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Digital Transformation in Public Health Surveillance: Lessons from Emerging Economies

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Abstract

Digital transformation has become an essential driver in strengthening public health surveillance systems, particularly in emerging economies where traditional methods often face limitations such as underreporting, fragmented data, and delayed response times. This examines the role of digital technologies—including mobile health (mHealth) tools, electronic health records (EHRs), geographic information systems (GIS), and artificial intelligence (AI)-powered analytics—in enhancing disease monitoring, outbreak detection, and response coordination in resource-constrained settings. Emerging economies are increasingly adopting digital platforms to improve data collection, real-time reporting, and decision-making, with notable examples from Africa, Asia, and Latin America. Mobile-based reporting systems have enabled rapid case identification and follow-up, while cloud-based dashboards facilitate seamless information sharing across government agencies and health institutions. The integration of AI and machine learning algorithms with surveillance databases supports predictive modeling and early warning systems for infectious diseases such as COVID-19, dengue, and cholera. However, these advancements are not without challenges. Key barriers include limited digital infrastructure, workforce capacity gaps, concerns about data privacy, and fragmented governance frameworks. Furthermore, disparities in access to digital technologies between urban and rural regions may exacerbate health inequities. Despite these hurdles, the digital transformation of public health surveillance in emerging economies offers valuable lessons in agility, innovation, and community engagement. Successful models emphasize the importance of interoperable systems, public-private partnerships, and capacity-building initiatives to sustain digital surveillance efforts. This concludes that investments in scalable, inclusive, and secure digital technologies, alongside policy reforms and cross-sector collaboration, are critical for building resilient surveillance systems capable of addressing current and future public health threats in emerging economies. The insights gained offer practical guidance for other low- and middle-income countries seeking to modernize their surveillance capabilities.

Keywords: Digital Transformation, Public Health Surveillance, Emerging Economies

1. Introduction

Public health surveillance is a cornerstone of disease prevention and control, playing a vital role in detecting, monitoring, and responding to health threats at local, national, and global levels (Efob *et al*., 2023; Obi *et al*., 2023; Uwumiro *et al*., 2023) [35, 50, 76]. Effective surveillance systems enable health authorities to identify disease outbreaks, track epidemiological trends, and guide policy decisions aimed at reducing disease burden and improving population health outcomes (Egbuhuzor *et al*., 2023 [36]; Akintobi *et al*., 2023). Historically, many countries have relied on traditional surveillance methods, which include manual data collection, paper-based records, and delayed reporting mechanisms. These approaches, while foundational, often face significant limitations in emerging economies, where health systems are frequently under-resourced and infrastructure is lacking (Adesemoye *et al*., 2023; Akintobi *et al*., 2023).

Emerging economies in Africa, Asia, and Latin America, in particular, face unique challenges in public health surveillance. These include delayed reporting due to logistical constraints in remote regions, underreporting of cases due to limited diagnostic capacity, and fragmented data systems that hinder comprehensive analysis (Adesemoye *et al*., 2023; Onyeke *et al*., 2023 [72]). Additionally, the absence of standardized reporting protocols often leads to poor data quality and limits the ability of health authorities to mount timely and effective responses. Such challenges became especially evident during the COVID-19 pandemic, when many countries struggled to track cases, coordinate responses, and disseminate accurate information promptly (Ogunnowo *et al*., 2023; Adesemoye *et al*., 2023).

In recent years, the rapid advancement and widespread adoption of digital technologies have transformed healthcare systems globally, including public health surveillance (Adewoyin *et al*., 2023; Fiemotongha *et al*., 2023) [16, 39]. Digital tools such as mobile health (mHealth) applications, electronic health records (EHRs), geographic information systems (GIS), cloud-based platforms, and artificial intelligence (AI) are being increasingly leveraged to improve health data collection, management, and analysis. In high-income countries, digital transformation has led to faster, more accurate, and more integrated surveillance systems, enhancing the capacity to detect and control disease outbreaks (ADIKWU *et al*., 2023 [17]; Onukwulu *et al*., 2023).

This global shift toward digital health has also reached emerging economies, where mobile phone penetration and internet connectivity have increased substantially (Ozobu *et al*., 2023 [74]; Onukwulu *et al*., 2023). These developments have created new opportunities for digital transformation in public health surveillance. Mobile-based reporting systems now enable frontline health workers to collect and submit real-time data, even from remote areas. Cloud-based dashboards offer centralized, accessible platforms for data visualization and decision-making. Furthermore, AI-driven analytics and machine learning models are being used to predict outbreak patterns and optimize resource allocation (Onukwulu *et al*., 2023; Ogunnowo *et al*., 2023).

The rationale for digital transformation in public health surveillance within emerging economies is both practical and strategic. Digital tools can address many of the limitations of traditional systems by automating data collection, reducing reporting delays, and enabling real-time analysis (Ogunnowo *et al*., 2023; Onukwulu *et al*., 2023). They also allow for more granular and geographically specific insights, which are essential for targeted interventions. In the context of frequent infectious disease outbreaks, non-communicable disease burdens, and environmental health risks, digital surveillance solutions can enhance preparedness and response capabilities. Importantly, digital transformation aligns with global health agendas, such as the World Health Organization (WHO) Global Strategy on Digital Health, which advocates for the equitable use of digital technologies to strengthen health systems worldwide.

Despite these opportunities, the implementation of digital surveillance in emerging economies is not without challenges. Issues such as insufficient digital infrastructure, limited technical capacity, data privacy concerns, and the need for robust governance mechanisms remain significant barriers. Furthermore, disparities in access to digital technologies—particularly between urban and rural populations—pose risks of deepening health inequities (Ogunnowo *et al*., 2023; Okolo *et al*., 2023). Understanding how emerging economies navigate these complexities is crucial for developing scalable, sustainable digital surveillance models.

The purpose of this, is to critically analyze the process of digital transformation in public health surveillance across emerging economies. It aims to examine the drivers, technologies, and strategies that have enabled successful adoption, while also identifying persistent challenges and lessons learned. By reviewing case studies from Africa, Asia, and Latin America, this highlights both the successes and limitations of digital surveillance initiatives in resource-constrained settings.

Ultimately, this analysis seeks to inform policymakers, healthcare providers, technology developers, and global health organizations on effective strategies for leveraging digital tools in public health surveillance. By identifying best practices and gaps, this contributes to the growing body of evidence on digital health transformation and offers practical insights for enhancing surveillance systems in emerging economies.

2. Methodology

This study applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to systematically review and synthesize the literature on digital transformation in public health surveillance, focusing on lessons from emerging economies. The review began with a comprehensive search of electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search strategy employed combinations of keywords and Boolean operators, including “digital health,” “public health surveillance,” “emerging economies,” “developing countries,” “mobile health,” “electronic health records,” “artificial intelligence,” and “disease monitoring.” Studies published between January 2010 and June 2025 were considered to capture the most recent developments in digital health technologies.

All retrieved articles were imported into a reference management system for screening. Duplicate entries were removed before initiating the screening process. Titles and abstracts were screened for relevance by two independent reviewers using predefined inclusion and exclusion criteria. Studies were included if they (1) focused on digital tools applied to public health surveillance, (2) presented evidence or case studies from emerging economies, and (3) were published in English. Exclusion criteria included studies unrelated to surveillance, those without digital health components, and papers focused solely on high-income countries.

Full-text reviews were then conducted for all studies passing the initial screening. Disagreements between reviewers were resolved through consensus or by consulting a third reviewer. Data were extracted using a standardized extraction form covering study characteristics, types of digital tools, geographic focus, health conditions addressed, implementation outcomes, and identified challenges.

The quality of included studies was assessed using appropriate appraisal tools, such as the Mixed Methods Appraisal Tool (MMAT) for studies employing qualitative, quantitative, or mixed methods designs. The final synthesis was performed through narrative analysis, identifying common themes, emerging technologies, implementation strategies, challenges, and lessons learned across diverse contexts. The review followed PRISMA guidelines throughout the process to ensure transparency, rigor, and reproducibility.

2.1 Drivers of Digital Transformation in Emerging Economies

The digital transformation of public health surveillance in emerging economies has accelerated in recent years due to a convergence of structural, epidemiological, technological, and policy-related drivers. While high-income countries have long leveraged digital tools for health system strengthening, emerging economies are now embracing such technologies to address gaps in disease monitoring and response capacity (Okolo *et al*., 2023; Ojika *et al*., 2023). Critical drivers include expanding mobile and internet connectivity, the growing frequency of infectious disease outbreaks, global and regional health initiatives advocating digital health, and an increasing demand for real-time data to enable rapid and informed public health responses.

One of the most significant enablers of digital transformation in emerging economies is the rapid growth in mobile phone and internet penetration. According to the International Telecommunication Union (ITU), mobile cellular subscriptions in low- and middle-income countries (LMICs) now exceed 90%, with a growing share of users adopting smartphones capable of supporting digital health applications. Furthermore, affordable mobile data plans and expanding broadband infrastructure have enabled widespread access to the internet, even in many rural areas. These advancements have provided a crucial foundation for deploying mobile health (mHealth) solutions that facilitate disease surveillance and data collection.

Mobile technology has dramatically improved the ability to reach remote and underserved populations where traditional public health infrastructure is weak. Community health workers can now use mobile devices to collect health data, report suspected cases, and receive alerts in real-time, thereby reducing reporting delays and improving outbreak detection. Additionally, the increasing availability of cloud-based data storage and analytics platforms allows health authorities to centralize data from disparate regions, creating a more cohesive and actionable surveillance network (Ojika *et al*., 2023; Okolo *et al*., 2023). This widespread connectivity has empowered governments, non-governmental organizations (NGOs), and private companies to implement scalable digital health solutions across diverse geographic and socioeconomic settings.

The increasing frequency and severity of infectious disease outbreaks have also played a critical role in driving digital transformation in emerging economies. Recent epidemics such as the COVID-19 pandemic, the Ebola outbreaks in West Africa and the Democratic Republic of Congo, and recurrent outbreaks of diseases like dengue, cholera, and Zika have exposed the weaknesses of conventional surveillance systems. In these contexts, delays in reporting, lack of interoperability between systems, and the inability to conduct real-time epidemiological analyses have severely hindered response efforts.

In response to these challenges, emerging economies have been compelled to adopt digital tools to enhance epidemic preparedness and response. During the COVID-19 pandemic, many LMICs rapidly deployed digital contact tracing apps, symptom monitoring platforms, and web-based dashboards to track cases and hospital capacity. These tools helped improve the timeliness of data collection, enabled better allocation of medical resources, and supported risk communication efforts. Similarly, during the Ebola outbreaks, digital surveillance tools such as the Open Data Kit (ODK) and mHero were utilized to facilitate rapid case reporting and coordination among health workers, especially in remote communities with limited access to healthcare facilities.

Beyond immediate outbreak response, digital technologies are increasingly being seen as integral components of long-term health security frameworks in emerging economies. Governments and health agencies recognize the need for resilient digital surveillance systems capable of monitoring both communicable and non-communicable diseases, thus reducing vulnerability to future health threats.

Global and regional health initiatives have further accelerated the digital transformation of public health surveillance in emerging economies. Organizations such as the World Health Organization (WHO), the World Bank, UNICEF, and the Africa Centres for Disease Control and Prevention (Africa CDC) have actively promoted digital health strategies through technical assistance, policy advocacy, and funding mechanisms (Ojika *et al*., 2023; Okolo *et al*., 2023). The WHO's Global Strategy on Digital Health (2020-2025) explicitly calls for strengthening digital health infrastructure and surveillance systems in LMICs, emphasizing the importance of equity, interoperability, and security.

Regional bodies, particularly in Africa, have also taken proactive steps to foster digital transformation. The Africa CDC's "Digital Transformation Strategy for Africa (2020-2030)" outlines a roadmap for leveraging digital tools to improve health surveillance, including plans for regional data repositories, cross-border information exchange, and AI-powered early warning systems. These initiatives are often supported by donor agencies such as the United States Agency for International Development (USAID), the Bill & Melinda Gates Foundation, and the Global Fund, which fund digital health projects focused on malaria, HIV, tuberculosis, and maternal health.

Public-private partnerships have emerged as a key mechanism in implementing these initiatives, with technology companies providing software platforms, cloud services, and data analytics solutions. For example, partnerships between African governments and private technology firms have enabled the use of digital health passports, e-surveillance apps, and supply chain monitoring tools to strengthen pandemic responses and routine disease tracking.

The increasing demand for real-time data to enable rapid decision-making represents another major driver of digital transformation in public health surveillance. Traditional paper-based reporting systems often involve delays of days or weeks before data reaches national health authorities, limiting their ability to respond swiftly to emerging threats. In contrast, digital surveillance platforms allow for near-instantaneous reporting, visualization, and analysis of health data.

Real-time data systems enable health authorities to detect and respond to outbreaks much faster, reducing the spread of infectious diseases and minimizing their impact on healthcare systems. Moreover, predictive analytics powered by machine learning algorithms can forecast disease hotspots, guide resource allocation, and optimize interventions (Okolo *et al*., 2023; Adelusi *et al*., 2023). For instance, during the COVID-19 pandemic, several emerging economies developed digital dashboards that integrated case counts, hospitalization rates, laboratory capacity, and vaccination data to guide policy decisions such as lockdowns, testing strategies, and vaccination rollouts.

The ability to access timely, disaggregated data is also critical for addressing health inequities within countries. Real-time surveillance systems can reveal geographic and demographic disparities in disease burden, enabling targeted interventions for vulnerable populations. Furthermore, the integration of geographic information systems (GIS) allows health officials to map disease patterns and allocate resources more effectively based on spatial epidemiology.

The drivers of digital transformation in public health surveillance in emerging economies are diverse but strongly interconnected. Expanding mobile and internet connectivity has enabled the widespread adoption of digital health tools, while recurrent infectious disease outbreaks have demonstrated the necessity of robust, responsive surveillance systems. Global and regional initiatives provide vital technical and financial support, encouraging governments to embrace digital strategies (Oluoha *et al*., 2023 [65]; Adelusi *et al*., 2023). Finally, the growing demand for real-time data to support rapid and effective decision-making has made digital transformation not only desirable but essential. Together, these drivers are reshaping public health surveillance in emerging economies, laying the foundation for more resilient and equitable health systems in the future.

2.2 Key Digital Technologies and Approaches

The digital transformation of public health surveillance in emerging economies is being driven by a range of innovative technologies that are reshaping how health data is collected, analyzed, and acted upon. These digital technologies enhance the capacity of health systems to detect disease outbreaks, monitor health trends, and implement timely interventions as shown in Fig 1 (Uzozie *et al*., 2023; Adelusi *et al*., 2023). Among the most impactful technologies and approaches are mobile health (mHealth) and SMS-based reporting systems, electronic health records (EHRs) and digital registries, geographic information systems (GIS) for disease mapping, artificial intelligence (AI) and predictive analytics, and cloud-based dashboards and decision support tools.

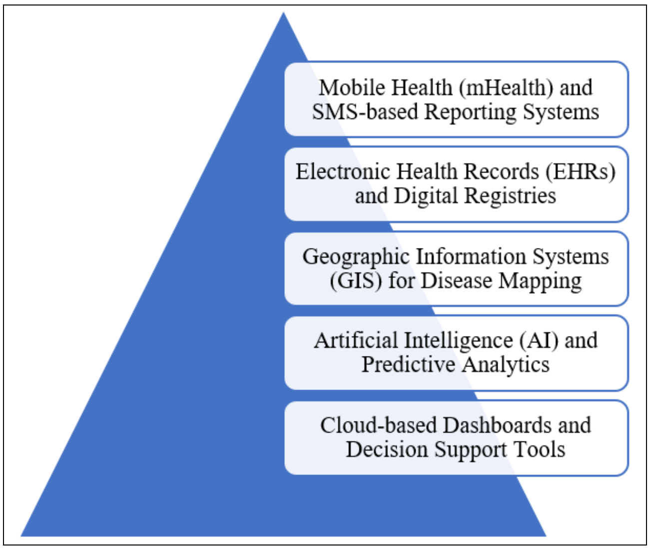

Fig 1: Key Digital Technologies and Approaches

mHealth technologies, including mobile applications and SMS-based reporting systems, have become central tools for public health surveillance in emerging economies. The widespread penetration of mobile phones provides a cost-effective and scalable platform for health data collection, particularly in remote and underserved regions. Health workers use mobile devices to report cases of infectious diseases, track immunization coverage, and monitor maternal and child health indicators.

SMS-based reporting systems are particularly valuable in areas with limited smartphone penetration or internet access. These systems allow community health workers and clinic staff to send coded health data through simple text messages to centralized databases. Programs such as RapidSMS in Rwanda and mTRAC in Uganda have demonstrated success in improving the timeliness of disease reporting and enhancing community-level disease surveillance (Adelusi *et al*., 2023; Uzozie *et al*., 2023). mHealth solutions also enable bidirectional communication, allowing health authorities to disseminate health alerts, treatment guidelines, or outbreak notifications to front-line workers in real time.

The adoption of electronic health records Electronic Health Records (EHRs) and digital health registries represents another significant advancement in public health surveillance. EHRs provide a structured, digital platform for recording patient-level data, allowing for more accurate and comprehensive tracking of disease cases, treatment outcomes, and vaccination status.

In emerging economies, EHR systems are increasingly deployed in primary healthcare centers and hospitals to improve the continuity of care and facilitate surveillance efforts. For example, OpenMRS, an open-source EHR platform, has been widely implemented in countries such as Kenya, Nigeria, and Haiti to track HIV, tuberculosis, and other infectious diseases. These systems enable health authorities to aggregate patient-level data to identify disease patterns, monitor outbreaks, and evaluate public health interventions (Adelusi *et al*., 2023; Esan *et al*., 2023).

Digital registries also play a crucial role in strengthening surveillance systems. Immunization registries, maternal health databases, and disease-specific registries allow for longitudinal monitoring of target populations. These registries help ensure high coverage of health interventions while enabling the early identification of emerging health threats.

Geographic Information Systems (GIS) are increasingly used to visualize and analyze spatial data for disease surveillance and outbreak response. GIS technology enables public health professionals to map the geographic distribution of disease cases, identify clusters of transmission, and assess the relationships between environmental factors and health outcomes.

In emerging economies, GIS-based tools are frequently used for vector-borne disease control, such as malaria, dengue, and Zika virus. For example, the Malaria Atlas Project integrates geospatial data from multiple sources to predict malaria transmission risk in endemic regions, guiding targeted interventions. During the COVID-19 pandemic, GIS-based dashboards were deployed to monitor the spread of infections at the district and neighborhood levels, facilitating the strategic allocation of healthcare resources and implementation of containment measures.

GIS tools are also used for planning vaccination campaigns, monitoring sanitation and water access, and assessing disaster-related health risks. By combining spatial analysis with epidemiological data, GIS supports more effective, data-driven decision-making in public health.

Artificial intelligence (AI) and predictive analytics are increasingly being integrated into public health surveillance systems to enhance disease forecasting, outbreak detection, and resource planning. Machine learning algorithms can analyze large and complex datasets to detect patterns, predict disease spread, and identify high-risk populations.

In emerging economies, AI tools have been applied to predict epidemics such as dengue, cholera, and COVID-19. These tools utilize diverse data sources, including climatic variables, social media activity, mobility data, and historical epidemiological records, to generate predictive models of disease dynamics (Uzozie *et al*., 2023; Abayomi *et al*., 2023). For instance, AI-powered platforms were used in India and Brazil during COVID-19 to forecast hotspots and support targeted lockdowns.

Predictive analytics also plays a role in non-communicable disease surveillance, with models predicting risks for conditions such as hypertension, diabetes, and cardiovascular disease based on health records and behavioral data. By enabling early detection and preventive interventions, AI tools hold significant potential to improve population health outcomes while optimizing the use of limited health system resources.

Cloud-based dashboards and decision support tools provide essential infrastructure for real-time data visualization, analysis, and communication among stakeholders. These platforms aggregate data from various sources—mHealth systems, EHRs, laboratories, and field reports—and present it through interactive dashboards accessible via the internet.

Such tools allow public health officials to monitor epidemiological trends, track outbreak progression, and evaluate program performance in real time. Notable examples include the District Health Information Software 2 (DHIS2), widely adopted across Africa and Asia, which offers customizable dashboards for monitoring diseases such as HIV, tuberculosis, malaria, and COVID-19. DHIS2 enables decentralized data entry at the community level, with aggregated data accessible at national and regional levels to guide policy and resource allocation.

Cloud-based decision support tools also enable automated alerts and recommendations for health workers and policymakers. These tools can flag abnormal disease patterns, suggest preventive measures, or recommend targeted interventions based on predictive modeling outputs (Esan *et al*., 2023; Kufile *et al*., 2023). The scalability and flexibility of cloud platforms make them particularly suitable for resource-constrained settings, where centralized data systems are essential for effective public health management.

Collectively, these key digital technologies and approaches are driving significant improvements in public health surveillance across emerging economies. mHealth and SMS-based systems extend the reach of surveillance networks to remote regions, while EHRs and digital registries offer structured, longitudinal data essential for monitoring disease trends and outcomes. GIS tools provide spatial insights that are critical for targeted interventions, and AI-powered predictive analytics enable proactive disease prevention and resource planning. Cloud-based dashboards and decision support tools facilitate real-time monitoring and coordinated responses. Together, these innovations are transforming how emerging economies collect, analyze, and act upon health data, ultimately strengthening their capacity to detect and respond to public health threats in a timely and efficient manner.

2.3 Challenges and Barriers

Despite the transformative potential of digital technologies in public health surveillance, emerging economies face numerous challenges and barriers that hinder the effective implementation, scalability, and sustainability of these innovations. While mobile health applications, electronic health records (EHRs), geographic information systems (GIS), and artificial intelligence (AI) have demonstrated significant value in enhancing surveillance systems, several structural, technical, and socio-political obstacles persist (Onifade *et al*., 2023 [67]; Akpe *et al*., 2023). Key challenges include digital infrastructure gaps, data privacy and cybersecurity concerns, fragmented governance and policy environments, limited digital literacy and workforce capacity, and pronounced urban-rural disparities in technology access as shown in Fig 2 below.

One of the foremost barriers to digital transformation in emerging economies is the inadequacy of digital infrastructure. Reliable internet connectivity, access to digital hardware, and stable electricity supply remain unevenly distributed across many low- and middle-income countries (LMICs). While mobile phone penetration has increased significantly, many rural and underserved areas still lack the high-speed internet connections necessary for data-intensive digital health applications such as cloud-based dashboards and telemedicine platforms. This digital divide limits the real-time reporting and analysis capabilities of surveillance systems in regions where disease outbreaks are most likely to emerge.

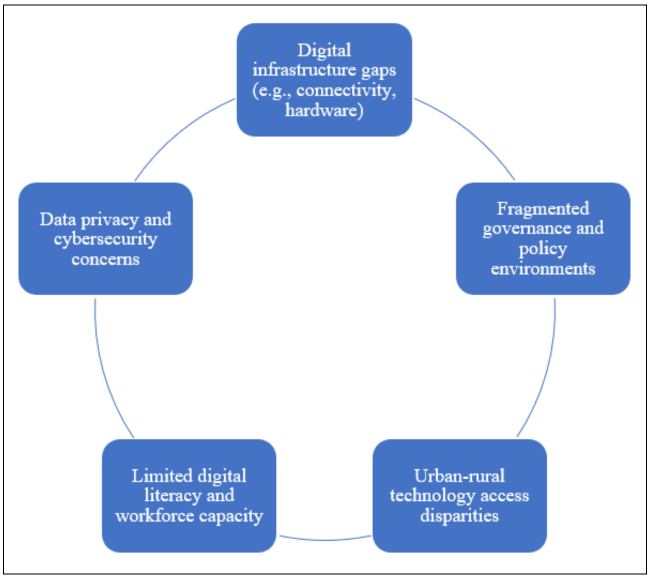

Fig 2: Challenges and Barriers

Furthermore, many health facilities in emerging economies operate with outdated or insufficient hardware, including computers, servers, and mobile devices. The absence of appropriate technical infrastructure not only limits data collection but also impedes the integration and interoperability of different digital health systems. In regions without reliable electricity, maintaining the functionality of digital systems becomes even more challenging, leading to system downtimes and data loss.

The digitization of health data raises significant concerns related to data privacy, security, and patient confidentiality. Emerging economies often lack comprehensive legal and regulatory frameworks to govern the collection, storage, and use of sensitive health information (Akpe *et al*., 2023; Kisina *et al*., 2023 [46]). Weak enforcement of existing laws further exacerbates vulnerabilities. In many cases, health data systems are developed without robust encryption or security protocols, making them susceptible to cyberattacks, data breaches, and unauthorized access.

Health data breaches not only compromise patient privacy but also erode trust in digital health systems, potentially discouraging individuals from participating in surveillance programs. The risk of cyberattacks increases with the proliferation of cloud-based systems, mobile applications, and online reporting tools. In the absence of stringent cybersecurity measures, digital public health infrastructure becomes an easy target for malicious actors, posing both ethical and operational risks.

Additionally, many emerging economies lack the technical expertise and institutional capacity to implement advanced cybersecurity protocols such as encryption, intrusion detection systems, and secure authentication processes. This creates a significant gap between the rapid adoption of digital health tools and the ability to safeguard the integrity and confidentiality of health data.

Another major barrier to effective digital transformation in public health surveillance is the fragmentation of governance and policy frameworks. In many emerging economies, responsibilities for digital health initiatives are distributed across multiple government agencies, resulting in overlapping mandates, conflicting priorities, and inefficient coordination. Ministries of health, communications, information technology, and local governments often operate in silos, complicating the integration of digital health solutions.

Moreover, the absence of clear national digital health strategies and standards impedes the development of interoperable systems. Without standardized data formats, coding protocols, and reporting requirements, different digital platforms cannot easily share information, leading to duplication of efforts and fragmented health surveillance data.

In addition, many countries lack robust policies that support the long-term sustainability of digital surveillance programs. Pilot projects funded by donors or international organizations often face difficulties in scaling up or transitioning to government ownership due to limited political commitment, resource constraints, or unclear operational plans (Chianumba *et al*., 2023; Akpe *et al*., 2023).

Human resource constraints represent a critical bottleneck in the digital transformation of health surveillance systems. Many health workers in emerging economies lack the digital literacy and technical skills required to effectively use digital tools for disease reporting, data analysis, and decision-making. This gap is particularly evident at the primary care and community health levels, where training opportunities and technical support are limited.

The implementation of sophisticated digital technologies such as AI-based predictive analytics, GIS mapping, and EHRs requires a specialized workforce with knowledge of health informatics, data science, and information systems management. However, emerging economies often face severe shortages of qualified professionals in these fields. Inadequate investment in workforce training and capacity building further exacerbates this problem, creating a mismatch between technological potential and operational capacity.

Additionally, high staff turnover, especially among frontline health workers, poses challenges to maintaining continuity in digital health programs. Without ongoing training and supportive supervision, digital tools may be underutilized, misused, or abandoned, leading to suboptimal performance and missed opportunities for improving health outcomes.

The uneven distribution of digital technologies between urban and rural areas presents another significant barrier to equitable public health surveillance. Urban centers tend to benefit from better infrastructure, higher internet penetration, and greater access to digital devices, enabling the effective use of digital surveillance tools. In contrast, rural areas—where many of the most vulnerable populations reside—often struggle with limited connectivity, poor technical support, and inadequate digital literacy.

These disparities exacerbate existing health inequities, as rural populations may be excluded from disease surveillance networks, resulting in incomplete or biased data. Surveillance systems that fail to capture data from rural areas are less effective in detecting and responding to outbreaks, particularly for diseases that emerge in remote regions before spreading to urban centers.

Efforts to extend digital health tools to rural settings are often constrained by high costs of infrastructure development, such as extending broadband networks or providing devices to remote clinics. Moreover, linguistic and cultural barriers can further limit the adoption of digital health technologies in rural communities, particularly where tools are not designed with local contexts in mind (KOLAWOLE *et al*., 2023 [47]; Chianumba *et al*., 2023).

While digital transformation offers transformative potential for strengthening public health surveillance in emerging economies, several critical challenges must be addressed to ensure effective, equitable, and sustainable implementation. Digital infrastructure gaps, data privacy and cybersecurity concerns, fragmented governance, limited workforce capacity, and urban-rural disparities collectively hinder the full realization of digital health benefits. Overcoming these barriers will require targeted investments in infrastructure, legal and regulatory reforms, capacity building, and inclusive technology design. Additionally, greater political commitment and multisector collaboration will be essential to developing integrated digital health systems that can improve surveillance, foster health equity, and enhance public health resilience across diverse settings.

2.4 Lessons Learned and Best Practices

The experience of emerging economies in implementing digital health technologies for public health surveillance offers valuable lessons and best practices that can inform future efforts. Despite numerous challenges, many countries have successfully piloted and scaled digital solutions that improve disease monitoring, outbreak detection, and health systems resilience. Key lessons from these initiatives highlight the critical importance of interoperability and open-source solutions, the role of public-private partnerships and donor support, community engagement strategies, continuous capacity building and training, and the establishment of policy frameworks for data governance and sustainability (Kelvin-Agwu *et al*., 2023 [45]; Chianumba *et al*., 2023).

Interoperability has emerged as a fundamental enabler of effective digital public health surveillance. In many emerging economies, disparate health information systems and databases have historically operated in silos, preventing efficient data sharing and integration. Successful surveillance programs have demonstrated that prioritizing interoperable systems significantly enhances data flow between different healthcare facilities, government agencies, and regions.

Open-source solutions are particularly advantageous for low- and middle-income countries (LMICs) seeking cost-effective and customizable technologies. Platforms such as District Health Information Software 2 (DHIS2) and OpenMRS have been widely adopted in Africa and Asia to facilitate disease surveillance, immunization tracking, and outbreak response. These systems allow local developers and health agencies to adapt the tools to their specific contexts while avoiding expensive proprietary software licensing fees. Furthermore, open-source systems foster collaboration across borders, as developers and implementers can share improvements and extensions, leading to collective innovation in digital surveillance.

Public-private partnerships (PPPs) and donor support have played a vital role in the digital transformation of public health surveillance in emerging economies. Many successful initiatives are the result of collaborations between governments, technology companies, international organizations, and philanthropic foundations. These partnerships provide financial resources, technical expertise, and infrastructure development necessary for large-scale digital health deployments.

For example, partnerships between governments and telecommunications companies have facilitated the rollout of SMS-based disease reporting systems, which rely on mobile network infrastructure. Technology firms also contribute advanced digital tools, such as artificial intelligence (AI) algorithms, cloud platforms, and geographic information systems (GIS), which may otherwise be financially out of reach for LMICs. Additionally, donors such as the Bill & Melinda Gates Foundation, the Global Fund, USAID, and Gavi have supported digital health projects targeting diseases like malaria, HIV, tuberculosis, and COVID-19, enabling rapid expansion of digital surveillance systems.

Sustained donor engagement is essential for the success of these programs, especially in their early stages. However, it is equally important for governments to develop long-term strategies for transitioning from donor-funded projects to domestically financed programs to ensure sustainability (Agboola *et al*., 2023; Ayobami *et al*., 2023 [31]).

Community engagement is another critical success factor in the adoption and effectiveness of digital health tools for surveillance. In many emerging economies, community health workers serve as the primary link between health systems and populations in remote or underserved areas. Their active involvement in digital surveillance programs ensures greater acceptance and utilization of new technologies.

Participatory approaches that involve communities in the design, testing, and implementation of digital tools help tailor solutions to local needs and contexts. For instance, involving community leaders and health workers in developing mobile health (mHealth) apps and SMS-based reporting platforms has resulted in higher uptake and more accurate data collection. In some cases, community-based incentives, such as mobile airtime or recognition programs, have been used to motivate consistent data reporting.

Culturally sensitive engagement is equally important, particularly when addressing concerns about data privacy and surveillance. Transparent communication about how health data will be used, protected, and shared can build trust and increase community willingness to participate in digital surveillance initiatives.

Continuous capacity building and training have proven indispensable in ensuring the effective and sustained use of digital health technologies in public health surveillance. Digital tools require skilled users, and many emerging economies face gaps in digital literacy and technical expertise among healthcare workers and administrators.

Successful programs invest heavily in regular training sessions, workshops, and mentorship programs tailored to different user groups, including frontline health workers, data managers, and decision-makers. Capacity-building initiatives often include both initial onboarding and ongoing refresher courses to keep pace with technological updates and evolving surveillance needs (Agboola *et al*., 2023; Adewale *et al*., 2023).

Blended learning approaches that combine in-person training with e-learning modules have been effective in enhancing accessibility and scalability. Additionally, peer-to-peer learning networks, where experienced users mentor new adopters, help create a sustainable support system within the health workforce. These initiatives not only improve the use of digital tools but also foster a culture of data-driven decision-making at all levels of the health system.

Establishing robust policy frameworks for data governance and sustainability is essential for the long-term success of digital public health surveillance systems. Several emerging economies have recognized that the absence of clear policies on data privacy, security, and interoperability can hinder digital health progress and erode public trust.

Best practices emphasize the importance of national digital health strategies that align with global guidelines, such as the World Health Organization's (WHO) Global Strategy on Digital Health 2020-2025. These strategies should outline clear standards for data protection, cybersecurity, and interoperability while promoting ethical principles such as equity, inclusivity, and transparency.

In countries where digital health policies have been enacted, such as Rwanda and Kenya, surveillance systems have benefitted from clearer legal protections, more efficient data sharing, and stronger institutional accountability. Moreover, frameworks that address financial sustainability, including mechanisms for government financing and integration of digital health into national health budgets, are key to ensuring continuity beyond donor-funded pilot phases (Adewale *et al*., 2023; Awoyemi *et al*., 2023).

The experiences of emerging economies in digital public health surveillance offer valuable lessons and best practices for advancing digital transformation in resource-limited settings. Prioritizing interoperability and open-source solutions facilitates cost-effective, scalable, and adaptable systems that meet diverse surveillance needs. Public-private partnerships and sustained donor support provide critical resources and expertise, while community engagement ensures local relevance and enhances participation. Continuous capacity building and training equip health workers with the necessary skills to use digital tools effectively, and robust policy frameworks for data governance lay the foundation for secure, ethical, and sustainable digital surveillance systems. Together, these best practices offer a roadmap for strengthening health surveillance systems in emerging economies, promoting resilience and health security in the face of future public health challenges.

2.5 Future Directions

As emerging economies continue to advance digital transformation in public health surveillance, several critical future directions have begun to take shape. These focus not only on improving technological capacities but also on addressing legal, ethical, and equity-related considerations to build sustainable and resilient surveillance ecosystems as shown in Fig 3 (Awoyemi *et al*., 2023; Ifenatuora *et al*., 2023). Moving forward, key priorities include scaling artificial intelligence (AI) and machine learning for early warning systems, expanding cross-border digital surveillance networks, strengthening legal and regulatory frameworks, and investing in inclusive and equitable digital health ecosystems.

AI and machine learning (ML) hold immense potential for revolutionizing disease surveillance through predictive analytics and early warning systems. In emerging economies where healthcare resources are often limited, AI can analyze large, complex datasets from multiple sources—ranging from electronic health records and climate data to social media and mobility patterns—to detect early signals of disease outbreaks.

By training ML models on historical data and real-time information, health authorities can forecast emerging threats and allocate resources more effectively. For example, AI-based systems have been used to predict outbreaks of diseases such as dengue fever, malaria, and cholera by analyzing environmental, meteorological, and population movement data. During the COVID-19 pandemic, several emerging economies used AI-powered dashboards to forecast case surges and hospital demands, improving preparedness and resource mobilization.

Future directions involve expanding the use of AI for syndromic surveillance, antimicrobial resistance monitoring, and non-communicable disease risk prediction. However, to maximize the impact of AI, emerging economies must invest in high-quality data collection, data integration from diverse sources, and the development of context-specific algorithms that account for local disease dynamics, socioeconomic factors, and infrastructure constraints.

Collaborative initiatives between governments, research institutions, and private technology firms will be necessary to build local capacities for AI research and application in public health surveillance. Moreover, ethical considerations, such as preventing algorithmic biases and ensuring transparency in predictive models, must be integrated into the design and implementation of AI-driven surveillance systems (Ifenatuora *et al*., 2023; Aniebonam *et al*., 2023 [28]).

Given the transnational nature of many infectious diseases, expanding cross-border digital surveillance networks is essential for early detection and coordinated responses. Emerging economies often share porous borders where diseases can spread rapidly, exacerbated by migration, trade, and ecological shifts.

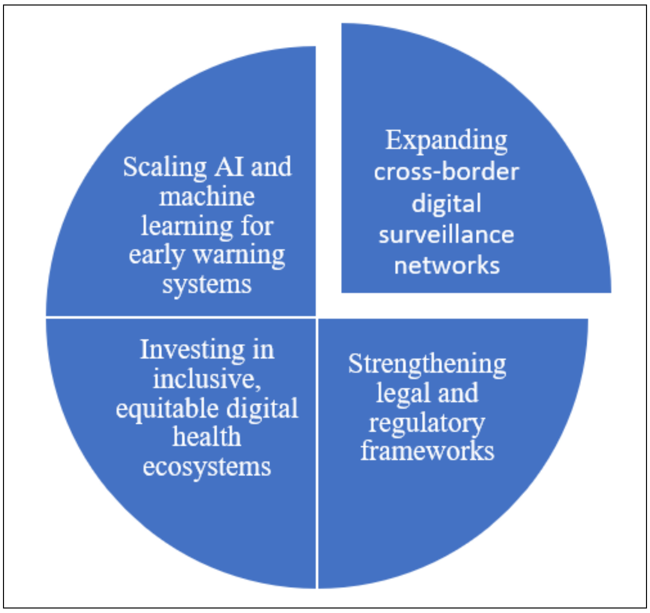

Fig 3: Future Directions

Existing regional efforts, such as the Africa CDC's Regional Collaborating Centers and the ASEAN Disease Surveillance Network, provide initial platforms for information sharing and collaborative surveillance. These networks enable neighboring countries to share standardized data on disease outbreaks, laboratory findings, and vaccination coverage, facilitating faster regional responses.

Future directions include leveraging cloud-based systems and AI tools to automate data exchange and joint risk assessment across countries. Shared digital platforms could also support cross-border contact tracing, vaccine supply chain monitoring, and predictive analytics for regional health threats. For such systems to be effective, participating countries must harmonize data collection protocols, disease definitions, and privacy regulations.

Cross-border digital surveillance will also benefit from the establishment of regional data hubs and analytics centers staffed by multidisciplinary experts, including epidemiologists, data scientists, and policy advisors. Investments in such regional collaborations can improve collective resilience and support joint pandemic preparedness and response strategies (Oke *et al*., 2023 [59]; Ifenatuora *et al*., 2023).

A robust legal and regulatory environment is essential for ensuring the ethical, secure, and sustainable deployment of digital surveillance technologies. Many emerging economies currently face fragmented or outdated legal frameworks that inadequately address issues such as data privacy, cybersecurity, and digital consent.

Future priorities include the development of comprehensive health data governance laws that establish clear rules on data ownership, consent, data sharing, and protection against misuse. These frameworks should align with international best practices such as the World Health Organization's

(WHO) recommendations on digital health ethics and data protection while considering country-specific contexts.

Regulations must also address cybersecurity risks, mandating technical safeguards such as encryption, user authentication, and intrusion detection systems. Furthermore, oversight bodies should be established to monitor compliance, investigate breaches, and enforce penalties where necessary.

In parallel, regulatory innovation is required to accommodate emerging technologies such as AI, blockchain, and wearable health devices. Adaptive regulatory frameworks that allow for sandbox testing and phased implementation of new technologies can support responsible innovation while protecting public health and individual rights (Oyeyemi, 2023 [73]; Ifenatuora *et al*., 2023).

Equity must be a central focus of future digital health strategies in emerging economies. Digital health ecosystems must be designed to ensure that vulnerable and marginalized populations—including those in rural areas, informal settlements, and conflict zones—benefit equally from surveillance systems.

Investments in digital infrastructure, including expanding mobile broadband, increasing access to digital devices, and improving electricity reliability in underserved areas, are critical for reducing the urban-rural digital divide. Furthermore, digital tools must be designed with accessibility in mind, including multilingual interfaces, low-literacy adaptations, and disability-friendly features.

Community-driven approaches that involve local organizations, community health workers, and civil society groups can enhance the cultural relevance and acceptability of digital surveillance tools. Participatory design methods, where communities co-create technologies and provide feedback during pilot phases, help ensure that solutions are responsive to local needs and contexts.

Additionally, efforts should be made to build local digital capacities through training programs in digital literacy, data science, and health informatics, particularly targeting women and underrepresented groups in the health workforce. Equitable digital health ecosystems also require fair allocation of funding and resources, ensuring that technology deployment does not exacerbate existing inequalities (Onibokun *et al*., 2023; Fredson *et al*., 2023) [66, 40].

The future of digital public health surveillance in emerging economies lies in leveraging cutting-edge technologies alongside inclusive, collaborative, and ethical approaches. Scaling AI and machine learning for predictive early warning systems can enhance outbreak detection and disease forecasting, while expanded cross-border surveillance networks will facilitate rapid regional responses to shared health threats. Strengthening legal and regulatory frameworks will ensure the ethical and secure use of digital tools, safeguarding individual rights while enabling innovation. Crucially, investments in inclusive digital health ecosystems will be required to address disparities and promote equitable health outcomes across diverse populations.

By aligning technological innovation with principles of equity, collaboration, and sustainability, emerging economies can build robust digital surveillance systems capable of withstanding future health crises (Umezurike *et al*., 2023 [75]; Kufile *et al*., 2023). These efforts will not only strengthen national health systems but also contribute to global health security, ensuring that all countries—regardless of income level—are better prepared for future pandemics and health emergencies.

3. Conclusion

The digital transformation of public health surveillance in emerging economies presents both significant opportunities and complex challenges. This has highlighted key findings that demonstrate how digital technologies—ranging from mobile health (mHealth) tools and electronic health records (EHRs) to geographic information systems (GIS), artificial intelligence (AI), and cloud-based decision support platforms—are reshaping disease monitoring and outbreak response capabilities. Successful initiatives emphasize the importance of interoperability, open-source solutions, public-private partnerships, community engagement, continuous workforce training, and robust policy frameworks to drive effective and sustainable surveillance systems.

A central conclusion is the strategic value of digital surveillance in strengthening public health infrastructure. By enabling real-time data collection, advanced analytics, and predictive modeling, digital tools allow for faster outbreak detection, better resource allocation, and improved epidemic preparedness. Digital surveillance also facilitates regional collaboration, enhances accountability, and supports equitable health interventions, especially in settings vulnerable to infectious disease threats and health emergencies.

Looking forward, there is an urgent need for sustained investment, strong partnerships, and continued innovation to fully realize the potential of digital surveillance in emerging economies. Governments, donors, and private sector stakeholders must work together to expand digital infrastructure, foster technological capacity, and build resilient, equitable health systems. Investments should prioritize AI-powered early warning systems, cross-border surveillance networks, data governance reforms, and inclusive digital ecosystems that serve all populations. By embracing a collaborative, forward-looking approach, emerging economies can modernize their public health surveillance systems, ensuring long-term health security and enabling more rapid, data-driven responses to future disease threats.

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