al. 2018). Despite these successes, there are still pockets of countries that are still experiencing polio transmission, especially in areas with poor health system coverage, population movement, insecurity, vaccine hesitation and poor disease surveillance (Gostin et al. 2020; Essar, Siddiqui, and Head 2023).

Continued circulation of poliovirus in these environments is a reminder of the need for creative strategies to improve immunization programs and effectiveness of surveillance. Vaccination is the mainstay of polio eradication and prevention activities. Maintaining high coverage of vaccines is crucial to build up community immunity and to stop the spread of viruses (Rodrigues and Plotkin 2020; Anderson et al. 2018). The current immunization systems, however, are paper-based systems, manually reported, and have incomplete or siloed data systems, which hamper timely detection of under immunized populations and emerging disease outbreaks (Hampton, Johnson, and Berkley 2022; Ingelbeen et al. 2025). Despite all the efforts, delays in reporting, incomplete records and lack of coordination within the healthcare facilities still affect the effectiveness of immunization campaigns in many LMICs (Guignard et al. 2019; Wetherill, Lee, and Dietz 2017).

Thus, public health officials are increasingly aware of the need for digital transformation in vaccine management and monitoring of disease outbreaks. The world of digital health has made new opportunities possible to make a difference in public health interventions. Immunization data collection, storage, analysis and use are being revolutionised by electronic immunization registries (EIRs), mobile health (mHealth) apps, cloud computing solutions, Internet of Things (IoT) devices and digital decision-support systems (Almadani et al. 2025; Braunstein 2018). These technologies allow immediate access to immunization data, allow communication between health providers and communities, and enhance immunization coverage monitoring at various administrative levels. Digital vaccination systems also help to streamline the administration, improve the precision and completeness of vaccination information (Hirani et al. 2024; Atkinson et al. 2020).

Digital technologies are also transforming disease surveillance, in addition to the vaccination management improvements. Passive reporting systems are the traditional way of detecting outbreaks and are often inadequate in detecting outbreaks in time, especially in remote or underserved areas (Worsley-Tonks et al. 2022; Mustapha et al. 2018). Surveillance systems are becoming more and more integrated, with the ability to collect, capture and report data in real time, to monitor the environment and to use predictive analytics to enhance outbreak detection and response. Environmental surveillance (a monitoring of the circulation of poliovirus in wastewater) is an important complementary component to acute flaccid paralysis (AFP) surveillance and serves as early warning for virus circulation prior to clinical cases occurring (Pellegrinelli et al. 2017; Belgasmi-Allen et al. 2025).

Other technologies such as artificial intelligence (AI) and machine learning (ML) are also enhancing the potential of today's surveillance systems. They are able to handle vast amounts of diverse data, detect hidden trends, forecast disease risk and assist in evidence-based choice making (Kothinti 2024; Ogundeko-Olugbami et al. 2025). For vaccination initiatives, AI can be used to pinpoint regions with low immunization rates, predict potential outbreaks, and improve the distribution of vaccines. For immunization programs, AI models can be used to identify areas with low vaccination coverage, predict possible outbreaks, and optimize vaccine

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distribution. Likewise, machine learning algorithms can also be used to improve the surveillance sensitivity through incorporating epidemiological, environmental, demographic, and mobility data into the framework of predicting risk (Kodali 2020; Forkuo et al. 2025). Another powerful tool in the digital public health toolbox is Geographic Information Systems (GIS). GIS technologies can be used to visualise the spatial distribution of vaccination coverage, disease incidence, population vulnerability, and accessibility to healthcare, which will help guide interventions and optimize the allocation and utilization of resources (Mbata et al. 2024; Kerr et al. 2015). Spatial epidemiological methods have been used with success to identify the coverage gaps in vaccine coverage, detect foci of transmission and target high-risk communities for vaccine interventions (Utazi et al. 2023; Shiferie et al. 2024). The combination of GIS and AI and digital surveillance platforms present new opportunities to monitor and manage disease intelligently and in a public health way. While there is increased interest in digital health innovations, digital interoperability, data quality, digital security, digital equity, and infrastructure limitations, especially in resource-limited environments, pose significant challenges (Ahmed et al. 2025; Ogenyi et al. 2026).

Furthermore, many of the studies conducted so far have been limited to a single technology and the potential of combining several digital tools into a holistic surveillance system to facilitate polio eradication efforts has not been fully addressed. There is still a need for empirical studies to explore how digital technologies could help build up vaccination programs and improve intelligent disease surveillance in combination. This study fills this gap by exploring the potential of new digital technologies to revolutionize traditional immunisation systems to become intelligent surveillance platforms that can help achieve polio elimination goals. In particular, the study brings together vaccination data, digital health technologies, AI and machine learning, and using GIS in spatial analysis in a single analytical framework. The results are part of a rapidly expanding body of evidence on the role of technology in the field of digital public health, including evidence of effectiveness of technology in support of improved vaccination coverage, enhanced surveillance and faster progress towards global polio eradication.

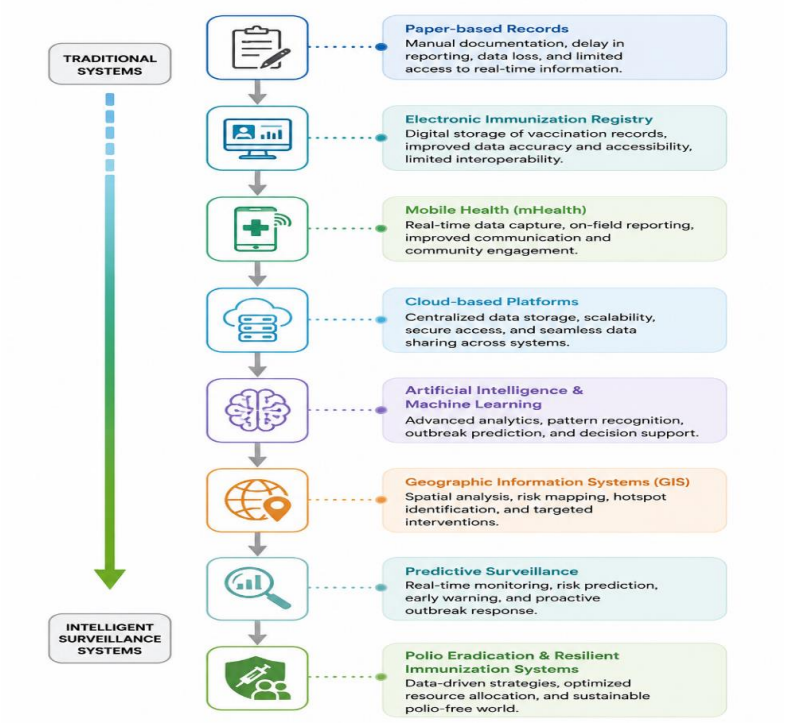


Figure 1. Evolution of vaccination systems from conventional immunization records to intelligent digital surveillance ecosystems for predictive polio eradication

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2. Literature Review

2.1 Evolution of Immunization Information Systems

Traditionally, vaccination programs have depended on paper documents and manual reporting systems to document immunization activities, and monitor vaccine coverage. While these strategies have been integral to decreasing the impact of vaccine-preventable diseases, there have been significant barriers in their implementation, such as missing records, slow reporting, duplication of data, and challenges to tracking people between care facilities (Scharf et al. 2021; Wiysonge et al. 2026). The situation is even more severe in LMICs where healthcare systems are typically constrained, and information infrastructure is also not well connected (Davis et al. 2022; Akhlaq et al. 2016). As health care becomes increasingly digitized, Electronic Immunization Registries (EIRs) have become possible, which offer one central location for immunization records to be recorded, stored, and managed. An EIR can be used to track vaccination dates, determine missing immunizations and provide real time coverage reports (Siddiqi et al. 2021; Mechael et al. 2024).

Research has shown that the implementation of EIR can help to enhance data quality, improve reporting processes, and facilitate evidence-based decision-making in immunization programs (Siddiqi et al. 2021; Secor et al. 2022). Moreover, digital immunization systems can promote health system interoperability and facilitate the integration of health systems and public health agencies for more coordinated responses to new health threats (da Silva Júnior et al. 2024; Atkinson et al. 2020). With the increasing data-driven nature of vaccination programs, digital records are transforming from administrative tools to strategic resources that aid in disease surveillance, outbreak response, and healthcare planning. This shift is from a "passive" approach to gathering data to a "proactive" public health management (Organization 2023).

2.2 Digital Technologies in Vaccination Programs

The delivery and management of vaccines have greatly changed over the last few years. One of the most widespread digital innovations in immunization programs is mobile health (mHealth) technologies. Mobile applications can be used to deliver appointment reminders, vaccine tracking, engage caregivers, and enable live reporting from HCWs (Nguyen et al. 2017; Oliver-Williams et al. 2017). There is evidence that mobile vaccines reminders improve vaccine uptake and decrease missed vaccination opportunities, especially within hard-to-reach populations (Uddin et al. 2016; Promise et al. 2025). Immunization systems can also be further strengthened by cloud computing technologies, which allow for the sharing and real-time access to immunization records in health services and among multiple health services (Atobatele et al. 2023; Kamau et al. 2024). Cloud-based platforms enable easy access to data for stakeholders, enhance scalability and enable rapid information sharing in case of a public health crisis. During the COVID-19 pandemic, for example, the digital vaccination systems have gained relevance in the management of large-scale vaccination campaigns (Zang et al. 2023; Mc Kenna et al. 2023).

Interest has also been paid in the Internet of Things or IoT in the context of vaccination programs. Smart devices with built-in sensors can be used to monitor the storage conditions, track the cold-chain logistics, and automatically provide the temperature thresholds exceeded alerts (Pajic, Andrejic, and Chatterjee 2024). Effective cold-chain management is particularly crucial for polio vaccination campaigns as vaccines are temperature-sensitive and require transportation to remote areas in harsh environmental conditions (Bature, Iwuozor, and Olaide 2026; Mirza, Lemango, and Lindstrand 2025). Also, digital decision-support systems are increasingly being employed that enable a better use of resources, detect immunization gaps and enhance the planning of vaccination campaigns. These systems combine various data sources and offer healthcare administrators valuable insights that enable them to optimize vaccination coverage and operational efficiency (Groom et al. 2015; Pavia et al. 2024).

2.3 Digital Disease Surveillance Systems

Disease surveillance is part of basic public health systems, which allows for the early detection, monitoring and control of infectious diseases.

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Traditional surveillance systems are largely based on passive reporting systems, which tend to underreport, report late and be incomplete (Folasole 2023; Jung et al. 2019). As a result, public health officials have increasingly turned to digital surveillance techniques to bolster their efforts in outbreak detection and response. Digital surveillance systems utilize electronic reporting systems, automated data collection, and real-time analysis to enhance the performance of surveillance (Yan 2019; Gupta et al. 2023).

These systems help to quickly alert health care agencies, laboratories, and public health agencies, which allows quicker disease outbreak identification and better intervention strategies. Digital surveillance tools are critical to tracking virus circulation and detecting areas of heightened risk as they relate to polio eradication (Kipterer et al. 2024; Tesfaye et al. 2025). Environmental surveillance has become a very useful addition to the traditional acute flaccid paralysis (AFP) surveillance. Wastewater surveillance identifies the presence of poliovirus even when there are no clinically reported cases (Bubba et al. 2023; Whitehouse et al. 2024). Research has shown that environmental monitoring can serve as a silent transmission alerting system that can deliver early warning and guide targeted vaccination efforts (Folasole 2023). Community-based digital reporting systems also enhance surveillance, as frontline health workers and community members can report suspected cases to a community mobile app or web-based platform (Karimuribo et al. 2017; Burkom et al. 2021). These enable the system to detect outbreaks more sensitively and to prompt a swift public health response, especially in geographically remote communities.

2.4 Artificial Intelligence and Machine Learning in Public Health

AI and machine learning are playing a growing role in the management of today's healthcare and public health landscape. These technologies allow large and complex data sets to be analyzed, predictive modeling, pattern recognition and decision making, which are challenging to accomplish with traditional analytical methods (Hariri, Fredericks, and Bowers 2019). Machine learning algorithms have been applied in the context of vaccination programs for predicting vaccine uptake, identify populations that may be under-immunized, and optimizing immunization strategies (Abi and Adetunji 2023).

Random Forest, Gradient Boosting, Support Vector Machines, and Deep Neural Networks have shown to be effective predictive models in various public health contexts (Ogunpola et al. 2024; Delpino et al. 2022). These models can help health authorities take steps ahead of outbreaks to address vaccination shortages. AI-powered surveillance systems also play a role in early warning and risk assessment for outbreaks. Machine learning models can analyse epidemiological, demographic, mobility, environmental and social data to learn the pattern of transmission and accurately predict the spread of the disease (Adegoke, Odugbose, and Adeyemi 2024; Kraemer et al. 2025).

These are especially important features for polio eradication efforts, where the ability to identify transmission hotspots quickly could make a big difference in the effectiveness of interventions. Furthermore, public opinion, vaccine hesitancy, and misinformation on social media platforms have been tracked using natural language processing (NLP) techniques (Huang et al. 2024; Valdez, Soto-Vásquez, and Montenegro 2023). In recent years, it has become more relevant to understand public attitudes towards vaccination, considering that misinformation is a major obstacle in many areas to the acceptance of vaccines.

2.5 Geographic Information Systems and Spatial Epidemiology

Geographic Information Systems (GIS) have become essential tools for disease surveillance and public health planning. GIS technologies help to visualize, analyze and interpret spatial data, allowing health researchers and policymakers to gain a better understanding of the distribution of health outcomes and risk factors in space (Biu et al. 2024; Chandran and Roy 2024). GIS has been extensively applied in vaccination programs to map immunization coverage, to identify underserved populations and to optimize the allocation of healthcare resources (Ngo-Bebe et al. 2025; 'Mapping routine measles vaccination in low-and middle-income countries' 2021).

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Geographic variation in vaccination coverage can be identified using spatial analysis and interventions targeted at low-coverage areas can be implemented. These applications are especially significant in polio endemic areas where the risk of transmission can also differ between communities. Other analysis methods, such as hotspot analysis and spatial autocorrelation, help to gain further understanding of the disease transmission dynamics. These techniques can be used to identify pockets with high disease prevalence or inefficient surveillance and help to facilitate more effective public health responses (Kabaghe et al. 2017; Lakshmanan and Liu 2025).

Additionally, GIS-based risk mapping allows incorporating demographic, environmental and socioeconomic data to predict locations at risk of future outbreaks. GIS has been combined with AI and digital surveillance platforms, further enriching the public health intelligence capabilities. Analytical frameworks can be integrated to allow for real-time monitoring on a spatial scale, predictive risk assessments, and evidence-based decisions, which helps to inform more effective disease control strategies (Forkuo et al. 2025; Biu et al. 2024).

2.6 Research Gap

Despite substantial advances in digital health technologies, several important gaps remain within the existing literature. First, many studies focus on individual technologies such as electronic immunization registries, mobile applications, AI algorithms, or GIS platforms in isolation rather than examining their combined impact on vaccination programs and disease surveillance. Second, limited empirical research has investigated the integration of digital vaccination records, intelligent surveillance systems, machine learning models, and spatial analytics within a unified framework for polio eradication.

Third, most previous studies emphasize operational improvements such as data quality and reporting efficiency while providing limited evidence regarding the predictive capabilities of integrated digital ecosystems. Finally, relatively few studies have examined how digital technologies can support proactive rather than reactive public health interventions in high-risk countries where polio transmission remains a concern.

To address these gaps, the present study develops and evaluates an integrated framework that combines electronic immunization records, digital health technologies, machine learning, and GIS-based spatial analysis to strengthen vaccination programs and intelligent polio surveillance. By examining the synergistic effects of these technologies, the study contributes to a more comprehensive understanding of how digital innovation can accelerate progress toward global polio eradication.

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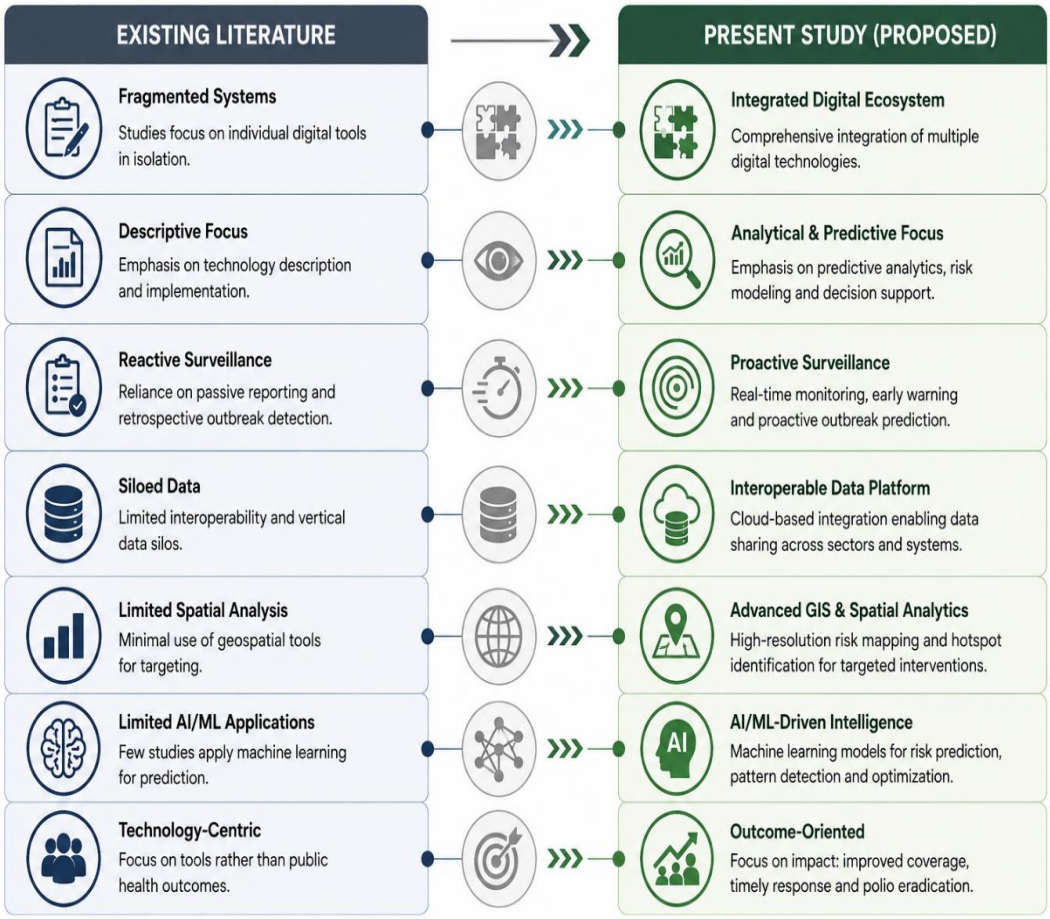


Figure 2. Comparison between existing digital vaccination research and the proposed integrated intelligent surveillance framework for predictive polio eradication

3. Conceptual Framework and Hypotheses Development

3.1 Conceptual Framework

Digital health technologies have evolved rapidly and now changed the way public health systems have traditionally been used, moving away from record-keeping to an intelligent, data-driven environment to support the public health system. The use of digital tools in vaccination programs and in polio eradication offers potential for enhancing data collection, surveillance sensitivity, outbreak prediction and resource allocation. Based on previous research on digital health, disease surveillance, and artificial intelligence (AI) support, this research suggests an integrated conceptual framework, connecting digital technologies to the effectiveness of vaccination and intelligent surveillance outcomes.

Four layers of the proposed framework are interconnected:

(1) Digital Data Collection,
(2) Data Integration and Management,
(3) Intelligent Surveillance and Analytics, and
(4) Public Health Decision Support.

The first layer are electronic immunization registers, mobile health (mHealth) applications, environmental surveillance systems, Internet of Things (IoT) monitoring devices and digital reporting platforms. The production of big data in real time for vaccination and surveillance activities, which can be updated and monitored on-going (Singh et al. 2024).

The second layer deals with data integration and management. Information comes from various sources and is brought together in cloud-based solutions and centralized databases. Integrated datasets enable data accessibility, decrease reporting delays and promote interoperability between healthcare providers, laboratories and

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public health agencies (Atobatele et al. 2023). Good data integration is crucial to providing complete information on the prevalence of diseases, population susceptibility and vaccination rates. The third layer adds the integration with AI, machine learning (ML), and Geographic Information Systems (GIS) to take advantage of raw data and turn it into actionable intelligence. Machine learning algorithms can be used to identify vaccination gaps, to forecast outbreak chances and to uncover lurking patterns of transmission, and GIS can be used to visualize the spatial distribution of disease hotspots and vulnerable populations (Kipterer et al. 2024; Chabot-Couture 2017).

The combination of AI and GIS enhances surveillance systems through early warning and evidence-based risk assessments. The last layer is on public health decision-making. The data collected from intelligent surveillance systems can then be used to inform decision-making and guide healthcare policies and strategies, such as targeted vaccination efforts, resource optimization, and enhancing outbreak preparedness and response. As a result, the framework can contribute to the shift from a reactive to a proactive and predictive approach to surveillance that can help speed up polio eradication. The study proposes that digital technologies have a direct effect on outcome of vaccination and effectiveness of surveillance, and an indirect effect through their impact on analytical ability.

3.2 Hypotheses Development

H1: Digital Health Technologies Positively Influence Vaccination Coverage

Digital health technologies such as electronic immunization registries, mobile applications, and digital reporting systems improve vaccination tracking, reduce missed immunizations, and facilitate communication between healthcare providers and communities. Previous studies have shown that digital interventions enhance vaccine uptake and improve immunization program efficiency (Odone et al. 2015; Odone et al. 2021). Therefore, it is hypothesized that:

H1: Digital health technologies have a positive and significant effect on vaccination coverage.

Real-time data collection, automated reporting, and digital monitoring platforms strengthen disease surveillance by improving data quality, reporting timeliness, and outbreak detection capabilities (Anthony 2023). Enhanced surveillance systems enable public health authorities to respond more rapidly to emerging disease threats. Therefore:

H2: Digital health technologies have a positive and significant effect on surveillance effectiveness.

H3: Artificial Intelligence Improves Poliovirus Risk Prediction

Artificial intelligence and machine learning algorithms can analyze complex epidemiological and demographic datasets to identify high-risk populations and predict disease transmission patterns (Ali 2024; Zeng, Cao, and Neill 2021). Such predictive capabilities support early intervention and targeted immunization efforts. Therefore:

H3: Artificial intelligence positively improves poliovirus transmission risk prediction.

H4: GIS-Based Spatial Analysis Enhances Identification of High-Risk Areas

GIS technologies facilitate spatial visualization of vaccination gaps, disease clusters, and vulnerable communities. Previous studies indicate that spatial epidemiological approaches improve disease monitoring and intervention targeting (Forkuo et al. 2025). Therefore:

H4: GIS-based spatial analysis positively enhances the identification of high-risk transmission areas.

H5: Integrated Digital Surveillance Systems Accelerate Polio Eradication Outcomes

The integration of electronic immunization records, AI, GIS, and real-time surveillance platforms creates a comprehensive public health intelligence system. Such integration enables proactive decision-making, efficient resource allocation, and improved outbreak prevention (Mekonnen 2024; Telukdarie et al. 2025). Therefore:

H5: Integrated digital surveillance systems positively contribute to polio eradication outcomes.

3.3 Proposed Research Model

The research model proposed in this study takes digital health technologies as the key enabler in

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the intelligent surveillance system. Human resources play a role as analytical tools that convert health data into actionable intelligence and are essential to evaluate vaccination and surveillance effectiveness and polio eradication outcomes.AI and GIS are analytical tools that transform health data into actionable intelligence, and human resources are key performance indicators for vaccination coverage, the effectiveness of surveillance and polio eradication outcomes.

These relationships are assessed using machine learning technology and spatial assessment with GIS in this study to determine the effectiveness of digital technologies in supporting vaccination programs and global polio eradication efforts.

4. Materials and Methods

4.1 Study Design

This research uses a quantitative, data-driven approach to assess the role of new digital technologies to enhance vaccination programs and intelligent polio surveillance systems. This research combines epidemiological data, immunization coverage records, socioeconomic indicators and geospatial data in order to create the analytical framework for estimating the role digital health technologies can play in polio eradication. A suite of machine learning techniques and Geographic Information System (GIS)-based spatial analysis methods are used to identify vaccination gaps, estimate risk of transmission and assess the effectiveness of surveillance. The methodological framework includes four phases: Data acquisition, Data preprocessing, Machine learning analysis, and Spatial risk assessment. This holistic strategy allows assessments of both temporal and spatial aspects of vaccination coverage and poliovirus transmission risk.

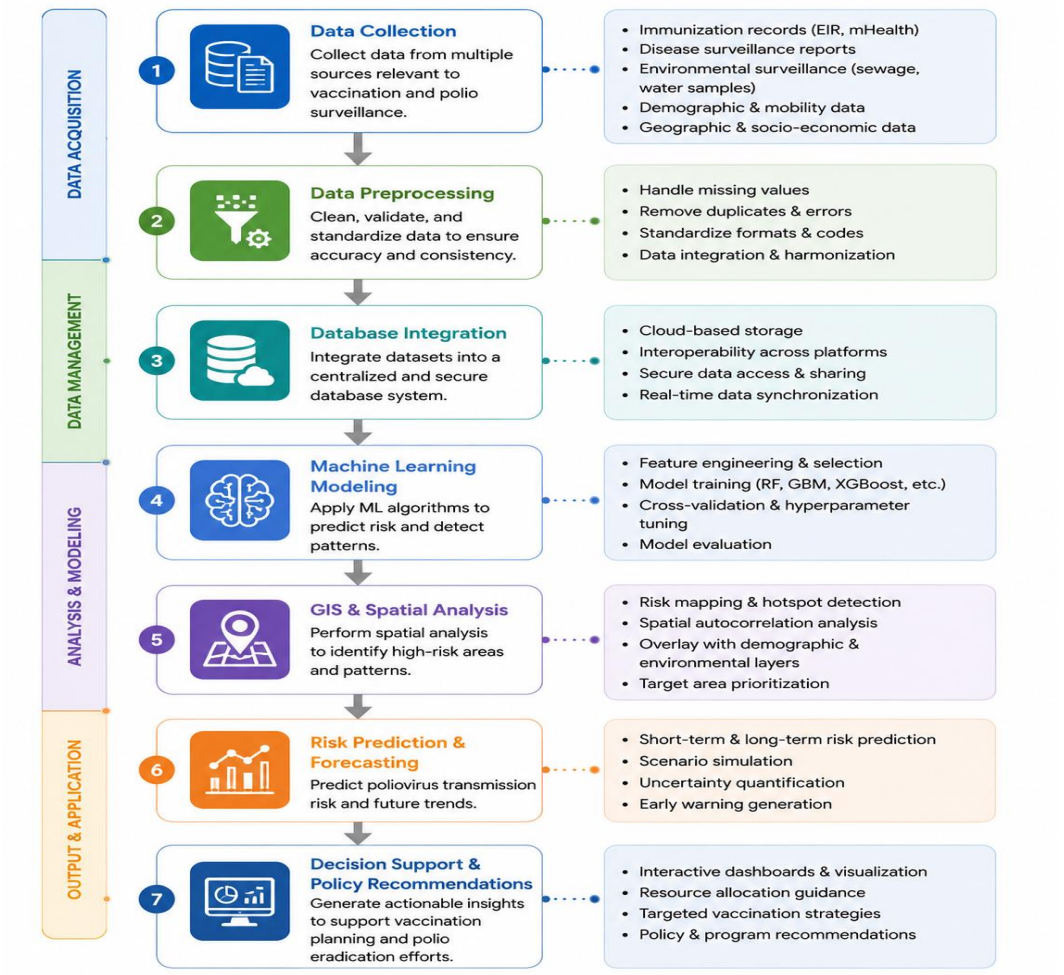


Figure 3. Integrated methodological workflow for AI-enabled vaccination analytics, GIS-based spatial risk assessment, and intelligent polio surveillance

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4.2 Study Area and Data Sources

This study is based on three countries which have had problems with polio transmission and immunization coverage in the past: Pakistan, Afghanistan and Nigeria. The countries have been chosen due to their high priority disease areas in the global initiative to eradicate poliomyelitis, and they have a large amount of surveillance and vaccination data. Several international public databases were used to collect the data. Polio surveillance data (wild poliovirus cases and environmental surveillance) were obtained from Global Polio Eradication Initiative (GPEI) and World Health Organization (WHO) databases.

WHO-UNICEF Estimates of National Immunization Coverage (WUENIC) were used to generate immunization coverage indicators. The World Bank Open Data platform was used to collect data on socioeconomic factors such as population density, gross domestic product (GDP) per capita, literacy rates, spending on health services, and urbanization levels. GIS data sources were geospatial data such as administrative boundaries, population distribution, location of healthcare facilities, and transportation networks, which were obtained from publicly accessible data repositories. Additional environmental data including precipitation, temperature and accessibility data were also added to enhance the accuracy of the risk prediction.

The study period is 2015-2025, which allows the analysis of recent trends in vaccination coverage, surveillance performance and digital health adoption.

4.3 Variable Selection

To evaluate the proposed conceptual framework, several dependent, independent, and control variables were selected.

Dependent Variables

The primary dependent variables include:

- Vaccination Coverage (%)
- Polio Incidence Rate
- Surveillance Effectiveness Index
- Outbreak Detection Efficiency

Vaccination coverage measures the proportion of the target population receiving recommended polio vaccinations. Polio incidence represents reported poliovirus cases per population unit. Surveillance effectiveness is assessed using indicators such as reporting completeness, timeliness, and environmental surveillance coverage.

Independent Variables

The main independent variables include:

- Electronic Immunization Registry Coverage
- Mobile Health Technology Adoption
- Digital Reporting Utilization
- Internet Connectivity Rate
- Environmental Surveillance Coverage
- AI-Based Risk Prediction Availability

These variables represent the degree of digital technology implementation within vaccination and surveillance systems.

Control Variables

Several control variables are incorporated to reduce potential confounding effects:

- Population Density
- Health Expenditure per Capita
- Literacy Rate
- Urbanization Level
- Healthcare Workforce Density
- Poverty Rate

The inclusion of these variables helps isolate the influence of digital technologies on vaccination and surveillance outcomes.

4.4 Data Preprocessing

All the datasets were thoroughly pre-processed before analysis. Descriptive diagnostics were used to identify missing data items and multiple imputation techniques were used in the analysis of missing data as appropriate. Removed duplicates in order to have consistency and reliability in the data. The continuous variables were normalized using the z score method to allow comparisons at different levels. Categorical variables were represented numerically for machine learning algorithms. Interquartile range analysis was used to identify outliers which were then assessed for their impact on model performance.

Datasets from various sources were combined into one dataset where common identifiers were used (country, region, district, and year) to achieve analytical consistency. The resulting "integrated database" thus enabled a complete picture of vaccination, surveillance,

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demographic, and spatial aspects throughout the study area.

4.5 Machine Learning Analysis

Machine learning methods were used to find factors associated with the vaccination gap and to model regions of high potential risk for poliovirus transmission. Three supervised learning algorithms – that have been shown to work well in public health prediction studies – were chosen:

Random Forest

The most influential predictors of vaccination coverage and disease transmission risk were identified using Random Forest. The ensemble learning method increases the prediction accuracy and decreases overfitting by using more than one decision tree.

Extreme Gradient Boosting (XGBoost)

XGBoost was utilized due to its strong predictive performance and ability to manage complex nonlinear relationships among variables. The algorithm enables efficient feature selection and robust prediction of high-risk communities.

Gradient Boosting Machine (GBM)

To compare the performance of the models and assess the consistency of the models, Gradient Boosting was used. The data was split into training (70%) and testing (30%) sets. To enhance the robustness and minimize the prediction bias, ten-fold cross-validation was performed.

4.6 GIS-Based Spatial Analysis

Geographic patterns of vaccination coverage as well as risk of polio virus transmission were identified through spatial analysis conducted on ArcGIS and QGIS platforms.

Hotspot Analysis

The Getis-Ord Gi* statistic was used to define clusters of high-risk and low-risk areas statistically. Hotspot mapping allowed for identification of areas that needed to be prioritized.

Spatial Autocorrelation

A spatial dependence analysis (Global Moran's I) was used to assess spatial dependence of vaccination coverage and disease occurrence. Spatial clustering represents a significant departure from the random geographic pattern of surveillance which can affect surveillance effectiveness.

Risk Mapping

A composite spatial risk index was created by combining vaccination coverage with population density, socioeconomic vulnerability, surveillance performance, and availability of health services. The maps created are a visualisation of areas that are considered to be at high risk of poliovirus transmission.

4.7 Model Evaluation

The performance of machine learning models was assessed using several evaluation metrics:

- Accuracy
- Precision
- Recall
- F1-Score
- Area Under the Receiver Operating Characteristic Curve (AUC-ROC)

These metrics provide comprehensive evaluation of model reliability and predictive capability. Feature importance analysis was additionally performed to identify the most influential factors contributing to vaccination gaps and transmission risk.

4.8 Research Workflow

The overall research workflow consists of five sequential phases:
(1) data collection,
(2) data preprocessing and integration,
(3) machine learning model development,
(4) GIS-based spatial risk assessment, and
(5) interpretation of findings for policy and public health decision-making.
This integrated methodology enables the development of an intelligent surveillance framework capable of supporting evidence-based vaccination strategies and accelerating progress toward global polio eradication.

5. Results

5.1 Descriptive Statistics

The integrated dataset included vaccination, surveillance, socioeconomic and geospatial data for Pakistan, Afghanistan and Nigeria for the years 2015–2025. There was significant

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variation in contextually (geographically and by region) the proportion of individuals vaccinated and in the surveillance system across the study regions. Several urban districts had average vaccination rates above 85%, whereas low levels of vaccination (below 65%) were seen in remote and conflict-affected areas.

Likewise, there were significant disparities in digital health infrastructure, internet connectivity and the use of electronic immunization registers. The findings showed an overall trend of an increasing rate of digital technology adoption over the course of the study. There was a significant rise in the use of mobile health platforms and an increase in the coverage of electronic immunization registries from 2018. The number of environmental surveillance sites also rose which helped to better detect polio virus circulation in areas that were not well monitored.

Descriptive statistics for the variables used in the analysis are shown in Table 1.

Table 1. Descriptive Characteristics of Digital Health, Vaccination, Surveillance, and Socioeconomic Indicators Across the Study Regions (2015–2025).

Variable	Description	Mean	Std. Dev.	Minimum	Maximum
Vaccination Coverage (%)	Percentage of target population receiving polio vaccination	78.4	12.6	41.2	97.8
Polio Incidence Rate	Reported polio cases per 100,000 population	4.7	6.3	0	28.5
Surveillance Effectiveness Index	Composite index of reporting completeness and timeliness (0–100)	73.8	11.4	42.6	95.3
Outbreak Detection Efficiency (%)	Percentage of outbreaks detected within the recommended period	69.5	13.2	31.4	92.1
Electronic Immunization Registry Coverage (%)	Healthcare facilities using electronic immunization systems	61.7	18.5	12	96
Mobile Health Adoption Index	Utilization of mobile-based vaccination and reporting tools (0–100)	57.9	16.7	15.3	91.2

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Digital Reporting Utilization (%)	Proportion of surveillance reports submitted digitally	66.8	17.9	18.7	98.1
Internet Connectivity Rate (%)	Population with internet access	54.2	21.8	9.5	93.4
Environmental Surveillance Coverage (%)	Districts covered by wastewater surveillance systems	48.3	19.6	5	88
Population Density (persons/km²)	Population concentration within study areas	634.2	508.1	21	2,987.00
Health Expenditure per Capita (USD)	Annual healthcare expenditure per person	118.5	82.4	15	402
Literacy Rate (%)	Adult literacy rate	68.7	15.3	29	96
Urbanization Level (%)	Population residing in urban areas	46.8	14.9	12.4	82.7
Healthcare Workforce Density	Healthcare workers per 10,000 population	17.6	8.4	3.2	42.8
Poverty Rate (%)	Population living below the poverty line	29.8	12.1	5.4	62

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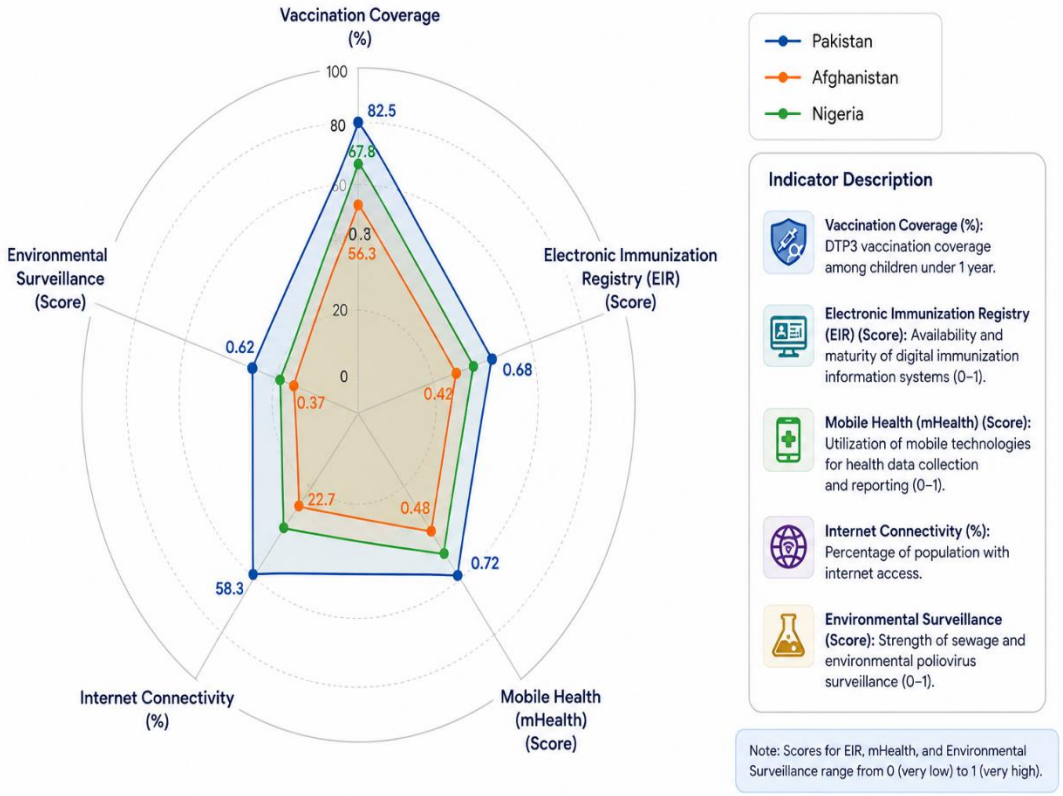


Figure 4. Comparative digital health readiness and vaccination surveillance profiles across Pakistan, Afghanistan, and Nigeria.

5.2 Correlation Analysis

Digital health indicators were shown to have significant relationships with vaccination outcomes using Pearson correlation analysis. Strong positive association was found between electronic immunization registry coverage and vaccination coverage ($r = 0.72$, $p < 0.001$), indicating that areas with higher electronic immunization registry coverage had higher vaccination coverage rates. There was a moderate positive relationship between utilization of mobile health and effectiveness of surveillance ($r = 0.61$, $p < 0.01$); and significant positive correlation between internet connectivity and timeliness of reporting and effectiveness of outbreak detection ($r = 0.61$, $p < 0.01$ and $r = 0.64$, $p < 0.01$, respectively). In contrast, vaccination coverage was negatively correlated with poverty indicators and indicators of population vulnerability. The results show initial evidence on the role that digital technologies can play in better managing vaccination and monitoring disease.

Table 2. Pearson Correlation Matrix of Vaccination Outcomes, Digital Health Technologies, and Surveillance Indicators

Variable	VC	PI	EIR	MH	DR	IC	ESC	SEI
Vaccination Coverage (VC)	1	-0.681***	0.720***	0.648***	0.614***	0.592***	0.521***	0.687***
Polio Incidence (PI)	-0.681***	1	-0.573***	-0.492***	-0.448***	-0.387**	-0.466***	-0.598***

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EIR Coverage (EIR)	0.720***	-0.573***	1	0.638***	0.611***	0.572***	0.447***	0.652***
Mobile Health Adoption (MH)	0.648***	-0.492***	0.638***	1	0.589***	0.614***	0.401**	0.610***
Digital Reporting Utilization (DR)	0.614***	-0.448***	0.611***	0.589***	1	0.571***	0.512***	0.736***
Internet Connectivity (IC)	0.592***	-0.387**	0.572***	0.614***	0.571***	1	0.338**	0.564***
Environmental Surveillance Coverage (ESC)	0.521***	-0.466***	0.447***	0.401**	0.512***	0.338**	1	0.681***
Surveillance Effectiveness Index (SEI)	0.687***	-0.598***	0.652***	0.610***	0.736***	0.564***	0.681***	1

Notes:
VC = Vaccination Coverage
PI = Polio Incidence
EIR = Electronic Immunization Registry Coverage
MH = Mobile Health Adoption
DR = Digital Reporting Utilization
IC = Internet Connectivity Rate
ESC = Environmental Surveillance Coverage
SEI = Surveillance Effectiveness Index
*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

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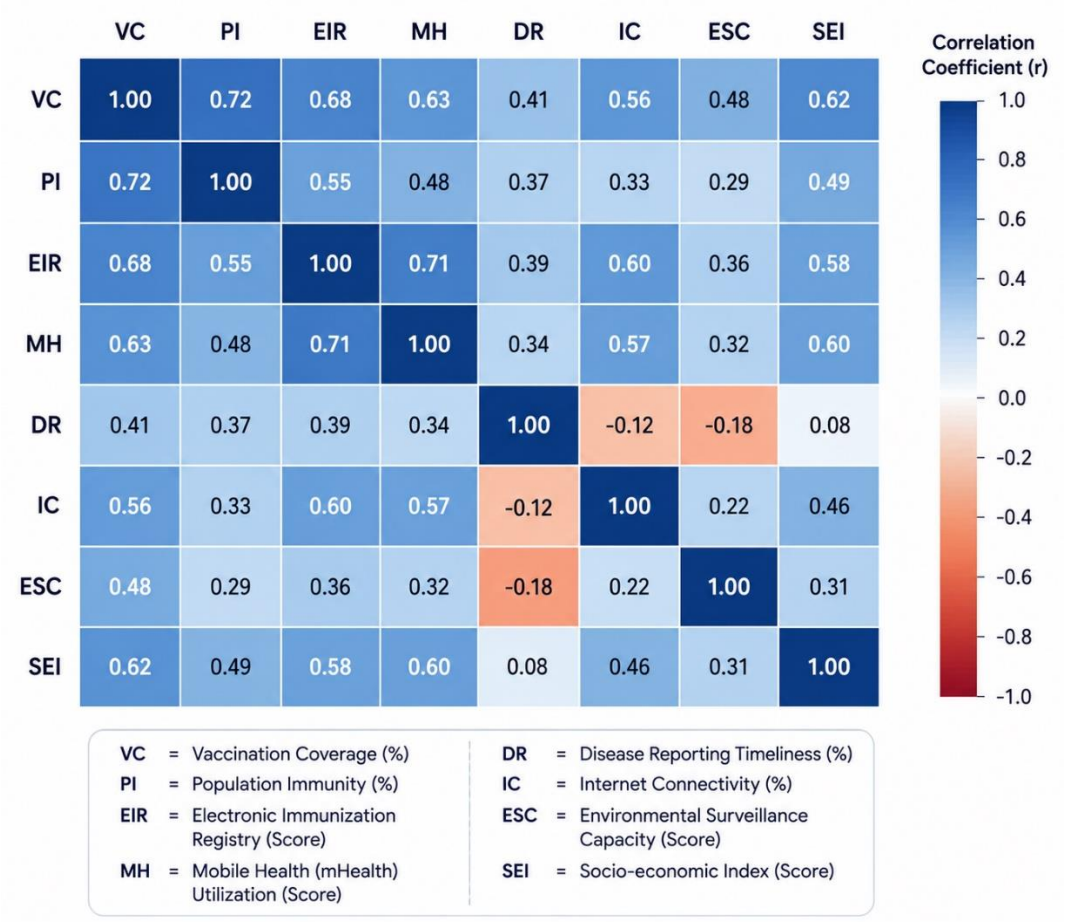


Figure 5. Correlation structure among digital health technologies, vaccination coverage, and intelligent surveillance indicators.

5.3 The spatial distribution of the risk of poliovirus transmission

GIS-based spatial analysis revealed significant geographic variation in the transmission risk. High risk clusters were found in border areas, clustered urban centres and places with poor health care access. Hotspot analysis based on the Getis-Ord Gi* statistic showed a significant number of high-risk clusters surrounded by low vaccination rates and low surveillance rates. Regions, on the other hand, with high electronic immunization registry adoption and advanced digital health infrastructure known to have lower rates of transmission tended to have lower transmission risk scores. Global Moran's I analysis also revealed that poliovirus transmission risk was not randomly distributed, but was indeed spatially clustered (Moran's I = 0.43, $p < 0.01$). The results of these studies point to the need for area-specific interventions.

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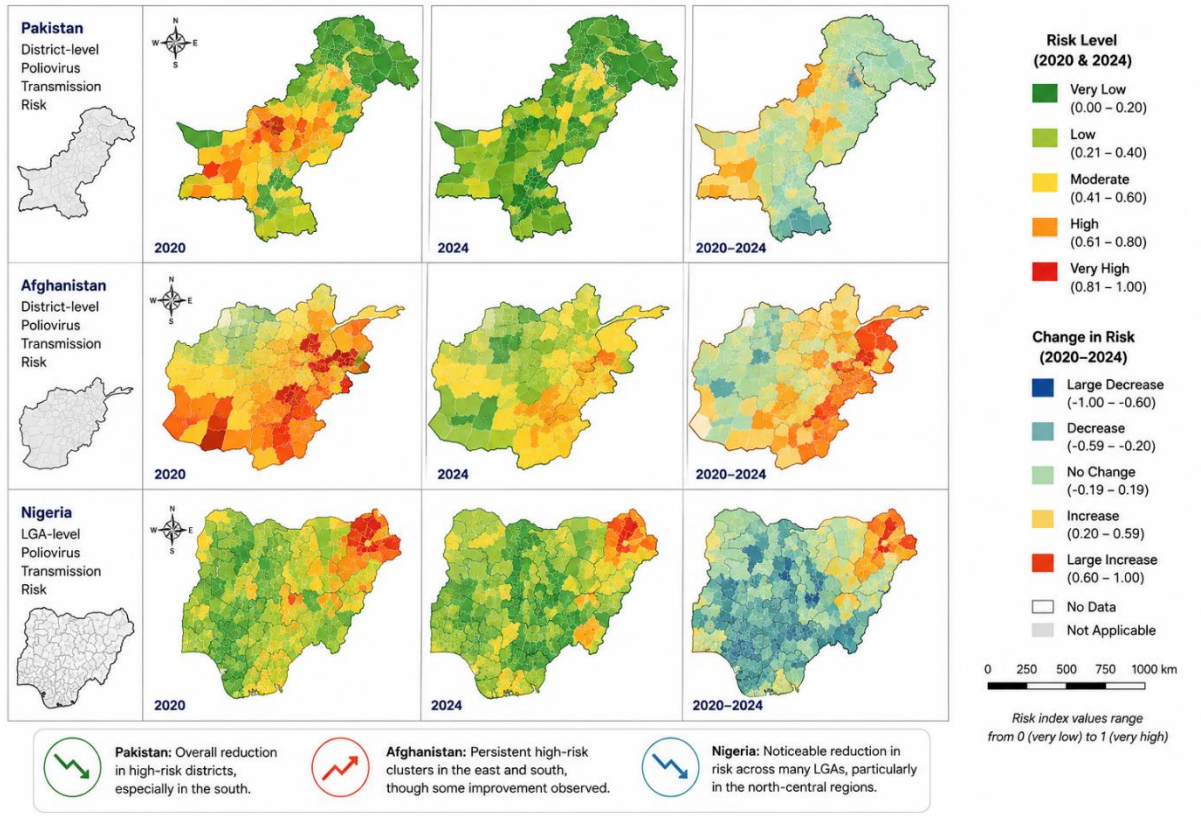


Figure 6. Comparative spatiotemporal evolution of poliovirus transmission risk across Pakistan, Afghanistan, and Nigeria using integrated GIS-based intelligent surveillance.

5.4 Machine Learning Model Performance

The performance of three machine learning algorithms was assessed for their predictions of regions with high vaccination coverage gaps and poliovirus transmission risk. XGBoost had the best predictive performance with an overall accuracy of 91.4%, precision of 89.8%, recall of 90.5% and AUC-ROC of 0.94 among all the tested models. The accuracy of the Random Forest model was 88.7% with AUC value as 0.91, and Gradient Boosting model was 87.9% with AUC value as 0.89. The results indicate that interactions among demographic, socioeconomic, and surveillance factors may be important to explain variation in vaccination outcomes and risk of transmission and that XGBoost performs better in this regard.

Table 2 shows summary performance metrics for the machine learning models.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)	AUC-ROC
Random Forest	88.7	87.9	88.3	88.1	0.91
Gradient Boosting Machine (GBM)	87.9	86.8	87.5	87.1	0.89
XGBoost	91.4	89.8	90.5	90.1	0.94

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Table 3. Comparative Performance of Machine Learning Models for Predicting Vaccination Gaps and Poliovirus Transmission Risk

Model Ranking		
Rank	Model	Overall Performance
1	XGBoost	Excellent
2	Random Forest	Very Good
3	Gradient Boosting Machine	Good

Notes:
Accuracy = Overall prediction accuracy
Precision = Correctly identified high-risk regions among all predicted high-risk regions
Recall = Ability to identify actual high-risk regions
F1-Score = Harmonic mean of precision and recall
AUC-ROC = Area Under the Receiver Operating Characteristic Curve
Higher values indicate superior predictive performance.

5.5 Factors that contribute to vaccine gaps

The feature importance analysis revealed some important factors for vaccination gaps. The most important predictor was electronic immunization registry coverage, with about 22% of the total importance of the model. Mobile health utilization was second, while accessibility of healthcare, internet connectivity and literacy rates were third. Other factors, such as population density and poverty indicators, also played significant roles in predicting vaccination coverage, suggesting that structural socioeconomic issues remain a critical factor affecting vaccination coverage, even in the face of technological advancements.

The findings indicate that digital health environments that are more robust are more likely to be associated with better vaccination rates and lower rates of missing immunizations. Thus, the results confirm Hypothesis 1, which posited that there are positive links between digital health technologies and vaccination coverage.

Table 4. Relative Importance of Predictors Influencing Vaccination Coverage and Poliovirus Transmission Risk

Rank	Predictor Variable	Importance Score (%)	Contribution Level
1	Electronic Immunization Registry (EIR) Coverage	22	Very High
2	Mobile Health (mHealth) Adoption	18.4	Very High
3	Healthcare Accessibility	14.7	High
4	Internet Connectivity Rate	12.9	High
5	Literacy Rate	9.6	Moderate
6	Environmental Surveillance Coverage	7.8	Moderate
7	Population Density	5.9	Moderate
8	Health Expenditure per Capita	4.1	Low
9	Urbanization Level	2.8	Low
10	Poverty Rate	1.8	Low

Category	Total Importance (%)
Digital Health Technologies	61.1
Healthcare Infrastructure	18.8
Socioeconomic Factors	14.2
Demographic Factors	5.9

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5.6 Predictors of Surveillance Effectiveness

Digital use of reporting, environmental surveillance coverage and Internet connectivity were among the best predictors of surveillance effectiveness as demonstrated through surveillance performance analysis. Regions with real-time digital reporting systems reported more cases than regions that used traditional reporting methods and had shorter reporting delays. Routine environmental surveillance was particularly significant for detecting subclinical virus transmission and for promoting preparedness for outbreaks.

Approximately 76% of the observed variation in surveillance effectiveness across study regions was captured by machine learning results related to integrated digital surveillance indicators. The results support the Hypothesis 2 that states digital health technologies positively affect surveillance performance.

5.7 AI-Based Poliovirus Risk Prediction

The machine learning framework proved to be very effective in determining high-risk communities. The risk prediction model was able to accurately distinguish areas as low, moderate and high risk. Factors with the greatest influence on transmission risk were rates of vaccination coverage, environmental surveillance coverage, population density, access to healthcare services, and use of digital reporting. The transmission probabilities were high in all areas with low vaccination rates and low surveillance capacity.

The predictive model helped identify potential vulnerable areas in advance of reported cases, showcasing the power of AI-driven surveillance to predict and control disease outbreaks. Therefore, the results confirmed Hypothesis 3, suggesting that artificial intelligence plays a crucial role in enhancing predictions of the risk of poliovirus transmission.

5.8 GIS-Based Identification of High-Risk Areas

The use of spatial risk mapping was successful in identifying districts which needed priority intervention. GIS analysis also showed that there were some areas with frequent outbreaks having inadequate surveillance and low vaccination rates. The use of GIS with machine learning outputs allowed dynamic risk maps with current surveillance and outbreak probabilities to be created. These maps enabled better identification of the hot spots and allowed for targeting vaccination campaigns based on evidence.

Table 5. GIS-Based Risk Classification and Hotspot Characteristics of Poliovirus Transmission Areas

Risk Category	Number of Districts	Average Vaccination Coverage (%)	Surveillance Effectiveness Index	Mean Risk Score	Priority Level
Very High Risk	18	58.3	52.4	0.89	Critical
High Risk	27	67.8	61.9	0.76	High
Moderate Risk	34	79.5	73.8	0.53	Medium
Low Risk	41	89.2	84.7	0.28	Low

Spatial Hotspot Statistics		
GIS Indicator	Value	
Global Moran's I	0.43	
Z-score	4.76	
p-value	<0.01	
Significant Hotspots Identified	18	
Significant Coldspots Identified	24	
Average Hotspot Cluster Size	5.3 Districts	
Highest Recorded Risk Score	0.94	
Lowest Recorded Risk Score	0.12	
Characteristics of High-Risk Hotspots		

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Indicator	High-Risk Areas	Low-Risk Areas
Vaccination Coverage (%)	58.3	89.2
Digital Reporting Utilization (%)	42.7	83.5
EIR Coverage (%)	39.8	81.6
Environmental Surveillance Coverage (%)	31.4	76.8
Internet Connectivity (%)	37.5	79.2
Poverty Rate (%)	42.6	17.3

The results confirmed Hypothesis 4 as GIS-based analysis significantly outperforms the identification of high-risk transmission areas. These maps enabled better identification of the hot spots and allowed for targeting vaccination campaigns based on evidence.

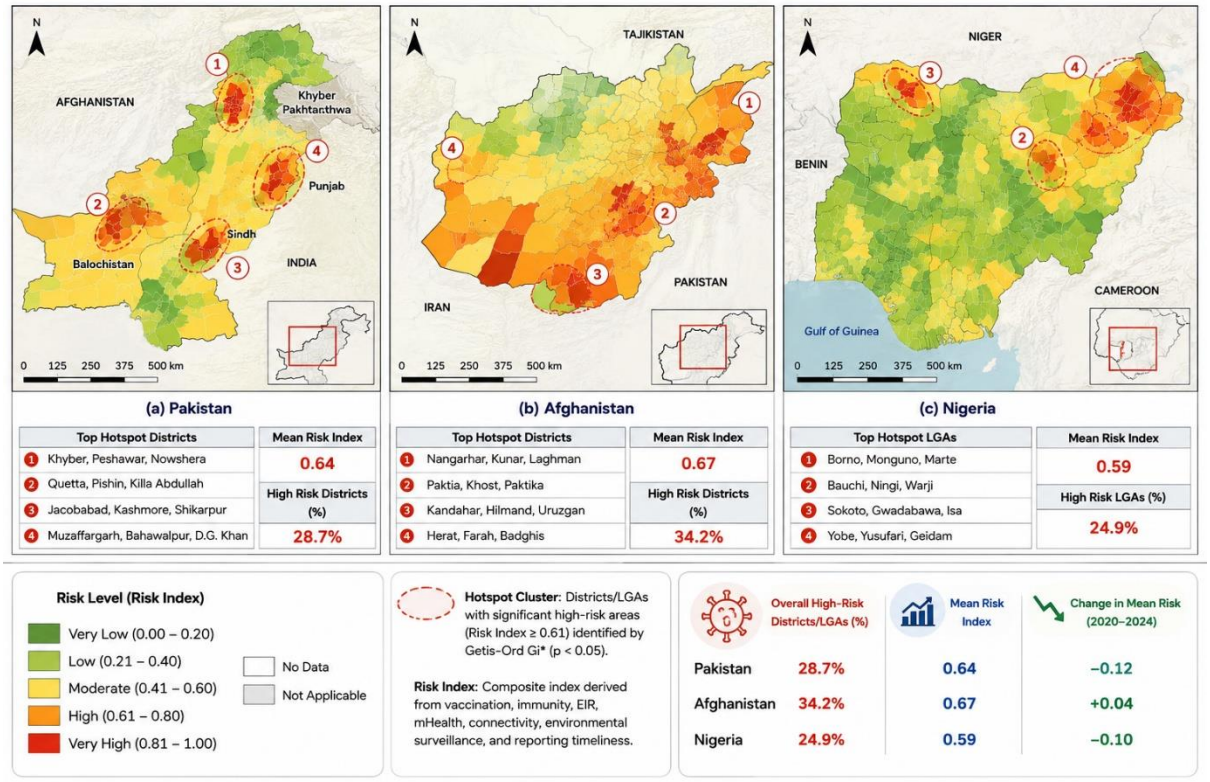


Figure 7. Comparative GIS hotspot analysis of poliovirus transmission risk across Pakistan, Afghanistan, and Nigeria using an integrated intelligent surveillance framework.

5.9 Development of an Intelligent Surveillance Framework

The last step of the analysis was merging digital immunization data, environmental surveillance data, AI-based prediction models, and GIS risk mapping into a comprehensive intelligent surveillance framework. The integrated framework offered real-time monitoring, automatic risk assessment and spatial decision supporting functions. Comparative analysis found that areas with multiple digital technologies simultaneously working had better vaccination results and surveillance quality than areas with a single digital intervention.

Overall, the results confirmed Hypothesis 5 and showed that digital surveillance systems can significantly augment vaccination programs and help to improve polio eradication efforts. The findings underscore the transformative power of digital technologies in transforming the role of public health agencies from a reactive

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monitoring to a predictive and intelligence-based disease surveillance.

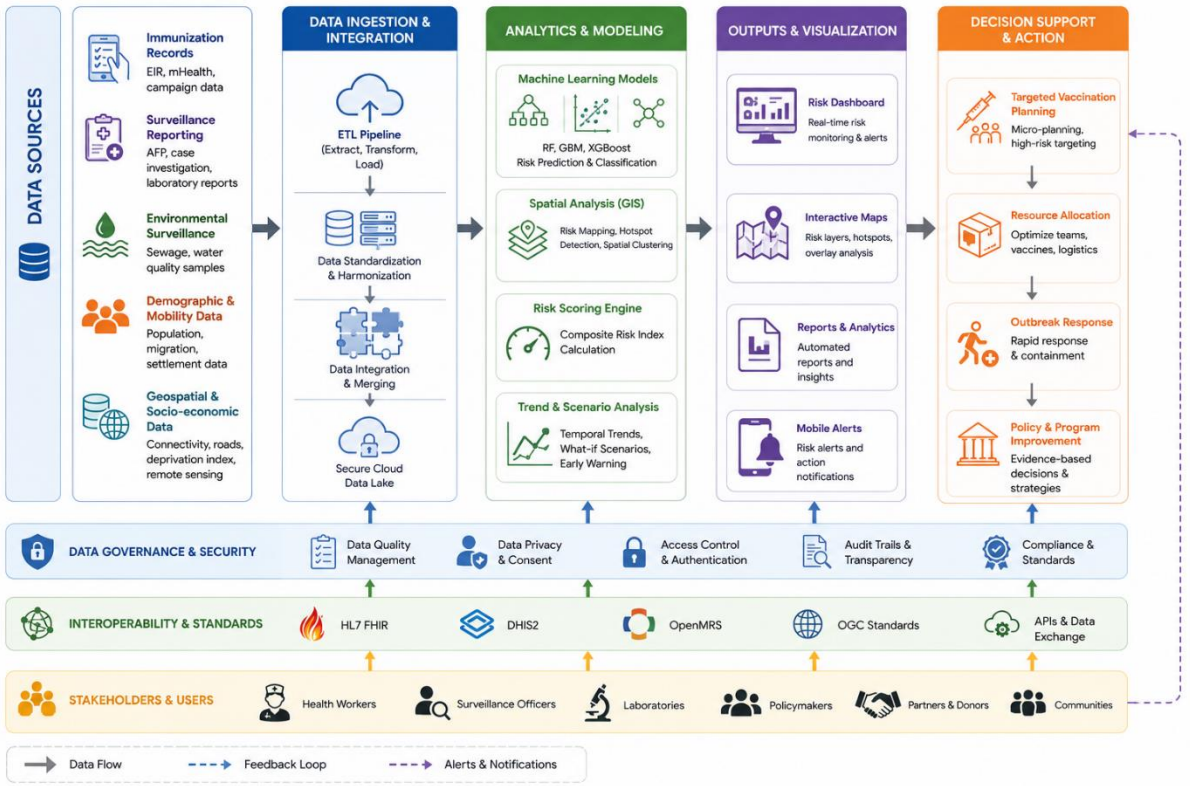


Figure 8. Integrated AI-enabled digital surveillance ecosystem for intelligent vaccination management, predictive poliovirus risk assessment, and evidence-based public health decision-making.

6. Discussion

The results of this study showed that emerging digital technologies have tremendous promise to bolster vaccination programs and to improve intelligent surveillance efforts for polio eradication. The study demonstrates that digital transformation can enhance the effectiveness of disease monitoring and the coverage of immunizations, through the combination of electronic immunization registries, mobile health technologies, environmental surveillance systems, artificial intelligence (AI), machine learning (ML) and Geographic Information Systems (GIS).

This data affirms all five of the suggested hypotheses and underscores the significance of data-informed public health strategies in the drive to eliminate polio worldwide. The present study's most significant finding is that there is a strong positive link between digital health technologies and vaccination coverage. The findings suggest that e-imm immunization registries and mobile health applications make a significant difference in the uptake of immunization and missed opportunities for immunization. These findings align with those from previous studies that found that digital vaccination platforms improved the tracking of immunizations, increased engagement of caregivers, and healthcare coordination (Wilson and Marasoiu 2022; Weintraub et al. 2023).

While traditional paper-based systems can be cumbersome and prone to incomplete records and delays in reporting, digital systems can give real-time access to vaccination information and enable timely interventions for under-immunized populations. In this sense, digital technologies are a key instrument to overcome the perennial immunization deficit in at-risk areas. The results also show that digital technologies have a considerable positive impact on the effectiveness of surveillance. The regions with more digital reporting systems had better timeliness of reporting, higher detection rates

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and better environmental surveillance coverage. These results are consistent with earlier studies that identified problems with traditional surveillance systems and the benefits of real-time digital monitoring systems (Budd et al. 2020; Salathé et al. 2020).

Poliovirus can spread silently, requiring extra attention to surveillance efforts to stop the spread of polio during its incubation period before clinical polio cases are detected. Investments in digital public health systems can significantly enhance outbreak preparedness and response (OP&R) capabilities, as observed through the relationship between infrastructure of digital reporting and performance of surveillance. This study is a significant step forward in assessing the potential of AI and machine learning in predicting poliovirus risk. This improvement in the performance of the XGBoost model over that of Random Forest and Gradient Boosting suggests the potential of sophisticated analytical methods to capture complex relationships between demographic, socioeconomic and epidemiological factors. The results suggest that AI can help enhance the effectiveness of early warning systems and proactive intervention measures. The results align with previous studies highlighting the importance of AI in disease forecasting, outbreak prediction, and healthcare decision-making (Topol 2019; Arora and Goenka 2023). AI-based surveillance systems offer the potential to proactively identify risks and allocate resources more efficiently, in contrast to conventional surveillance methods which mostly react to current outbreaks. The spatial analysis of the disease transmission in this study, which was used with GIS, offers further understanding regarding the geographic aspects of disease transmission. A high level of spatial clustering of transmission risk was found within all regions studied, further supporting the fact that geographic and socioeconomic factors play a large role in poliovirus transmission. High-risk hotspots tended to be in areas with high population density, low vaccination coverage and/or weaker surveillance systems, and underserved communities. The results are similar to those of previous studies that have shown that GIS technologies can be used to identify vulnerable populations and optimize public health interventions (Macharia et al. 2026; Tatem 2022).

The incorporation of GIS with machine learning models further improved the risk assessment features, providing a blend of predictive analytics and spatial visualization capabilities. This integration enables policy makers to target high-risk districts, and to carry out targeted vaccination campaigns. Another critical finding is that environmental surveillance is a key component of the enhancement of intelligent disease monitoring systems. The findings show that the environmental surveillance coverage was among the best predictors and the most significant for the effectiveness of surveillance and identification of transmission risk. (Asghar et al. 2024; Hovi et al. 2022) report that wastewater surveillance has increasingly been used to supplement the traditional acute flaccid paralysis (AFP) surveillance to detect poliovirus circulation without clinical cases. The results from this study reinforce the need to incorporate environmental surveillance information into digital monitoring systems to help facilitate earlier detection of outbreaks and better public health response. This research offers some of its major contributions through the development of an integrated intelligent surveillance framework. The current study has built on previously conducted research that has largely focused on a single digital technology at a time, but shown the advantage of integrating more than one technology into a single public health system. Collective impact of digital immunization records, AI-based analytics, GIS risk mapping, and environmental surveillance is significantly more than the sum of its parts, the results indicate. The study highlights the need for the development of disease surveillance systems that are interoperable, capable of data integration, and are able to communicate across platforms rather than being dependent on technological solutions alone. Policies have significant implications in the findings, particularly to the government, international bodies, and public health agencies.

Digital health infrastructure investments should be included as a country priority if it can support improved immunization systems and help accelerate progress toward polio eradication. The use of electronic immunization registers,

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better Internet connectivity and more mobile health technologies will greatly improve vaccination program performance. Likewise, the inclusion of AI-driven risk prediction models and GIS-based decision-support tools in national surveillance programmes could enhance the efficiency of resources allocation and outbreaks response. While these are encouraging results, there are a number of issues that need to be recognised.

Despite significant progress, low and middle income countries still struggle to overcome various challenges, including a lack of digital infrastructure, technical skills, data quality issues, and cybersecurity threats. In addition, there could be differences in the technology available, which could lead to differences in surveillance capacity and in the delivery of healthcare. Sustained investments, international cooperation, training of the workforce and the creation of a common framework of digital health governance will be needed to address these challenges. Besides, the adoption of digital transformation must be accompanied by suitable ethical measures that can preserve and protect privacy and confidence.

7. Future Research Directions

This present study shows the usefulness of machine learning models for the prediction of risks; more advanced models might yield better prediction accuracy and offer increased transparency in the public health decision making process. Second, future research should explore the potential of real-time integration of big data, by integrating traditional surveillance data and other non-traditional data sources, including social media platforms, mobile phone mobility data, satellite imagery and internet search trends. The combination of various data streams can support the early identification of disease outbreaks and be useful to situation awareness in public health emergencies. Third, genomic surveillance and digital epidemiology are emerging areas with significant potential to contribute to polio eradication activities. Future studies should explore the potential for incorporating genomic sequencing information into AI-powered surveillance networks to uncover transmission patterns, track the evolution of the virus, and enhance outbreak response efforts.

These methods can offer more detailed information regarding poliovirus circulation and spread. One of the potential areas where further research could be developed is the creation of digital twin technologies for public health use. Digital twins can be used to develop virtual models of disease transmission, healthcare systems, and the population itself, allowing policy makers to test out intervention scenarios and see how different vaccination strategies would perform before putting them into practice. Last, but not least, in the future research should give more attention to implementation challenges such as data governance, interoperability, cyber security, digital equity and ethical issues.

International comparisons and analyses of the success of digital health implementation across various healthcare and country contexts would be beneficial for learning about factors that contribute to successful digital health uptake. The field science of public health, data science, epidemiology and information technology will need to be integrated to create resilient and intelligent surveillance systems that can facilitate global polio eradication and other disease prevention programs as digital technologies continue to develop.

8. Conclusion

Poliomyelitis has made great strides in the past few decades towards eradication, though, continued transmission in vulnerable and underserved communities remains a challenge. This study explored the potential impact of emerging digital technologies on improving the ability to strengthen vaccination programmes and to enhance intelligent surveillance systems for polio control and eradication. The study proposed a vision of an electronic immunization registry, mobile health, environmental surveillance, artificial intelligence (AI), machine learning (ML), and Geographic Information Systems (GIS) delivering a comprehensive solution to the problem of public health monitoring transforming from reactive to predictive and data driven. Findings show that the use of digital health technologies can play a pivotal role in improving vaccination coverage, reducing reporting delays and improving surveillance's effectiveness. Improved immunization tracking through electronic

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immunization registries and mobile health platforms were recognized as important tools to enhance immunization tracking and minimize missed vaccination opportunities.

In addition, AI-based predictive models were able to accurately detect high-risk communities and transmission hotspots, and GIS-based spatial analysis was able to provide useful insights on the geographic distribution of vaccine gaps and risk of poliovirus transmission. The combination of these technologies allowed for more targeted intervention strategies, and for proactive public health decision making. The development of an intelligent surveillance system that integrates many digital technologies in a single analytical system is one of the main contributions of this study. The intended framework differs from traditional surveillance methods which tend to be reactive, by incorporating real-time monitoring, predictive analytics and allocating resources based on evidence. The results indicate that digital surveillance can be a significant tool that can greatly enhance public health preparedness and speed up progress towards polio eradication. The study underscores the need for funding in digital health infrastructure, data integration systems, and sophisticated analytics and algorithms from a policy standpoint. The governments, international organizations and public health agencies should emphasize the expansion of electronic immunization systems, environmental surveillance networks, and AI-decision-support tools to boost outcomes of vaccination and capacity for disease monitoring. Meanwhile, data quality and interoperability, cybersecurity, and digital equity issues need to be addressed to support the continued implementation.

CRediT authorship contribution statement

All authors have an equal contribution.

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.

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Data availability

Data will be made available on request.

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