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The Role Of Public Health Surveillance In Strengthening Health Security

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Abstract

Background

Public health surveillance involves the systematic collection, analysis, interpretation, and dissemination of health data to inform actions against threats like pandemics and bioterrorism, integrating with frameworks such as the International Health Regulations (IHR) and Global Health Security Agenda (GHSA) to enhance global resilience. Surveillance tracks disease trends, detects outbreaks early, and supports evidence-based policies amid globalization's risks, where travel amplifies threats, as seen in historical gaps during epidemics.

Methods

This narrative review synthesizes peer-reviewed literature, case studies (Ebola, COVID-19, Zika, mpox), and real-world data from diverse global contexts, evaluating surveillance typologies, innovations like digital tools and wastewater monitoring, and frameworks including One Health and IHR core capacities.

Results

Case studies reveal surveillance strengths in early detection (e.g., wastewater providing 6-8 day leads for COVID-19) but gaps like underfunding, data silos, and LMIC workforce shortages prolonging outbreaks (e.g., Ebola's 28,000+ cases); innovations such as AI prediction (>94% accuracy) and genomic networks mitigate these.

Conclusions

Robust, equitable surveillance is essential for health security; recommendations include AI integration, interoperable global platforms, LMIC capacity-building, and climate-adaptive strategies to preempt emerging threats.

Keywords Public health surveillance, Health security, Early detection, Outbreak response, Digital innovations.

Introduction

Public health surveillance entails the ongoing, systematic collection, analysis, interpretation, and dissemination of health-related data essential for planning, implementing, and evaluating public health actions, as defined by authoritative bodies like the World Health Organization and Centers for Disease Control and Prevention. This process not only tracks disease incidence and trends but also monitors determinants of health, detects outbreaks early, evaluates interventions, and informs resource allocation to address population health needs comprehensively, ensuring that decision-makers receive actionable insights promptly to prevent and control diseases and injuries. Health security, at national and global levels, focuses on safeguarding populations from acute public health threats such as pandemics, bioterrorism, and emerging infectious diseases through coordinated prevention, detection, and response mechanisms, with frameworks like the International Health Regulations (IHR) and Global Health Security Agenda (GHSA) emphasizing multisectoral collaboration to minimize cross-border risks and enhance collective resilience. The rationale for strengthening surveillance lies in its capacity to empower evidence-based policies amid globalization, where interconnected travel and trade amplify threat propagation, as evidenced by historical gaps that prolonged outbreaks and strained systems, underscoring the need for robust infrastructure to protect vulnerable populations and sustain economic stability (Soucie, 2012).

Surveillance directly bolsters health security by facilitating prevention through trend monitoring and risk factor identification, early detection via sentinel systems and event-based reporting, and rapid response coordination that limits outbreak spread and saves lives, serving as the foundational loop connecting data providers, analysts, and responders. In the 2014-2016 West African Ebola epidemic, strengths like CDC-supported databases in Guinea and multidisciplinary surges in Sierra Leone enabled cluster containment, yet weaknesses such as insufficient trained staff, community mistrust, and limited technology delayed alerts and fueled over 28,000 cases across three countries, highlighting surveillance as a critical firewall against further dissemination. Similarly, COVID-19 exposed global disparities where robust digital and wastewater surveillance accelerated case identification in some regions, but data delays, testing shortages, and fragmented systems hindered real-time response, with infodemiology and mobility tracking emerging as vital tools despite ethical challenges, reinforcing surveillance's role in minimizing pandemic impacts through integrated, technology-enhanced approaches (Clark et al., 2024).

This review adopts a global scope with regional emphases on high-burden areas like Africa and Asia, where surveillance gaps have historically amplified threats, while drawing lessons from diverse contexts including low- and high-income settings to inform scalable strategies under frameworks like GHSA and IHR. Key objectives include evaluating surveillance's contributions to prevention, detection, and response; identifying strengths and weaknesses via case studies like Ebola and COVID-19; assessing technological integrations such as digital and wastewater methods; and proposing recommendations for capacity-building to achieve equitable health security amid emerging risks. Explicit research questions encompass: How has surveillance evolved to address transnational threats? What barriers impede effective implementation, and how can they be overcome? What metrics best measure its impact on health outcomes?

Following this introduction, the review proceeds to methodological approaches in surveillance systems, empirical evidence from outbreaks, challenges and innovations including digital tools, policy implications for global frameworks, and concludes with recommendations for future enhancements. Each section integrates evidence from peer-reviewed literature and real-world applications to provide a comprehensive roadmap for stakeholders.

Conceptual Foundations

Public health surveillance serves as the foundational mechanism for detecting, monitoring, and responding to health threats, directly bolstering health security by enabling timely interventions. This section explores its conceptual underpinnings, from core definitions and typologies to its integration within broader health security frameworks like the WHO surveillance-response cycle, IHR 2005, and GHSA. These elements collectively underscore surveillance's pivotal role in safeguarding populations against emerging risks (Gilbert & Cliffe, 2016).

Public health surveillance constitutes the ongoing, systematic collection, analysis, interpretation, and dissemination of data on health-related events, ensuring actionable insights reach decision-makers promptly to guide prevention, control, and policy formulation. Core attributes include timeliness, which facilitates rapid response to outbreaks by minimizing delays in data reporting and analysis; sensitivity, enabling detection of even low-level disease signals or epidemics; representativeness, ensuring data accurately reflect the population's health status across demographics and geographies; and simplicity, promoting ease of implementation to sustain long-term utility without excessive resource demands. These attributes, as outlined in foundational guidelines, allow systems to balance comprehensiveness with practicality, adapting to diverse contexts from local clinics to global networks while maintaining data quality and utility for evaluating interventions like vaccination campaigns. Various typologies enhance versatility: passive surveillance relies on voluntary provider reports for cost-effective trend monitoring of common conditions; active surveillance proactively contacts sources for complete data on rare or high-impact events; sentinel surveillance samples predefined sites for early warnings; syndromic surveillance tracks symptom clusters pre-diagnosis for rapid outbreak detection; event-based surveillance captures unstructured signals like media reports; and laboratory-based surveillance confirms pathogens through testing networks (Gilbert & Cliffe, 2016).

Health security emerged historically from early quarantine measures in the 14th century against plagues, evolving through international sanitary conferences (1851-1892) that standardized reporting, to the establishment of organizations like the Office International d'Hygiène Publique (1907) and WHO (1948), which formalized global coordination amid threats like influenza pandemics. This progression shifted from unilateral state actions to multilateral frameworks, culminating in responses to HIV/AIDS and SARS that securitized infectious diseases. Traditional security emphasizes state-centric military defense against external aggression, prioritizing sovereignty and deterrence, whereas human health security reframes threats around individual and population well-being, encompassing pandemics, bioterrorism, and non-communicable risks through cooperative, multisectoral strategies. This distinction highlights health security's broader scope, integrating public health with diplomacy and economics to address transnational vulnerabilities (Katz et al., 2012).

The WHO surveillance-response cycle integrates data collection from diverse sources, rigorous analysis for pattern detection, interpretation against baselines, prompt action like contact tracing, and feedback loops to refine systems, forming a continuous loop essential for outbreak containment. IHR 2005 mandates core capacities including indicator-based and event-based surveillance at local, subnational, and national levels, requiring states to detect, assess, report, and respond to public health emergencies of international concern (PHEICs) within defined timelines. GHSA complements this through action packages like Detect-1 (laboratory systems), Detect-2/3 (real-time surveillance), and Detect-4 (reporting), fostering multisectoral commitments to prevent, detect, and respond to infectious threats via workforce training and infrastructure (Katz et al., 2012).

Historical Evolution of Public Health Surveillance

The earliest systematic recording of mortality began in 1532 with London's Bills of Mortality, weekly publications compiled by parish clerks that tallied burials and causes of death, primarily to monitor plague outbreaks amid recurring epidemics like the Great Plague of London in 1665. John Graunt's 1662 analysis of these bills introduced statistical methods, revealing patterns such as higher male mortality and urban-rural disparities, marking the first comprehensive data interpretation for public health insights without direct intervention responsibility. William Farr advanced this in 1838 as the first Compiler of Abstracts at England's General Register Office, establishing universal death registration and medical certification in 1837 to provide accurate, population-based data on disease impacts, linking vital statistics to policy like sanitation reforms. These foundational efforts shifted surveillance from episodic epidemic tallies to ongoing, population-wide tracking, influencing global vital registration systems and enabling early detection of health trends beyond infectious diseases (Katz et al., 2012).

The 20th century formalized surveillance through national units and standardized definitions, with the U.S. Centers for Disease Control and Prevention (CDC), founded in 1946 as the Communicable Disease Center, defining it in 1963 via Alexander Langmuir as "the continued watchfulness over the distribution and trends of incidence through the systematic collection, consolidation, and evaluation of morbidity and mortality reports." Notifiable disease systems emerged, mandating physician reports of conditions like cholera and smallpox; by 1874, Massachusetts required weekly prevalence reports, expanding nationally post-1916 polio and 1918 influenza pandemics, with all U.S. states participating by 1925. Epidemic intelligence developed via tools like the CDC's Morbidity and Mortality Weekly Report (MMWR) from 1961 and WHO's 1965 Epidemiological Surveillance Unit, enabling rapid outbreak detection and response coordination. These advancements integrated data analysis with public action, broadening from infectious to chronic diseases and behavioral risks via systems like the Behavioral Risk Factor Surveillance System in 1984 (Chow & Leo, 2017).

The 2005 International Health Regulations (IHR) revisions mandated core capacities for surveillance, reporting, and response in all WHO member states, shifting from a cholera-plague-yellow fever focus to any public health emergency of international concern (PHEIC), emphasizing early warning and risk assessment. SARS (2003) exposed gaps in global detection, prompting IHR updates; H1N1 (2009) tested them, revealing uneven national capacities and overreactions like travel bans, while Ebola (2014) highlighted failures in notification and core capacities, leading to WHO Review Committees for strengthened implementation. These outbreaks influenced "modern surveillance thinking" by prioritizing real-time data sharing, joint external evaluations, and integration with emergency frameworks, fostering global solidarity against cross-border threats (Woolhouse et al., 2015).

Contemporary surveillance integrates human, animal, and environmental data under One Health, recognizing 75% of emerging diseases as zoonotic, with systems like WHO-FAO-WOAH's Global Early Warning System (GLEWS) merging sectors for early outbreak detection. Post-IHR and outbreaks like Ebola spurred multisectoral platforms combining pathogen surveillance across hosts, vectors, and ecosystems, addressing drivers like antimicrobial resistance and climate change. Frameworks emphasize output-based standards, laboratory integration, and data from wildlife, farms, and environments to prevent spillovers, optimizing health balance amid siloed traditional systems (Danasekaran, 2024).

Architecture and Functions of Surveillance Systems

Public health surveillance systems are built upon a foundation of diverse core components, primarily revolving around multiple data sources that provide comprehensive insights into health events across populations. Key data sources include clinical reports from healthcare providers such as hospitals and general practitioners, which capture diagnosed cases and symptoms; laboratory data offering confirmatory testing results for pathogens, toxins, or biomarkers; vital statistics encompassing birth, death, and mortality records that track overall health trends and disease burden; and environmental and vector data monitoring factors like air quality, water contamination, climate conditions, and insect populations that influence disease transmission. These sources collectively enable the estimation of disease magnitude, distribution portrayal, natural history tracking, hypothesis generation, research stimulation, control measure evaluation, trend monitoring, and planning facilitation, as seen in systems like those managed by the Centers for Disease Control and Prevention (CDC). Data flows in these systems follow a hierarchical structure from local to global levels, beginning with frontline collection at community health facilities or sentinel sites where initial reports are aggregated at the local level through district health offices for preliminary analysis and verification, then escalated to national centers for coordinated response planning and policy formulation, and finally shared with global entities like the World Health Organization (WHO) via networks such as the International Health Regulations (IHR) focal points to enable cross-border threat detection and international collaboration. This multi-tiered flow ensures real-time information exchange, as exemplified by the global network linking national IHR focal points for rapid dissemination during events like pandemics, while maintaining data security and standardization through protocols that support interoperability across electronic health records, registries, surveys, and administrative databases (Diseases, 2011).

Dissemination occurs through situation reports, epidemiological bulletins, real-time dashboards, and risk communication channels tailored to audiences, including weekly influenza summaries or annual notifiable disease overviews featuring tables, graphs, and narratives for policymakers, clinicians, and the public. Automation enhances efficiency, with formats prioritizing clarity during crises like daily pandemic updates. Feedback loops close the surveillance cycle by channeling interpreted data back to healthcare providers via targeted alerts on local trends, to policymakers through evidence briefs informing resource allocation, and to communities via public campaigns on risks like vaccination uptake, fostering iterative improvements such as enhanced case investigations or intervention adjustments based on performance metrics (Ahuja et al., 2022).

Surveillance as a Pillar of Health Security

Public health surveillance stands as a foundational pillar in strengthening health security by systematically collecting, analyzing, and interpreting data on health events to guide timely decision-making and preventive actions across global populations. This comprehensive framework not only identifies emerging threats but also informs resource allocation, policy development, and international collaboration, ensuring robust defenses against pandemics, antimicrobial resistance (AMR), and other public health crises. By integrating diverse data sources from clinical reports, laboratory results, environmental monitoring, and community feedback, surveillance systems enable proactive measures that mitigate risks before they escalate into widespread emergencies (Nahrgang et al., 2018).

Public health surveillance plays a critical role in prevention by enabling the early detection of risk factors and determinants such as antimicrobial resistance (AMR), vaccination gaps, and environmental hazards, allowing authorities to implement targeted interventions that avert potential outbreaks and reduce disease burden. For instance, ongoing monitoring of AMR trends through integrated surveillance networks tracks the emergence of resistant pathogens in clinical, veterinary, and environmental settings, facilitating stewardship programs that optimize antibiotic use and curb the spread of superbugs, which pose a rising global threat exacerbated by overuse in human medicine, agriculture, and poor sanitation. Similarly, surveillance identifies vaccination gaps by analyzing immunization coverage data alongside disease incidence, prompting catch-up campaigns in under-vaccinated communities, while environmental surveillance detects hazards like contaminated water sources or air pollutants that contribute to respiratory illnesses and vector-borne diseases, informing regulatory actions to safeguard public health. Surveillance data further supports preparedness planning by modeling scenarios for resource needs, such as stockpiling vaccines or personal protective equipment based on forecasted risks from climate change-induced environmental shifts or migration patterns that could amplify pathogen transmission. These functions underscore surveillance's preventive power, transforming raw data into actionable intelligence that builds resilient health systems capable of anticipating and neutralizing threats before they manifest clinically (Moghnieh et al., 2025).

Syndromic and event-based surveillance systems serve as vital early warning tools by capturing non-specific indicators of illness clusters, such as increased emergency department visits for fever or respiratory symptoms, ahead of laboratory confirmation, thereby providing public health officials with precious lead time to mobilize resources and contain potential outbreaks. These systems leverage real-time data from sources like hospital records, pharmacy sales of over-the-counter medications, and ambulance calls, employing anomaly detection algorithms that apply statistical models and machine learning to flag deviations from baseline patterns, such as unusual spikes during off-seasons for influenza. Media scanning and digital platforms complement these efforts by aggregating signals from social media, news reports, and crowd-sourced apps, using natural language processing to identify rumors of unexplained illnesses or environmental events like chemical spills that could herald health threats. In practice, integrated platforms have successfully detected events like heat-related illnesses or novel viral surges, as seen in implementations during the COVID-19 pandemic where syndromic alerts triggered rapid investigations. This multi-layered approach enhances situational awareness, reduces false alarms through refined thresholds, and supports a multi-hazard response framework adaptable to both infectious and non-infectious threats, ultimately shortening detection-to-response timelines and saving lives (Wu & Pan, 2025).

Surveillance data is indispensable in outbreak investigation and contact tracing, providing epidemiological insights that map transmission chains, identify high-risk clusters, and guide the deployment of control measures like quarantines or targeted testing to interrupt spread efficiently. During responses, real-time dashboards integrate case reports, genomic sequencing, and mobility data to hypothesize sources—whether zoonotic spillovers or nosocomial transmissions—enabling hypothesis-testing through case-control studies and forward-tracing of exposed individuals, as demonstrated in monkeypox contact investigations where no secondary cases emerged post-intervention. Furthermore, surveillance monitors the impact of interventions by tracking metrics such as reproduction numbers (Rt), hospitalization rates, and seroprevalence post-vaccination campaigns, allowing adaptive adjustments like scaling up treatments if resistance patterns shift. Post-event evaluation uses these longitudinal datasets to assess intervention efficacy, quantify averted cases, and refine protocols for future incidents, ensuring accountability and continuous improvement in response capabilities. This dynamic role positions surveillance as the nervous system of public health responses, coordinating multi-sectoral efforts from local clinics to international agencies (Thomas Craig et al., 2021).

Surveillance contributes profoundly to recovery and resilience by generating metrics that evaluate system performance during and after events, informing after-action reviews (AARs) that dissect coordination gaps, logistical failures, and successes to institutionalize lessons learned. Through structured AARs, facilitated discussions among responders analyze phases from detection to demobilization, identifying best practices like rapid data-sharing protocols while addressing weaknesses such as communication breakdowns, as observed in plague outbreaks where surveillance highlighted needs for better vector control integration. Resilience metrics derived from surveillance—such as recovery time to baseline service levels, health system absorption capacity, and post-event vulnerability indices—guide investments in surge capacity, digital infrastructure, and community engagement, fostering "building back better" strategies aligned with One Health principles. Ongoing monitoring during recovery phases tracks lingering effects like secondary infections or mental health surges, ensuring sustained vigilance that prevents resurgence and bolsters long-term adaptability to evolving threats like climate-amplified AMR dissemination. Thus, surveillance transitions from reactive tool to strategic asset for enduring health security (Stoto et al., 2019).

Case Studies

The 2014-2016 Ebola outbreak in West Africa exposed profound pre-outbreak surveillance weaknesses, including inadequate reporting systems, limited laboratory capacity, and fragmented early warning mechanisms, which led to delayed detection and substantial under-reporting of cases across Guinea, Liberia, and Sierra Leone. In Liberia's Lofa County, the epicenter, the absence of established surveillance and early warning systems meant unusual events like the index case from Guinea went undetected promptly, compounded by misdiagnosis as malaria or typhoid, poor understanding of case definitions, and cross-border movements that fueled chains of transmission, resulting in over 619 cases and a 53.3% fatality rate by September 2014. Reforms post-outbreak emphasized strengthening Integrated Disease Surveillance and Response (IDSR) systems, with investments in real-time reporting, laboratory infrastructure, mobile health technologies, GIS mapping, workforce training, and community engagement to enable faster outbreak detection and response coordination, as seen in Sierra Leone's restoration of high-performance IDSR indicators by 2017 and ongoing efforts to integrate big data analytics for persistent gaps in West Africa (Woolhouse et al., 2015).

Vector surveillance emerged as essential during the 2015-2016 Zika epidemic, integrating mosquito monitoring with congenital anomaly registries to track microcephaly clusters, particularly in Brazil where neonatal screening identified infections despite most cases being mild. Challenges in detecting asymptomatic infections, estimated at 82% of cases, arose from short viremia windows, cross-reactivity with dengue in diagnostics, and reliance on symptomatic reporting, leading to underestimation of prevalence and mother-to-child transmission risks up to 30%, necessitating expanded prenatal serology (IgM/IgG) and RT-qPCR in endemic areas (Haby et al., 2018).

The COVID-19 pandemic showcased advanced surveillance through genomic sequencing for variant tracking, digital tools for contact tracing, and wastewater monitoring that provided 6-8 day lead times on clinical trends by detecting SARS-CoV-2 RNA in sewage, even in asymptomatic populations and low-resource settings. Gaps revealed included inequities in data access favoring high-income countries, delays in global sharing hindering equity analysis, inconsistent reporting timelines, and underutilization in low/middle-income regions, underscoring needs for open dashboards, expanded low-resource sampling, and standardized protocols to enhance timeliness and equity (Wannigama et al., 2023).

Rapid genomic and event-based surveillance proved vital for the 2024 mpox outbreak in East Africa, deploying mobile labs across Burundi, Rwanda, Uganda, Tanzania, Kenya, and South Sudan for clade Ib detection, with sequencing networks monitoring variants and transmission dynamics via GeneXpert platforms achieving 98.8% sensitivity. These efforts highlight implications for future readiness, including decentralized diagnostics, real-time molecular epidemiology, and regional coordination to shorten confirmation times, track vaccine escape mutants, and integrate into IDSR for proactive containment of emerging threats (Gehre et al., 2024).

Technological and Methodological Innovations

Digital disease detection platforms and social media mining have transformed public health surveillance into a proactive, near-real-time system capable of identifying outbreaks before they overwhelm healthcare infrastructures, leveraging vast unstructured data from online sources such as Twitter, news feeds, and search queries to detect signals of influenza-like illnesses, vector-borne diseases, and novel pathogens with lead times of days to weeks ahead of official reports. Electronic health records (EHRs) provide structured, high-fidelity data streams that, when aggregated across hospitals and clinics, enable syndromic surveillance for early anomaly detection, while mobile apps and participatory surveillance tools empower citizens to self-report symptoms through user-friendly interfaces like Influenzanet or Flu Near You, fostering crowdsourced data that complements formal systems and improves spatiotemporal resolution in underserved areas, though ethical challenges such as electronic consent, data privacy, and the digital divide must be addressed to ensure equitable participation and minimize biases in representation. Big data analytics further amplify these capabilities by processing petabytes of information via natural language processing and machine learning algorithms to filter noise, geocode events, and visualize hotspots on interactive dashboards, as exemplified by systems like HealthMap and ProMED-mail, which have successfully flagged events like SARS and Ebola earlier than traditional networks, thereby strengthening global health security through enhanced epidemic intelligence and reduced response times (O'Shea, 2017).

Pathogen sequencing networks, such as GISAID-type platforms, serve as global repositories for real-time sharing of viral genomes, enabling variant tracking through phylogenetic analyses that identify mutations like those in SARS-CoV-2 from Alpha to Omicron, with automated pipelines facilitating weekly updates of co-mutation networks and community-based dictionaries to detect emerging lineages days before clinical dominance, thus informing vaccine updates and travel restrictions to bolster health security. Integration of genomic data with epidemiological information creates multilayered surveillance frameworks where whole-genome sequencing (WGS) clusters are overlaid with case metadata, contact tracing, and spatiotemporal patterns, as demonstrated in multidrug-resistant organism outbreaks involving Pseudomonas aeruginosa and Klebsiella pneumoniae, where genomic-epidemiologic congruence refined outbreak definitions, identified cryptic transmissions, and closed gaps in traditional methods, ultimately enhancing precision public health interventions. These innovations extend to routine surveillance of antimicrobial resistance and zoonoses, with platforms like GISAID supporting over 10 million sequences by processing high-quality submissions filtered by metadata criteria, yielding scalable solutions for regional monitoring as seen in studies from Brazil and Morocco, where they revealed local transmission dynamics and supported policy decisions (Huang et al., 2023).

Machine learning approaches, including random forests, XGBoost, and large language models, excel in outbreak prediction and hotspot detection by analyzing multimodal data from social media, mobility patterns, and historical cases to forecast epidemic trajectories with over 94% accuracy, as evidenced in COVID-19 studies detecting minor outbreaks up to two weeks early through sustained transmission labeling and hyperparameter optimization via grid search. Predictive analytics powered by AI integrates time-series modeling with agent-based simulations to anticipate hotspots, optimizing resource allocation like ventilator distribution during pandemics, while neural networks process unstructured text for multilingual surveillance, outperforming baselines in lead-time provision for influenza and dengue. However, challenges persist with algorithmic bias stemming from imbalanced training data that skews toward overrepresented demographics, reducing generalizability in low-resource settings; interpretability issues in black-box models like deep learning hinder clinical trust, necessitating techniques such as LASSO regression and decision trees; and data quality problems including missing values, noise from misinformation, and inconsistent reporting demand robust preprocessing pipelines with sensitivity analyses (Xiao & Zhang, 2023).

One Health surveillance monitors zoonotic reservoirs, vectors, and environmental samples like wastewater to detect spillovers from wildlife and livestock early, using multiplex PCR on sewage networks to track viruses with pandemic potential such as SARS-CoV-2, Zika, and influenza at sensitivities rivaling clinical testing, with genetic diversity analyses distinguishing human transmission from animal origins via phylogenetic clustering. Wastewater-based epidemiology (WBE) in urban systems captures excreted pathogens from high-risk populations including bushmeat traders and travelers, providing cost-effective (under $300,000/year for 25 sites) early warnings for flaviviruses and filoviruses shed at 10^2-10^6 genome copies/mL for weeks, integrated with GPS-mapped sampling to cover rural-urban interfaces and complement syndromic data. Environmental surveillance extends to vectors via mosquito traps sequenced for arboviruses and livestock wastewater for Nipah or avian flu precursors, fostering interdisciplinary networks under One Health that mitigate antimicrobial resistance and emerging threats through shared genomic platforms, though challenges like variable shedding durations and contamination require optimized concentration methods and longitudinal sequencing (Muller et al., 2025).

Challenges and Gaps

Underfunding, workforce shortages, and infrastructure gaps severely hamper public health surveillance, especially in low- and middle-income countries (LMICs), where limited financial resources lead to inadequate compensation for community health workers (CHWs) and force them to use personal funds for transportation, airtime, and equipment, resulting in demoralized staff, high turnover, and disrupted data collection from hard-to-reach populations. In many LMICs, the absence of dedicated infection preventionists at ratios like 1:250 beds, combined with overloaded healthcare personnel relying on manual data entry, prevents effective surveillance of healthcare-associated infections (HAIs) and antimicrobial resistance (AMR), as seen in African nations where logistical challenges such as poor road networks further delay reporting and epidemic control. These constraints are exacerbated by insufficient laboratory capacity and lack of modern tools like automated blood culture systems or MALDI-TOF for pathogen identification, leading to missed opportunities for early outbreak detection and inappropriate empirical antibiotic use, as evidenced in countries like Sri Lanka and Nepal where traditional paper-based systems persist despite initiatives like Integrated Disease Surveillance and Response (IDSR) (Alhassan & Wills, 2024).

Incomplete, delayed, and siloed data flows plague surveillance systems due to the lack of standardized collection methods and integrated health information systems, causing information loss, inefficient operations, and hidden costs from proprietary electronic health records (EHRs) that resist interoperability across platforms. Fragmentation arises from inconsistent data models, absence of universal patient identifiers, and poor calibration of laboratory results from different instruments, hindering real-time analysis and feedback loops essential for outbreak response, as highlighted in efforts like HL7 and OHDSI that fail without enforceable standards. In LMICs, manual reporting in systems like Sri Lanka's web-complemented paper-based dengue surveillance leads to incomplete and slow data, while the lack of linked EHRs prevents leveraging healthcare-seeking data for prevalence tracking, ultimately compromising the reliability needed for interventions (Jayatilleke, 2020).

Political interference, underreporting, and lack of transparency distort surveillance data, as seen in cases where weak legislative oversight allows bureaucratic underreporting of COVID-19 fatalities, creating a false perception of "autocratic advantage" and delaying public health responses. Inequities between and within countries manifest in surveillance benefiting high-income areas while marginalized communities suffer from historical mistrust, biased data practices, and inadequate disaggregation by race/ethnicity, leading to undetected disparities during pandemics like COVID-19. Social challenges, including community engagement barriers for CHWs and tolerance for proprietary systems that silo data, perpetuate racialized harms and undermine equity goals, necessitating ethical guidelines and regulation of surveillance technologies (Ford, 2023).

Weak laboratory networks, limited genomic capacities, and poor IT infrastructure restrict pathogen identification to species level and real-time genomic surveillance, with LMIC labs lacking automated systems, high-performance computing, and validated LIMS like WHONET for AMR analysis, resulting in delayed reporting and missed resistance patterns. Inadequate integration across human-animal-environment sectors hampers One Health approaches, as incompatible databases, privacy concerns, and absence of APIs or AI for data harmonization prevent cross-domain analytics essential for zoonotic threat detection. Operational gaps, such as non-Unix computing environments and insufficient sequencers in public health labs during COVID-19, underscore the need for cloud-based solutions and personnel training to scale surveillance (Nadon et al., 2022).

Future Directions

The potential of AI in public health surveillance lies in its ability to process vast datasets from diverse sources, including genomic sequencing, social media signals, and real-time syndromic reporting, to forecast disease trajectories with unprecedented accuracy. Wearable bioelectronics, enhanced by AI algorithms, enable continuous monitoring of physiological parameters such as heart rate variability, glucose levels, and inflammatory biomarkers, allowing for early detection of anomalies indicative of emerging infections even in asymptomatic individuals. Integrated digital health infrastructures, leveraging 5G connectivity and Internet of Things (IoT) ecosystems, facilitate seamless data aggregation from wearables, electronic health records, and environmental sensors, creating a unified platform for real-time risk assessment and intervention planning. For instance, AI-driven wearables have demonstrated efficacy in predicting cardiovascular events and infectious disease outbreaks by analyzing resting heart rate anomalies akin to early warning signals in meteorological radar data, providing public health officials with lead time to deploy resources like testing units and targeted alerts. Opportunities abound in increasing automation, where machine learning models optimize resource allocation during surges, automate contact tracing via smartphone proximity data, and personalize public health messaging to boost compliance with interventions. However, risks associated with heightened automation include algorithmic biases that could exacerbate health inequities, particularly in underrepresented populations where training data is sparse, leading to skewed predictions that overlook vulnerable communities. Privacy concerns arise from continuous data collection, necessitating robust encryption and federated learning approaches to process data locally without central aggregation. Data interoperability challenges persist, as siloed systems hinder cross-border surveillance, while over-reliance on automation might erode human oversight in nuanced epidemiological interpretations. Technical hurdles like battery life in wearables and computational demands for edge AI processing must be addressed through energy-harvesting nanomaterials and optimized neural networks. Regulatory frameworks lag behind innovation pace, requiring standardized validation protocols to ensure clinical reliability and ethical deployment. Despite these, interdisciplinary collaborations among technologists, epidemiologists, and policymakers can mitigate risks, fostering scalable solutions that enhance surveillance equity and efficacy (Nabi et al., 2025).

Climate change amplifies the transmission of vector-borne diseases like dengue and malaria by expanding mosquito habitats into temperate zones through warmer temperatures and altered precipitation patterns, while urbanization concentrates populations in heat islands that intensify pathogen spillover risks. Population mobility, driven by rural-to-urban migration and climate-induced displacement, accelerates the spread of climate-sensitive diseases, as dense megacities with inadequate sanitation become hotspots for cholera and respiratory pathogens amid flooding events. Implications for surveillance include the need for predictive models integrating climate data, such as sea surface temperatures and humidity indices, with human mobility patterns from mobile phone geolocation to anticipate resurgence zones. Urbanization exacerbates vulnerabilities by straining infrastructure, leading to increased air pollution that weakens respiratory defenses and facilitates airborne disease propagation in poorly ventilated high-rises. The synergy of urban heat islands and greenhouse gas emissions further heightens heat-related mortality, compounding infectious disease burdens during co-occurring epidemics. Climate-informed surveillance strategies must incorporate satellite-derived environmental metrics, like normalized difference vegetation index for vector breeding sites, with ground-based syndromic surveillance to enable early warnings. Urban-sensitive approaches demand hyper-local monitoring via community sentinel networks and drone-deployed sensors for real-time air and water quality assessment in slums. Machine learning can disentangle climate-urban interactions by modeling spatiotemporal expansions of impervious surfaces and their correlation with disease incidence spikes. Investments in green infrastructure, such as urban forests and cool roofs, integrated into surveillance dashboards, can mitigate risks while providing dual benefits for environmental and health monitoring. Challenges include data gaps in low-resource urban peripheries and the computational intensity of coupling climate models with epidemiological forecasts, underscoring the urgency for capacity-building in global south cities (Reiner et al., 2015).

Envisioning a unified global surveillance ecosystem requires interoperable platforms under WHO auspices, linking national systems through standardized data protocols for genomic, clinical, and epidemiological intelligence sharing. Linkages to the Pandemic Treaty, currently under negotiation, could mandate pathogen access and benefit-sharing (PABS) mechanisms, ensuring that genetic sequence data from outbreaks yields equitable distribution of vaccines, diagnostics, and therapeutics. Emphasis on equity demands prioritizing low- and middle-income countries (LMICs) through technology transfers, training hubs, and subsidized digital tools to bridge surveillance disparities exposed by COVID-19. Solidarity principles advocate for enforceable commitments where high-income countries fund regional One Health observatories monitoring zoonotic spillovers at human-animal-environment interfaces. A phased architecture rollout—starting with regional interoperability pilots—fosters trust via transparent governance and data sovereignty safeguards. AI-enhanced global networks could automate anomaly detection across borders, flagging novel variants via wastewater genomics and travel-linked cases. Integrating climate and migration data ensures resilience against non-traditional threats, while blockchain secures data provenance. Equity-focused financing, like a global health security levy, sustains investments in LMIC capacities, preventing siloed responses. Challenges persist in geopolitical tensions over data sharing and varying national priorities, but treaty linkages offer leverage for binding solidarity pacts. This architecture promises a paradigm shift from fragmented reporting to proactive planetary health defense (Wang & Yue, 2025).

Conclusion

Public health surveillance remains indispensable for strengthening health security by enabling early detection, rapid response, and resilient recovery against threats like pandemics and emerging diseases. Despite challenges such as underfunding, data silos, and inequities in low- and middle-income countries, innovations in AI, genomic sequencing, wastewater monitoring, and One Health approaches offer transformative potential to bridge gaps and enhance global equity. Prioritizing interoperable platforms, workforce capacity-building, and equitable investments under frameworks like IHR and GHSA will ensure surveillance evolves into a proactive shield for planetary health amid climate change and urbanization pressures.

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