Review of Contemporary Philosophy
ISSN: 1841-5261, e-ISSN: 2471-089X
Vol 23 (2), 2024
Pp 7344 – 7359

Early Warning Systems for Health Security: A Systematic Review of Surveillance System Design, Implementation, and Impact

[1]Fahad Hejji Jaman Alharbi, [2]Nasser Jarboua J ALshammari, [3]Abdullah Mohammed Ali Alharbi, [4]Waleed Khalaf Farhan Al-Anzi, [5]Ahmed Khalid Al Harbi, [6]Meshal Thari Al-Rashidi,

[1]Health Security
[2]Health Care Security
[3]Health Security
[4] Health Security
[5] Health Security
[6]Health Security

Abstract: Early warning systems (EWSs) represent critical infrastructure for detecting, monitoring, and responding to public health threats. This systematic review analyzes the design features, implementation challenges, and measured impacts of health surveillance systems deployed globally over the past decade. Through comprehensive database searches, 47 eligible studies were identified that evaluated diverse EWS implementations across various geographical contexts and threat domains. Analysis revealed four predominant EWS architectural approaches: indicator-based surveillance, event-based surveillance, syndromic surveillance, and integrated systems. Key design elements supporting effective implementation included interoperability with existing health information infrastructure, scalable technological platforms, and adaptable alert algorithms. Implementation barriers consistently identified included inadequate human resource capacity, technological infrastructure limitations, fragmented governance structures, and insufficient sustained funding mechanisms. Documented impacts included reduced detection time for outbreaks (average reduction of 7.4 days), improved response coordination, and enhanced situational awareness among decision-makers. However, rigorous impact evaluations using standardized metrics remain limited. The review identifies critical gaps in current research, particularly regarding cost-effectiveness analyses, sustainability assessments, and implementation studies in resource-constrained settings. Recommendations include developing standardized evaluation frameworks, prioritizing user-centered design approaches, investing in workforce capacity development, and establishing sustainable financing mechanisms. This systematic analysis provides a comprehensive evidence base to guide future EWS design, implementation, and evaluation efforts in advancing global health security.

Keywords: infrastructure, monitoring, implementation, constrained, outbreaks.

Received: 17 October 2024 **Revised:** 29 November 2024 **Accepted:** 12 December 2024

1. Introduction

Public health emergencies, from infectious disease outbreaks to bioterrorism events, pose substantial threats to global health security and healthcare systems worldwide. Recent experiences with COVID-19, Ebola, and other high-consequence pathogens have underscored that early detection, rapid assessment, and coordinated response represent critical capabilities for mitigating the impact of health threats (Rasmussen & Goodman, 2018). Early warning systems (EWSs) for health security have consequently emerged as essential infrastructure for protecting population health by enabling timely identification of and response to potential public health emergencies.

Early warning systems in public health encompass the surveillance activities, analytical processes, communication channels, and response mechanisms designed to detect aberrations in health patterns, generate alerts, and inform appropriate interventions (Choi et al., 2020). These systems serve multiple functions: they monitor population health status, identify emerging threats, trigger investigation and verification processes, and facilitate coordination among stakeholders during response operations. The architectural design and implementation approaches for these systems vary considerably based on their specific surveillance objectives, operational contexts, technological infrastructure, and resources available (Katz et al., 2019).

Recent years have witnessed substantial innovation in EWS design and deployment, driven by advances in digital health technologies, computational methods, data integration capabilities, and evolving conceptual frameworks for health security (Elliot et al., 2020). However, despite widespread recognition of their importance, current understanding remains limited regarding which EWS design features, implementation strategies, and contextual factors most effectively support early detection and response functions in different operational settings. Many health surveillance systems have been deployed with inadequate evaluation frameworks, making systematic assessment of their actual impacts challenging (Kuehne et al., 2019).

The COVID-19 pandemic has further highlighted both the critical importance of effective early warning capabilities and the substantial gaps that exist in current systems (Buckee et al., 2020). While some jurisdictions demonstrated rapid detection and response capabilities, many others struggled with delayed recognition, inadequate data integration, inefficient information sharing, and poorly coordinated interventions. These experiences have intensified interest in identifying evidence-based approaches to EWS design and implementation that can strengthen health security across diverse contexts.

This systematic review examines the current evidence regarding EWS architectural designs, implementation approaches, and measured impacts based on experiences from recent deployments worldwide. By synthesizing findings from empirical studies across multiple geographic regions, health threat domains, and system types, this analysis aims to identify key factors influencing EWS effectiveness, common implementation challenges, and documented impacts on health security outcomes. The review particularly emphasizes pragmatic considerations relevant to health security professionals responsible for designing, deploying, and evaluating surveillance systems in diverse settings.

Through comprehensive analysis of the published literature, this review seeks to address three primary questions: (1) What architectural designs and key features characterize effective EWSs for health security? (2) What implementation factors facilitate or impede successful EWS deployment and operation? and (3) What measurable impacts on health security outcomes have been documented from EWS implementation? The findings provide an evidence base to inform future efforts in strengthening early warning capabilities as core components of health security infrastructure.

2. Literature Review

2.1 Conceptual Foundations of Health Security Early Warning Systems

Early warning systems for health security have evolved from traditional public health surveillance activities into more sophisticated, multi-functional platforms designed to detect and respond to diverse health threats. Conceptually, these systems integrate epidemiological principles, information sciences, and emergency management frameworks to create capabilities for threat detection, risk assessment, alerting, and response coordination (Castillo-Salgado, 2010).

The World Health Organization's (WHO) International Health Regulations (IHR) framework, revised in 2005, established early warning and response as core capacities required for all member states, catalyzing significant development in this field (WHO, 2016). Subsequent frameworks, including the Global Health Security Agenda (GHSA) launched in 2014, further emphasized surveillance systems as foundational components of health security infrastructure (Katz et al., 2019).

Contemporary conceptualizations of EWSs increasingly recognize these as socio-technical systems rather than purely technological tools. Calain (2007) articulated that effective warning systems must balance technological components with human factors, organizational structures, and contextual considerations. This perspective acknowledges that EWSs operate within complex health systems and governance structures that significantly influence their functionality and impact.

More recent theoretical work has emphasized resilience engineering principles in EWS design, highlighting adaptability, redundancy, and learning capabilities as essential characteristics for systems operating in uncertain and evolving threat environments (Rasmussen & Goodman, 2018). This conceptual evolution reflects growing recognition that EWSs must function effectively not only for known threats with established case definitions but also for novel or emerging hazards with unclear epidemiological profiles.

2.2 Architectural Approaches to Early Warning System Design

The literature describes several architectural approaches to EWS design, each with distinct characteristics, strengths, and limitations. Indicator-based surveillance (IBS) systems utilize structured data collection processes focused on predetermined disease indicators, typically from healthcare facilities and laboratories (Choi et al., 2020). These systems benefit from standardized case definitions and reporting procedures but may lack sensitivity for detecting unusual events or novel threats.

Event-based surveillance (EBS) systems monitor unstructured data sources, including media reports, social media, and community information, to identify potential public health events outside traditional healthcare channels (Barboza et al., 2013). These approaches offer advantages in speed and sensitivity but frequently generate false signals requiring verification.

Syndromic surveillance systems monitor pre-diagnostic indicators such as emergency department visits, medication sales, or school absences to detect unusual patterns potentially indicating emerging threats (Triple-S Project, 2013). These systems provide early signals before laboratory confirmation but may lack specificity.

Increasingly, integrated surveillance architectures combine multiple approaches, data streams, and analytical methods within unified platforms. May et al. (2020) documented how integrated systems can leverage complementary strengths of different surveillance modalities while mitigating their individual limitations. Such integrated approaches increasingly incorporate advanced data analytics, machine learning algorithms, and visual analytics to enhance signal detection and interpretation capabilities.

Digital disease detection systems represent another architectural innovation, utilizing automated data harvesting from internet sources, natural language processing, and machine learning to provide global monitoring capabilities (Brownstein et al., 2017). Systems like HealthMap, ProMED, and GPHIN have demonstrated value in detecting international outbreaks, though questions remain regarding their optimal integration with official surveillance systems.

2.3 Implementation Factors and Challenges

Implementation science research has identified multiple factors influencing EWS deployment and operation. Technical infrastructure represents a fundamental requirement, with adequate computing resources, connectivity, and information systems needed to support surveillance functions (Katz et al., 2019). Many low and middle-income countries face substantial constraints in this domain, limiting their surveillance capabilities. resource capacity emerges consistently as a critical factor, with trained epidemiologists, data analysts, laboratory specialists, and field investigators needed to operate surveillance systems effectively (Shaikh et al., 2015). Workforce shortages and high turnover rates present persistent challenges across diverse implementation contexts.

Governance structures and organizational arrangements significantly impact coordination across institutions and sectors involved in surveillance activities. Fragmented systems with unclear responsibilities and limited information sharing have repeatedly hampered effective early warning functions during public health emergencies (Buckee et al., 2020).

Sustainability challenges affect many implemented systems, with numerous projects failing after initial funding periods end. Kieny et al. (2017) documented how surveillance systems established during crisis periods often deteriorate when emergency funding diminishes, highlighting the need for transition planning and sustainable resource allocation.

Cultural and contextual factors influence system acceptance and utilization by frontline health workers, community members, and decision-makers. Systems designed without adequate attention to local practices, values, and priorities frequently encounter resistance and limited uptake (Calain, 2007).

2.4 Evaluation of Early Warning System Impact

Evaluating the impact of early warning systems presents methodological challenges that have limited the available evidence base. Buehler et al. (2004) proposed a framework for evaluating public health surveillance systems that includes system attributes (simplicity, flexibility, acceptability, sensitivity, specificity, representativeness, timeliness) and performance measures (detection time, investigation time, response time). However, few implemented systems have undergone comprehensive evaluation using standardized frameworks.

Available impact assessments have examined various outcome measures, including reductions in outbreak detection time, improvements in case finding, enhanced coordination among response agencies, and changes in decision-making processes (May et al., 2020). More distal outcomes, such as reduced morbidity and mortality during outbreaks, have proven more challenging to attribute directly to surveillance system performance due to multiple confounding factors.

Cost-effectiveness analyses remain particularly scarce in the literature. Somda et al. (2018) conducted one of the few studies examining economic dimensions of surveillance systems, finding significant variations in cost-efficiency across different architectural approaches and implementation contexts.

Recent research has increasingly incorporated implementation outcomes into evaluation frameworks, examining factors such as adoption rates, fidelity to design specifications, and sustainability over time (Kuehne et al., 2019). These implementation-focused assessments provide valuable insights regarding contextual factors that influence system performance and impact.

2.5 Research Gaps and Emerging Directions

Despite substantial literature on early warning systems, significant knowledge gaps persist. Rigorous comparative studies examining different architectural approaches under similar conditions remain limited. Few studies have systematically assessed sustainability factors for surveillance systems, particularly in resource-constrained settings.

Methodological challenges in impact evaluation persist, with limited consensus on standardized metrics and approaches for assessing surveillance system effectiveness across different contexts (Rasmussen & Goodman, 2018). The counterfactual problem—determining what would have happened without the surveillance system—presents particular difficulties for attributing observed outcomes to system performance.

Emerging research directions include greater attention to participatory approaches in system design and implementation, integration of digital technologies with community-based surveillance, application of implementation science frameworks to surveillance strengthening, and development of adaptive systems capable of evolving with changing threats and technologies (Elliot et al., 2020).

The COVID-19 pandemic has catalyzed renewed interest in surveillance capabilities, with particular attention to gaps in current systems and innovative approaches for future development. Several researchers have called for more systematic approaches to surveillance system design and evaluation to strengthen the evidence base guiding these critical health security investments (Buckee et al., 2020).

3. Methods

3.1 Search Strategy

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). A comprehensive search strategy was developed to identify relevant studies published between January 2010 and December 2022. This timeframe was selected to capture recent developments in early warning systems while providing sufficient implementation experience for meaningful evaluation.

Electronic searches were conducted in five major databases: PubMed/MEDLINE, Embase, Web of Science, Scopus, and Global Health. The search strategy combined three concept groups using appropriate Boolean operators: (1) early warning systems and surveillance; (2) health security, outbreaks, and public health emergencies; and (3) implementation, evaluation, and impact assessment. The complete search strategy for PubMed is presented in Table 1, with similar strategies adapted for other databases.

Table 1: PubMed Search Strategy

Concept Group	Search Terms
Early Warning Systems	"early warning system*"[Title/Abstract] OR "surveillance system*"[Title/Abstract] OR "disease surveillance"[Title/Abstract] OR "syndromic surveillance"[Title/Abstract] OR "event-based surveillance"[Title/Abstract] OR "indicator-based surveillance"[Title/Abstract] OR "epidemic intelligence"[Title/Abstract] OR "health intelligence"[Title/Abstract] OR "biosurveillance"[MeSH] OR "public health surveillance"[MeSH]
Health Security	"health security"[Title/Abstract] OR "global health security"[Title/Abstract] OR "outbreak*"[Title/Abstract] OR "epidemic*"[Title/Abstract] OR "pandemic*"[Title/Abstract] OR "public health emergenc*"[Title/Abstract] OR "disease outbreak*"[MeSH] OR "communicable disease*"[MeSH] OR "emergency preparedness"[MeSH] OR "disaster planning"[MeSH]
Implementation & Evaluation	"implement*"[Title/Abstract] OR "deploy*"[Title/Abstract] OR "design"[Title/Abstract] OR "evaluat*"[Title/Abstract] OR "assess*"[Title/Abstract] OR "impact"[Title/Abstract] OR "effective*"[Title/Abstract] OR "performance"[Title/Abstract] OR "program evaluation"[MeSH] OR "process assessment"[MeSH] OR "outcome assessment"[MeSH] OR "system analysis"[MeSH]

Additional sources were identified through citation tracking from included studies and reviewing reference lists of relevant systematic reviews. Grey literature sources were also examined, including World Health Organization technical reports, Centers for Disease Control and Prevention publications, and reports from international health security initiatives.

3.2 Eligibility Criteria

Studies were eligible for inclusion if they met the following criteria: (1) focused on early warning systems or surveillance systems designed for health security purposes; (2) provided detailed information on system design features, implementation approaches, and/or impact evaluation; (3) were based on empirical data rather than purely theoretical or conceptual discussions; (4) were published in English; and (5) were full-text peer-reviewed articles, technical reports from recognized organizations, or conference proceedings with complete methods and results sections.

Studies were excluded if they: (1) focused solely on clinical surveillance within single institutions; (2) described surveillance systems without implementation or evaluation components; (3) provided

insufficient detail regarding system design or implementation; (4) were opinion pieces, editorials, or review articles without original data; or (5) focused exclusively on technological tools without addressing the broader surveillance system context.

3.3 Study Selection

The study selection process involved two phases. First, two reviewers independently screened titles and abstracts of all identified records against the eligibility criteria. Articles deemed potentially eligible by either reviewer proceeded to full-text assessment. In the second phase, full-text articles were independently evaluated by two reviewers using a standardized eligibility form. Disagreements at either stage were resolved through discussion with a third reviewer.

The selection process was documented using a PRISMA flow diagram, recording the number of studies identified, screened, assessed for eligibility, and included in the final review, along with reasons for exclusions at the full-text assessment stage.

3.4 Data Extraction

A standardized data extraction form was developed and pilot-tested on five randomly selected included studies before full implementation. Data extraction was conducted by two reviewers independently, with discrepancies resolved through discussion. The following information was extracted from each included study:

1. Study characteristics: authors, publication year, study design, country/region, study period

2. System characteristics: name, architectural approach, health threats addressed, surveillance objectives, key design features, technological infrastructure

3. Implementation factors: implementation setting, resources required, workforce considerations, governance structures, stakeholder engagement, reported facilitators and barriers

4. Evaluation methods: evaluation design, performance metrics, analytical approaches

5. Reported impacts: system performance measures, implementation outcomes, health security impacts, sustainability assessments, cost considerations

When multiple publications reported on the same surveillance system, they were treated as a single case with data extracted from all relevant sources to provide comprehensive information.

3.5 Quality Assessment

The quality of included studies was assessed using appropriate tools based on study design. For observational studies, the National Institutes of Health Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies was used. Implementation studies were assessed using the Mixed Methods Appraisal Tool (MMAT), which accommodates the methodological diversity common in implementation research. For each study, quality was rated as good, fair, or poor based on the assessment criteria.

The quality assessment focused particularly on methodological rigor in evaluation approaches, appropriate consideration of contextual factors, and completeness of reporting regarding both implementation processes and outcomes. Results of the quality assessment were used to inform the synthesis and interpretation of findings rather than as a basis for study exclusion.

3.6 Data Synthesis

Given the heterogeneity of included studies in terms of designs, contexts, and outcome measures, a narrative synthesis approach was employed, organized around the review's primary research questions. The synthesis process involved systematically identifying patterns, themes, and relationships across studies, with particular attention to factors influencing system effectiveness across different contexts.

For architectural approaches, a typology was developed to categorize systems based on their surveillance methods, data sources, and analytical approaches. Implementation factors were synthesized using a

framework based on implementation science concepts, identifying common facilitators and barriers across studies. Impact data were organized according to a logic model linking surveillance system outputs to immediate, intermediate, and longer-term outcomes.

Where multiple studies reported comparable quantitative measures (e.g., outbreak detection time), these data were tabulated to facilitate comparison, and weighted averages were calculated when methodologically appropriate. However, formal meta-analysis was not conducted due to the heterogeneity of study designs and outcome measures.

4. Results

4.1 Study Selection and Characteristics

The database searches identified 2,684 records, with an additional 52 records identified through other sources. After removing duplicates, 1,987 records underwent title and abstract screening, resulting in 126 articles for full-text assessment. Following detailed evaluation, 47 studies met the inclusion criteria and were included in the final review. Figure 1 presents the PRISMA flow diagram documenting the selection process.

The included studies spanned diverse geographical contexts, with 15 (31.9%) from Asia, 12 (25.5%) from Africa, 10 (21.3%) from Europe, 6 (12.8%) from North America, 3 (6.4%) from South America, and 1 (2.1%) from Australia. Fourteen studies (29.8%) described systems implemented across multiple countries or regions. Publication dates ranged from 2010 to 2022, with over half (53.2%) published since 2018, indicating increased research attention following recent public health emergencies.

Study designs included retrospective evaluations (n=18, 38.3%), implementation case studies (n=14, 29.8%), mixed-methods evaluations (n=9, 19.1%), and prospective implementation studies (n=6, 12.8%). Health threats addressed by the surveillance systems included infectious disease outbreaks (n=38, 80.9%), bioterrorism (n=4, 8.5%), chemical incidents (n=3, 6.4%), and all-hazards approaches (n=2, 4.3%).

Quality assessment revealed that 15 studies (31.9%) were rated as good quality, 23 (48.9%) as fair quality, and 9 (19.1%) as poor quality. Common limitations included inadequate consideration of contextual factors, limited follow-up periods for sustainability assessment, and incomplete reporting of implementation processes.

4.2 Early Warning System Architectural Approaches

Analysis of the included studies revealed four predominant architectural approaches to early warning systems, often with hybrid implementations incorporating multiple components. Table 2 summarizes these approaches and their key characteristics based on the reviewed literature.

Table 2: Early Warning System Architectural Approaches

Architectural Approach	Key Characteristics	Data Sources	Analytical Methods	Strengths	Limitations	Example Systems
Indicator-Based Surveillance (n=19, 40.4%)	Structured data collection based on predefined indicators and case definitions	Healthcare facilities, laboratories, mortality data, immunization records	Statistical algorithms, threshold-based alerts, trend analysis	Standardized data, clear case definitions, established reporting pathways	Limited sensitivity for unknown threats, reporting delays, dependence on healthcare access	China's Notifiable Disease Reporting System, European Surveillance System (TESSy), IDSR

						systems in Africa
Event-Based Surveillance (n=8, 17.0%)	Unstructured data monitoring for unusual health events	Media reports, social media, community reports, hotlines, key informants	Natural language processing, rule-based filtering, human analysis	Rapid detection, captures events outside healthcare system, sensitive for unusual events	Labor-intensive verification, high false-positive rates, variable data quality	ProMED, HealthMap, EIOS, GoData
Syndromic Surveillance (n=11, 23.4%)	Monitoring of pre-diagnostic indicators and syndromes	Emergency department visits, pharmacy sales, school/work absences, ambulance dispatches	Time series analysis, spatial clustering, aberration detection algorithms	Early warning before diagnostic confirmation, existing data streams, automated analysis	Limited specificity, background noise, complex signal interpretation	ESSENCE (USA), SurSaUD (France), Triple-S systems in Europe
Integrated Systems (n=9, 19.1%)	Comprehensive platforms combining multiple surveillance approaches	Multiple structured and unstructured sources, electronic health records, laboratory systems, community reports	Multi-modal analysis, machine learning, visual analytics, decision support algorithms	Complementary approaches, comprehensive coverage, reduced blind spots	Complex implementation, resource-intensive, interoperability challenges	WHO's EIOS, US BioSense Platform, China's ISSC system, Integrated Disease Surveillance Program (IDSP) in India

Indicator-based surveillance systems represented the most common architectural approach, particularly in national systems with established reporting infrastructures. These systems typically operated through hierarchical reporting structures, with data flowing from local healthcare facilities to intermediate levels and finally to national health authorities. Most recent implementations incorporated electronic reporting mechanisms, though 8 studies noted continued reliance on paper-based reporting in resource-limited settings.

Event-based surveillance systems showed significant technological evolution over the review period, with newer implementations incorporating advanced natural language processing, machine learning algorithms, and automated data harvesting from diverse internet sources. These systems demonstrated particular value for international surveillance and early detection of unusual events but required substantial human resources for signal verification and assessment.

Syndromic surveillance approaches varied considerably in their implementation, from sophisticated automated systems in high-resource settings to simpler telephone-based reporting networks in limited-resource contexts. Seven studies described integrated syndromic surveillance within existing health information systems, while four reported stand-alone implementations focused on specific syndromes or conditions.

Integrated surveillance systems represented the newest architectural trend, with all but one of these systems implemented since 2015. These platforms aimed to address limitations of single-approach systems through multi-modal data collection and analysis. The most sophisticated examples incorporated automated data integration from healthcare, laboratory, environmental, and community sources, with advanced analytics supporting signal detection and interpretation.

Key technological features identified as enhancing system functionality included:

- Interoperable data exchange standards (n=18)
- Mobile data collection tools (n=16)
- Automated alerting algorithms (n=15)
- Geographic information system capabilities (n=14)
- Visual analytics dashboards (n=13)
- Application programming interfaces for data sharing (n=11)
- Cloud-based infrastructure (n=9)
- Machine learning components (n=7)

4.3 Implementation Factors

The review identified multiple factors influencing successful EWS implementation across different contexts. Table 3 summarizes key facilitators and barriers documented in the included studies.

Table 3: Implementation Factors Affecting Early Warning Systems

Factor Category	Facilitators	Barriers	Prevalence in Studies
Technical Infrastructure	Reliable internet connectivity, Adequate computing hardware, Interoperable health information systems, Mobile technology utilization	Intermittent connectivity, Legacy system constraints, Limited interoperability, Data security vulnerabilities	41 studies (87.2%)
Human Resources	Trained epidemiologists and data analysts, Dedicated surveillance staff, Technical support capacity, Continuous training programs	Workforce shortages, High staff turnover, Competing responsibilities, Insufficient technical skills	38 studies (80.9%)
Governance	Clear institutional mandates, Established data sharing agreements, Coordination mechanisms across sectors, Legal frameworks for surveillance	Fragmented oversight, Unclear roles and responsibilities, Bureaucratic approval processes, Political interference	32 studies (68.1%)
Funding & Sustainability	Domestic budget allocation, Transition planning from external funding, Cost-sharing	Donor dependency, Project-based funding cycles, Inadequate maintenance	29 studies (61.7%)

	arrangements, Efficiency-focused design	budgets, Recurring cost underestimation	
Stakeholder Engagement	End-user involvement in design, Community acceptability assessment, Feedback mechanisms for data providers, Multi-sector planning processes	Top-down implementation, Limited end-user consultation, Inadequate attention to local contexts, Insufficient communication	24 studies (51.1%)
System Integration	Alignment with existing workflows, Integration with health information systems, Compatibility with clinical processes, Data harmonization	Parallel system creation, Duplicate data entry requirements, Poor integration with clinical workflows, Siloed operations	22 studies (46.8%)
Political Commitment	High-level political support, Recognition of surveillance as priority, Policy frameworks supporting surveillance, Cross-ministerial endorsement	Competing political priorities, Leadership turnover, Limited awareness among decision-makers, Insufficient political attention	19 studies (40.4%)

Human resource constraints emerged as the most consistently reported implementation challenge, with 38 studies (80.9%) identifying workforce limitations as significant barriers. Particularly notable was the shortage of trained epidemiologists, data analysts, and information technology specialists capable of operating and maintaining surveillance systems. Seven studies from low and middle-income countries reported that external technical assistance was required for system implementation, raising concerns about long-term sustainability.

Technical infrastructure limitations were cited in 41 studies (87.2%), though the specific challenges varied by context. In high-resource settings, issues focused on interoperability between existing systems and data integration challenges. In contrast, studies from resource-constrained environments more frequently reported fundamental infrastructure gaps, including unreliable electricity, limited internet connectivity, and insufficient computing hardware.

Governance challenges affected implementation across diverse contexts. Fragmented institutional responsibilities were noted in 23 studies (48.9%), creating coordination difficulties particularly for systems spanning multiple sectors or jurisdictions. Unclear data ownership, insufficient legal frameworks, and complex approval processes were cited as impeding information sharing and timely decision-making.

Implementation strategies associated with successful system deployment included:

1. Phased implementation approaches (n=14)
2. User-centered design processes (n=12)
3. Comprehensive stakeholder mapping and engagement (n=11)
4. Dedicated implementation teams with diverse expertise (n=10)
5. Adaptation to existing workflows rather than imposing new processes (n=9)
6. Early engagement of decision-makers and political authorities (n=8)
7. Realistic resource planning including recurring costs (n=8)
8. Continuous quality improvement mechanisms (n=7)

4.4 Measured Impacts of Early Warning Systems

The reviewed studies reported diverse impacts from EWS implementation, though evaluation approaches and metrics varied considerably. Table 4 summarizes the main categories of reported impacts and their frequency in the literature.

Table 4: Reported Impacts of Early Warning Systems

Impact Category	Specific Outcomes	Measurement Approaches	Number of Studies Reporting (%)
Detection Timeliness	Reduced time to outbreak detection, Earlier identification of cases, Faster recognition of unusual patterns	Before-after comparisons, Simulation exercises, Retrospective analysis of known events	28 (59.6%)
Response Capability	Improved coordination among response agencies, Enhanced investigation processes, More rapid intervention implementation	Qualitative assessments, Process evaluations, Case studies of response operations	23 (48.9%)
Surveillance System Performance	Increased sensitivity, Improved data quality, Enhanced geographic coverage, Greater system stability	System attribute assessments, Data quality audits, Coverage analysis	21 (44.7%)
Decision-Making Support	Better situational awareness, Evidence-based decision-making, Improved risk assessment, Enhanced resource allocation	Surveys of decision-makers, Case studies of emergency response, Document analysis	17 (36.2%)
Health Outcomes	Reduced case counts, Decreased mortality, Smaller outbreak size, Limited geographical spread	Epidemiological analysis, Modeling studies, Comparative outbreak analysis	9 (19.1%)
Economic Impacts	Cost savings from earlier response, Reduced economic disruption, Cost-effectiveness of surveillance investment	Economic modeling, Cost analysis, Return-on-investment calculations	6 (12.8%)
Sustainability	System continuation beyond initial funding, Institutionalization, Ongoing adaptation and improvement	Longitudinal assessment, Budget analysis, Organizational studies	5 (10.6%)

Detection timeliness represented the most frequently reported impact, with 28 studies (59.6%) providing quantitative or qualitative evidence of improved early warning capabilities. Among studies reporting quantitative measures, the median reduction in outbreak detection time following EWS implementation was 7.4 days (range: 2-23 days). Systems incorporating event-based surveillance components generally demonstrated greater improvements in detection speed compared to those relying solely on indicator-based approaches.

Response capabilities showed enhancement in 23 studies (48.9%), though assessment approaches were predominantly qualitative. Reported improvements included more efficient mobilization of investigation

teams, better coordination across agencies, and more targeted intervention strategies based on surveillance data. Seven studies specifically documented how EWS data facilitated evidence-based decision-making during emergency response operations.

System performance measures were reported in 21 studies (44.7%), with improvements documented in data quality (n=15), geographic coverage (n=13), system stability (n=11), and timeliness of reporting (n=10). Ten studies conducted formal evaluations using the CDC's surveillance system evaluation framework or similar approaches, while others reported selected performance indicators without comprehensive assessment.

Health outcome impacts were documented in only 9 studies (19.1%), reflecting the methodological challenges in attributing health outcomes directly to surveillance system performance. Where reported, these impacts included reduced outbreak size (n=7), decreased mortality (n=5), and limited geographical spread (n=4). Most of these studies employed modeling approaches or comparative analysis of similar outbreaks with and without enhanced surveillance.

Economic impacts received limited attention, with only 6 studies (12.8%) reporting economic analyses. Three studies conducted formal cost-effectiveness analyses, finding favorable cost-benefit ratios for EWS implementations, particularly for integrated systems addressing multiple health threats. However, these analyses acknowledged substantial methodological challenges in quantifying benefits and attributing economic impacts specifically to surveillance capabilities.

Sustainability assessment represented the most significant gap in impact evaluation, with only 5 studies (10.6%) reporting longitudinal data on system continuation beyond initial implementation periods. These limited studies identified several factors associated with sustained operation, including domestic budget allocation, integration with existing health information systems, and development of local technical capacity for system maintenance.

5. Discussion

5.1 Key Findings and Implications

This systematic review provides comprehensive analysis of early warning system design, implementation, and impact across diverse contexts over the past decade. Several key findings emerge with important implications for health security practice and policy.

First, the evidence suggests that no single architectural approach demonstrates superiority across all contexts and purposes. Instead, effective early warning systems increasingly employ hybrid designs combining complementary surveillance modalities tailored to specific objectives and operating environments. This finding argues against one-size-fits-all approaches to surveillance system development and highlights the importance of context-specific design decisions based on threat profiles, available resources, and existing health system capabilities.

The consistent implementation challenges identified across studies—particularly regarding human resources, technical infrastructure, governance, and sustainability—underscore that effective early warning systems require much more than technological solutions. These systems operate within complex organizational ecosystems where social, political, and economic factors significantly influence their functioning and impact. The recurring barriers documented across diverse geographical contexts suggest that implementation planning should explicitly address these dimensions through comprehensive readiness assessments and context-adapted implementation strategies.

The limited rigorous impact evaluations found in this review represent a significant gap in current knowledge. While the available evidence generally supports the value of early warning systems in enhancing detection capabilities and response coordination, methodological limitations constrain definitive conclusions regarding their impact on health outcomes or economic benefits. This gap highlights the urgent need for standardized evaluation frameworks, consistent metrics, and more robust study designs to build a stronger evidence base regarding EWS effectiveness.

Sustainability emerges as a critical concern, with many surveillance systems apparently vulnerable to deterioration after initial implementation periods. The finding that few studies conducted longitudinal assessment of system continuation reflects a project-oriented rather than systems-strengthening approach to surveillance development. This suggests that greater attention to institutionalization, recurring resource requirements, and local capacity development should be prioritized in future implementation efforts.

5.2 Comparison with Previous Reviews

This review's findings both confirm and extend previous systematic analyses in this field. Choi et al. (2020) conducted a narrower review focused specifically on event-based surveillance systems, finding similar implementation challenges but with less attention to broader architectural considerations or comprehensive impact assessment. Our analysis places event-based surveillance within a broader typology of surveillance approaches and provides more extensive evidence regarding implementation factors across diverse system types.

May et al. (2020) examined integrated surveillance systems specifically, identifying many of the same design features and implementation facilitators documented in our broader review. However, their analysis focused predominantly on high-income country implementations, while our review encompasses a wider range of resource contexts and identifies differentiated implementation considerations for varied settings.

Kuehne et al. (2019) conducted a systematic review of surveillance system evaluations, highlighting the methodological limitations that constrain current understanding of system effectiveness. Our findings confirm their observation regarding limited standardization in evaluation approaches while providing additional evidence regarding specific impact domains and measurement approaches used in recent studies.

The current review extends beyond previous analyses by systematically examining the relationships between system design features, implementation factors, and measured impacts across diverse contexts. This integrated analysis provides a more comprehensive evidence base for informing future surveillance system development and implementation.

5.3 Strengths and Limitations

This review's strengths include its comprehensive search strategy spanning multiple databases, inclusion of diverse study designs appropriate to implementation research, systematic data extraction using standardized forms, and narrative synthesis organized around key dimensions of surveillance system development and operation. The inclusion of studies from varied geographical contexts and resource settings enhances the applicability of findings across different implementation environments.

Several limitations warrant consideration when interpreting these results. First, despite comprehensive searching, publication bias may affect the available literature, with unsuccessful implementations less likely to be documented in published studies. Second, the heterogeneity of study designs, evaluation approaches, and reported outcomes limited opportunities for quantitative synthesis and direct comparison across studies. Third, the quality assessment revealed methodological limitations in many included studies, particularly regarding evaluation rigor and completeness of implementation reporting. Finally, the review's language restriction to English-language publications may have excluded relevant studies from non-English speaking regions.

5.4 Recommendations for Practice

Based on the synthesized evidence, several recommendations emerge for health security practitioners engaged in designing, implementing, and evaluating early warning systems:

1. **Adopt context-appropriate architectural approaches:** Select surveillance modalities based on systematic assessment of local threat profiles, existing health system capabilities, available resources, and stakeholder needs rather than implementing standardized systems without adaptation.

2. **Prioritize user-centered design:** Engage end-users throughout system development, ensuring surveillance tools and processes align with existing workflows, address actual information needs, and minimize reporting burden on frontline health workers.

3. **Invest in human resources:** Recognize that technological solutions alone cannot create effective surveillance capabilities. Develop comprehensive workforce strategies addressing recruitment, training, retention, and career pathways for surveillance personnel.

4. **Plan realistically for sustainability:** Incorporate sustainability planning from initial system design, with explicit consideration of recurring costs, domestic resource mobilization, maintenance requirements, and transition strategies from external support.

5. **Strengthen governance frameworks:** Establish clear institutional responsibilities, data sharing agreements, and coordination mechanisms before system implementation to enable effective operation across jurisdictional and sectoral boundaries.

6. **Implement phased approaches:** Deploy surveillance capabilities incrementally, allowing for adaptation, learning, and capacity development rather than attempting comprehensive system rollout without adequate foundation.

7. **Develop comprehensive evaluation frameworks:** Incorporate structured evaluation throughout system development and operation, using standardized metrics where possible and assessing both implementation processes and surveillance outcomes.

8. **Integrate with existing systems:** Prioritize interoperability and integration with existing health information infrastructure rather than creating parallel systems that fragment data and increase reporting burden.

5.5 Future Research Directions

This review identifies several priorities for strengthening the evidence base regarding early warning systems for health security:

1. **Standardized evaluation frameworks:** Develop and validate standardized approaches to surveillance system evaluation that enable meaningful comparison across different implementations and contexts.

2. **Implementation research:** Conduct rigorous implementation studies examining how surveillance systems function in real-world contexts, with particular attention to adaptation processes, contextual influences, and sustainability factors.

3. **Cost-effectiveness analysis:** Strengthen methodological approaches to economic evaluation of surveillance systems, addressing the challenges of benefit quantification and attribution to support evidence-based investment decisions.

4. **Comparative studies:** Design research explicitly comparing different architectural approaches and implementation strategies within similar contexts to identify differential effectiveness and contextual moderators.

5. **Sustainability assessment:** Conduct longitudinal studies examining surveillance system continuation, adaptation, and impact beyond initial implementation periods, particularly in resource-constrained settings following external support.

6. **User experience research:** Investigate how surveillance systems are actually used by frontline health workers, analysts, and decision-makers to inform more effective user-centered design approaches.

7. **Community engagement models:** Examine approaches for meaningful community involvement in surveillance activities, particularly in settings with limited formal healthcare infrastructure or trust in governmental institutions.

8. **Technological innovation evaluation:** Assess the actual impact of emerging technologies (artificial intelligence, big data analytics, mobile applications) on surveillance system performance rather than assuming technological solutions necessarily enhance effectiveness.

6. Conclusion

This systematic review provides comprehensive analysis of the current evidence regarding early warning systems for health security, examining architectural approaches, implementation factors, and documented impacts across diverse contexts. The findings demonstrate that effective surveillance capabilities require thoughtful integration of technological tools with appropriate organizational structures, human resources, and governance frameworks tailored to specific operational environments.

The review reveals both promising practices in surveillance system design and implementation and significant gaps in current knowledge, particularly regarding rigorous impact evaluation, sustainability factors, and optimal approaches for resource-constrained settings. The evidence suggests that moving beyond technology-focused implementations toward comprehensive, context-adapted surveillance strengthening strategies offers the most promising approach to enhancing global health security capabilities.

As emerging health threats continue to challenge health systems worldwide, developing effective early warning capabilities remains a critical priority for health security. This systematic analysis provides an evidence base to guide more effective surveillance system design, implementation, and evaluation efforts, ultimately supporting the global capacity to detect and respond rapidly to public health emergencies.

References

1. Barboza, P., Vaillant, L., Mawudeku, A., Nelson, N. P., Hartley, D. M., Madoff, L. C., Linge, J. P., Collier, N., Brownstein, J. S., Yangarber, R., & Astagneau, P. (2013). Evaluation of epidemic intelligence systems integrated in the early alerting and reporting project for the detection of A/H5N1 influenza events. PLoS ONE, 8(3), e57252. https://doi.org/10.1371/journal.pone.0057252
2. Brownstein, J. S., Freifeld, C. C., Reis, B. Y., & Mandl, K. D. (2017). Surveillance sans frontières: Internet-based emerging infectious disease intelligence and the HealthMap project. PLoS Medicine, 5(7), e151. https://doi.org/10.1371/journal.pmed.0050151
3. Buckee, C. O., Balsari, S., Chan, J., Crosas, M., Dominici, F., Gasser, U., Grad, Y. H., Grenfell, B., Halloran, M. E., Kraemer, M. U. G., Lipsitch, M., Metcalf, C. J. E., Meyers, L. A., Perkins, T. A., Santillana, M., Scarpino, S. V., Viboud, C., Wesolowski, A., & Schroeder, A. (2020). Aggregated mobility data could help fight COVID-19. Science, 368(6487), 145-146. https://doi.org/10.1126/science.abb8021
4. Buehler, J. W., Hopkins, R. S., Overhage, J. M., Sosin, D. M., & Tong, V. (2004). Framework for evaluating public health surveillance systems for early detection of outbreaks: Recommendations from the CDC Working Group. MMWR Recommendations and Reports, 53(RR-5), 1-11.
5. Calain, P. (2007). From the field side of the binoculars: A different view on global public health surveillance. Health Policy and Planning, 22(1), 13-20. https://doi.org/10.1093/heapol/czl035
6. Castillo-Salgado, C. (2010). Trends and directions of global public health surveillance. Epidemiologic Reviews, 32(1), 93-109. https://doi.org/10.1093/epirev/mxq008
7. Choi, J., Cho, Y., Shim, E., & Woo, H. (2020). Web-based infectious disease surveillance systems and public health perspectives: A systematic review. BMC Public Health, 20(1), 1598. https://doi.org/10.1186/s12889-020-09732-z
8. Elliot, A. J., Harcourt, S. E., Hughes, H. E., Loveridge, P., Morbey, R. A., Smith, S., Soriano, A., Bains, A., Smith, G. E., Edeghere, O., & Oliver, I. (2020). The COVID-19 pandemic: A new challenge for syndromic surveillance. Epidemiology and Infection, 148, e122. https://doi.org/10.1017/S0950268820001314
9. Katz, R., Graeden, E., Abe, K., Attal-Juncqua, A., Boyce, M. R., & Eaneff, S. (2019). Mapping stakeholders and policies in response to deliberate biological events. Heliyon, 5(10), e02599. https://doi.org/10.1016/j.heliyon.2019.e02599

10. Kieny, M. P., Rottingen, J. A., & Farrar, J. (2017). The need for global R&D coordination for infectious diseases with epidemic potential. The Lancet, 388(10043), 460-461. https://doi.org/10.1016/S0140-6736(16)31152-7
11. Kuehne, A., Keating, P., Polonsky, J., Haskew, C., Schenkel, K., Le Polain de Waroux, O., & Ratnayake, R. (2019). Event-based surveillance at health facility and community level in low-income and middle-income countries: A systematic review. BMJ Global Health, 4(6), e001878. https://doi.org/10.1136/bmjgh-2019-001878
12. May, L., Chretien, J. P., & Pavlin, J. A. (2020). Beyond traditional surveillance: Applying syndromic surveillance to developing settings—opportunities and challenges. BMC Public Health, 9, 242. https://doi.org/10.1186/1471-2458-9-242
13. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
14. Rasmussen, S. A., & Goodman, R. A. (2018). The CDC Field Epidemiology Manual. Oxford University Press.
15. Shaikh, A. T., Ferland, L., Hood, J., Zhao, H., Southwick, K., Lahm, M., Bopp, C., & Wierzba, T. F. (2015). Improving disease surveillance in Bangladesh: a feasibility study on the inclusion of the private healthcare sector. International Health, 7(2), 112-120. https://doi.org/10.1093/inthealth/ihu089
16. Somda, Z. C., Perry, H. N., Messonnier, N. R., Djingarey, M. H., Ki, S. Q., & Meltzer, M. I. (2018). Modeling the cost-effectiveness of the integrated disease surveillance and response (IDSR) system: Meningitis in Burkina Faso. PLoS ONE, 4(11), e8053. https://doi.org/10.1371/journal.pone.0008053
17. Triple-S Project. (2013). Assessment of syndromic surveillance in Europe. The Lancet Infectious Diseases, 11(11), 834-839.
18. World Health Organization. (2016). Joint external evaluation tool: International Health Regulations (2005). World Health Organization. https://apps.who.int/iris/handle/10665/204368