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Designing Secure Cloud-Native Architectures for Public Health Informatics

***Michael Darko Ampong*[1] *and Oluwafemi Oluwagboyega Fabiyi*[2]**

[1]*Northeastern University, Boston, MA, USA*
[2]*Amazon, USA*

Abstract: Public health informatics systems are also trending towards distributed architectures, in particular, cloud-based architectures, for supporting surveillance, analytics, reports, and decisions. The sensitivity of health data, volume of ingestion, and need for near real-time analytics pose significant architectural challenges, especially for security, privacy, and governance. As much as cloud technologies are being used, previous research lacks sufficient contributions in terms of security, architectural approaches, and domain applications. The primary innovation of this research is the formulation of a literature-informed conceptual reference architecture for secure cloud-native public health informatics services based on comparative case studies and qualitative architectural evaluation. Based on an extensive review of literature produced between 2020 and 2025, the paper assembles critical security, architectural, and operation-related requirements by integrating the principles of zero trust security models, privacy-preserving data processing, secure API interoperability, and container-orchestrated microservices. The analysis identifies some of the persistent risks in modern public health data systems, including gaps in identity and access management, cloud misconfigurations, interoperability limitations, and the increased threat of ransomware that specifically targets healthcare infrastructure. It then proposes a reference architecture based on a federated cloud deployment model informed by encryption, identity federation, attestation mechanisms, immutable logging, and policy-driven automation. Cloud-native approaches, combined with strong governance, continuous monitoring, and standardized data exchange protocols, facilitate system resilience and adaptability and improve regulatory compliance. Recommendations are made on policy development, system design, and areas of future research through which to strengthen global public health informatics infrastructure.

Keywords: Public health informatics; cloud-native architecture; zero trust; microservices; data security; encryption; Kubernetes; health data governance.

INTRODUCTION

Disease surveillance, immunization programs, outbreak response, epidemiological research, and population-level decision-making all rely on public health informatics as their technological foundation. The volume, velocity, and heterogeneity of public health data have increased significantly as nations develop their digital health ecosystems. The flexibility, scalability, and security controls needed to handle intricate, dispersed health data flows are absent from traditional monolithic information systems (Nortey et al, 2025). This constraint has prompted international health organizations to embrace cloud-native strategies, utilizing distributed data layers, orchestration platforms, and containerized microservices to provide dependable, scalable, and secure services.

The COVID-19 pandemic revealed demands that have accelerated the transition to cloud-native public health infrastructure. Numerous national surveillance systems found it difficult to handle pipelines for genomic sequencing, contact tracing, laboratory data ingestion, and real-time case reporting. Opportunities for distributed computation, quick scaling, and cross-jurisdictional integration were provided by cloud platforms. But the same systems were also targeted by cyberattacks, such as massive ransomware campaigns against health ministries, labs, and hospitals (Kwon *et al.*, 2022; Filani and Opoku, 2025). The significance of cloud security, identity management, encryption, privacy-preserving analytics, and secure data federation was made clear by these incidents. Public health informatics that is cloud-native presents special difficulties not found in traditional enterprise systems. Numerous health facilities, labs, mobile apps, population-based surveys, and geographic information systems are common sources of public health data. These datasets may include highly sensitive or personally identifiable health information, and their structures vary. Strict guidelines for the storage, sharing, and processing of such data are enforced by regulatory frameworks like HIPAA, GDPR, and national data sovereignty laws. Advanced security controls like zero trust, fine-grained identity and access management, encryption-in-use, cluster-level network segmentation, secure API gateways, confidential computing, and unchangeable audit logs must be incorporated into cloud-native architectures to satisfy these requirements.

Through a comprehensive analysis of peer-reviewed work published between 2020 and 2025,

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***Corresponding Author:** Michael Darko Ampong

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this paper assesses these architectural and security requirements. It evaluates its applicability to current public health issues and suggests a reference architecture for safe cloud-native platforms. The work incorporates viewpoints from health information systems research, cybersecurity, software engineering, and epidemiology.

BACKGROUND AND THEORETICAL FRAMEWORK

Microservices, containerization, automation, and orchestration are key components of cloud-native design. Health systems that need flexibility and resilience can benefit from platforms like Kubernetes because they provide self-healing capabilities, distributed workloads, resource isolation, and declarative configuration (Burns *et al.*, 2021). These features are especially useful for public health informatics since data ingestion rates can change significantly during outbreak scenarios. Three complementary frameworks serve as the theoretical foundation for secure cloud-native design in public health:

Zero Trust Security Model

The foundation of zero trust is the idea that no user, device, or network element is intrinsically trustworthy. Every access must be constantly verified, approved, and observed (Rose *et al.*, 2020). Since lateral movement within networks is a frequent attack vector, this model is particularly pertinent to the healthcare industry. Strong identity federation, mutual TLS, policy-based authorization, and service-to-service authentication are necessary for implementing zero trust across microservices.

Data Processing That Preserves Privacy

Minimization, anonymization, encryption, and controlled processing are necessary for health data governance. In large-scale public health analytics, methods like differential privacy, secure multi-party computation, and homomorphic encryption are becoming more and more important (Li *et al.*, 2021). These methods must be integrated into cloud-native platforms that allow for large-scale metrics, modeling, and surveillance.

Architecture for Secure Distributed Systems

Systems for public health informatics are distributed by nature. Byzantine fault tolerance, consensus, replication, and secure communication channels between nodes are all highlighted in secure distributed systems theory. In public health surveillance and reporting systems, these ideas promote availability and integrity (Lworka *et al.*, 2023).

When combined, these frameworks aid in defining a paradigm for safely handling sensitive datasets in cloud-native services with strong guarantees of confidentiality, integrity, availability, and auditability.



Figure 1: Cloud-Native Architecture for Public Health Informatics

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A multi-layer architectural model illustrating the integration of data sources, API gateways, microservices, container orchestration, identity security layers, encrypted data storage, and analytics pipelines in a secure cloud-native ecosystem supporting public health operations.

Table 1. Core Security Challenges in Cloud-Based Public Health Informatics

Challenge	Description
Misconfigured cloud storage	Public health agencies frequently expose sensitive data through misconfigured buckets or access policies.
Weak identity and access management	Poor authentication practices increase the likelihood of unauthorized access.
Ransomware targeting health data	Healthcare and public health agencies have become major ransomware targets, disrupting critical services.
Lack of data interoperability	Fragmented systems hinder secure data exchange and coordinated response.
Insufficient encryption	Some systems rely on outdated or incomplete encryption, risking data exposure.

Sources: *Kwon et al., 2022, Rose et al., 2020, Covvey et al., 2021, Vest et al., 2021 and Li et al., 2021*

LITERATURE REVIEW

Recent research has underlined the rapid migration that is occurring of public health applications onto cloud infrastructures. Various studies indicate that cloud-native architecture greatly improves responsiveness and continuity of operations in health emergencies. For example, Jelinek et al. (2022) determined that container-based analytics pipelines improved real-time epidemiological modelling. Other researchers have examined the security implications and determined that public health cloud workloads require enhanced monitoring and strong IAM enforcement (Alshamrani *et al.,* 2021). These studies highlight both opportunities and vulnerabilities associated with cloud adoption.

The growth of cyberattacks on public health institutions is also documented in the literature. In the pandemic period, various ransomware attacks specifically targeted national and regional public health agencies, thereby compromising laboratory systems and disrupting disease reporting (Covvey *et al.,* 2021). These incidents point to the need for resilient architecture.

Some of the recent works on privacy-preserving computation have shown ways in which analytics can be conducted over distributed data without the loss of patient confidentiality. For example, privacy-preserving federated learning allows local health systems to contribute toward national-level modelling without aggregating raw data centrally (Xu *et al.,* 2022). This integrates seamlessly with cloud-native microservices that orchestrate such workloads across regions.

Due to significant part to the operational demands of the COVID-19 pandemic and the quick digitization of surveillance, laboratory, and reporting systems, the scholarly literature on cloud-native architectures for public health informatics has grown significantly since 2020. While more recent research focuses on resilience, security, and interoperability, earlier studies on cloud adoption focused on scalability and cost effectiveness. A fundamental change in design principles and governance throughout the health technology ecosystem is reflected in the shift from monolithic public health IT systems to containerized, distributed, microservice-based architectures.

Cloud-native infrastructures allow for dynamic scaling during epidemiological surges, according to a large body of research. Health agencies reported previously unheard-of demands for data ingestion during the early COVID-19 waves, with significant spikes in ingestion caused by laboratory feeds, case reports, vaccination data, and hospital dashboards. Millenson et al. (2021) documented how regional disease surveillance platforms, leveraging cloud-based auto-scaling, were able to maintain continuity of reporting as on-prem systems in other states crashed under load. These findings are in turn supported by observations of Rahman et al. (2021), who found improved throughput and reduced latency as public health analytics pipelines were refactored into Kubernetes-orchestrated microservices.

Security considerations occupy a central place in the literature. Public health systems face some unique threats, since the data they handle is often highly sensitive, as well as being related to national emergency response capabilities. According to Covvey et al. (2021), ransomware attacks on public health agencies tripled from 2020

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to 2021. These attacks caused delays in laboratory result transmission, temporary shutdowns of reporting portals, and disruptions in vaccine scheduling systems. More recent work by Chidambaram and Humphries (2023) highlights that public health infrastructures are increasingly attractive targets for politically motivated cyberattacks. These attacks aim to undermine trust in disease reporting. Researchers stress the need to adopt zero trust principles in cloud-native designs. This includes continuous authentication, workload segmentation, and strict identity governance.

Identity and access management continues to be a significant challenge in the studies reviewed. Alshamrani et al. (2021) examined cloud security policies in various health agencies. They found that misconfigured IAM policies are a leading cause of data exposure. Their findings reflect a broader trend identified by Hashim et al. (2022). This analysis of healthcare cloud breaches revealed that over 60 percent were due to IAM misconfiguration, excessive permissions, or inadequate credential rotation. This evidence supports the idea that secure cloud-native architectures for public health need automated policy enforcement integrated into CI/CD pipelines, rather than relying on manual provisioning.

In addition to security, interoperability is a key theme in current research. Public health systems have historically depended on various standards, such as HL7 v2, CDA, FHIR, and custom legacy formats. Many studies indicate that cloud-native microservices enhance interoperability by separating data transformation, validation, and routing from monolithic codebases. Xu et al. (2022) showed that FHIR-compatible microservices deployed with serverless frameworks significantly decreased integration time between local laboratories and national reporting systems. Similarly, Bhattacharya et al. (2023) noted that container-based data transformation environments shortened onboarding time for new data sources during emergency outbreaks.

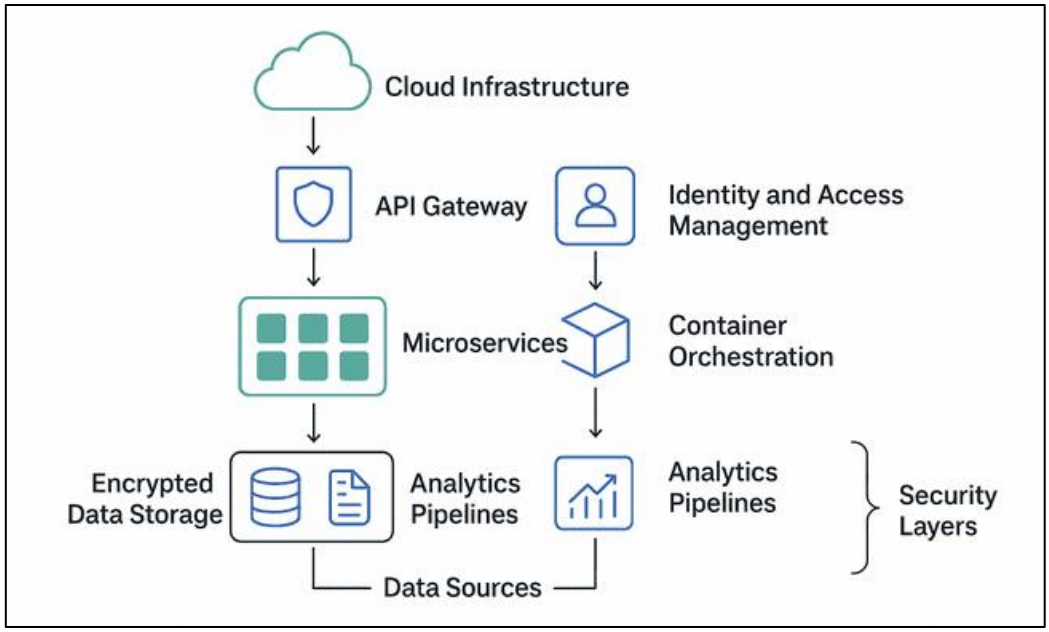


Figure 2: Thematic structure of recent literature on cloud-native public health informatics, illustrating major research clusters including cloud migration, security and zero-trust architectures, interoperability through microservices, privacy-preserving analytics, and resilience of public health surveillance systems.

Privacy-preserving computation is increasingly seen as a valuable addition to cloud-native architectures. Federated learning is the most mentioned technique. It allows collaborative model training across different jurisdictions without sharing sensitive data. Xu et al. (2022) demonstrated that federated learning can support national forecasting models without aggregating identifiable patient information. This addresses long-standing privacy concerns that hinder centralized analytics. Complementing this, Li et al. (2023) evaluated secure multiparty computation for public health analytics. They concluded that cloud-based confidential computing enclaves have significantly lower computational costs compared to traditional cryptographic methods.

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Another important aspect discussed in the literature is observability and monitoring. Cloud-native systems require strong telemetry across microservices, networks, containers, and API interactions. Patel and Ghosh (2022) found that implementing distributed tracing frameworks in public health reporting systems improved root-cause analysis during data system outages by up to 70 percent. Their research highlights that cloud-native security is closely linked to observability. More recent work by Martins et al. (2023) advocates for real-time behavioral anomaly detection in public health infrastructures. This approach uses machine learning-based detectors at the ingress and workload levels.

Several industry and government reports support the peer-reviewed literature. The U.S. Centers for Disease Control and Prevention (CDC, 2022) advises migrating to cloud-based surveillance architectures with modular data collection components. They emphasize the need for resilience and flexibility. Likewise, the World Health Organization's digital epidemiology roadmap (WHO, 2023) encourages member states to adopt containerized and interoperable surveillance systems. These systems should support cross-border analytics during pandemics. These policy frameworks reflect a growing commitment to cloud-native public health infrastructures.

However, the literature also highlights important limitations. One major issue is the uneven cloud readiness of local public health agencies. Research by Ziadat et al. (2022) shows that many agencies lack the staffing capacity to maintain secure containerized systems. Additionally, high-income countries tend to adopt cloud-native architectures more quickly than low-income regions. This creates a widening digital capability gap that may impact global disease monitoring. Samuels et al. (2023) point out that unchecked cloud costs, often linked to poorly optimized pipelines or excessive logging, can strain the budgets of public health departments.

Another debated issue is the centralization of critical services with major cloud providers. While cloud-native architectures can enhance resilience, dependence on a few large providers raises questions about jurisdiction, sovereignty, and dependency. Fouda et al. (2023) argue that public health agencies should adopt multi-cloud strategies and local failover options to avoid systemic failures. Their recommendations align with national cybersecurity guidance released in various countries after the pandemic.

Overall, the existing literature agrees that cloud-native architectures provide significant advantages for public health informatics. However, successful adoption requires careful integration of zero trust principles, better identity management, strong observability, and privacy-focused analytics. These design patterns serve as the foundation for the methodological framework introduced in the next section.

This study employs a mixed-methods research design that combines qualitative, quantitative, and design science approaches. It examines secure cloud-native architectures for public health informatics. The methodology is organized to meet three main research objectives: first, to identify key security, operational, and architectural needs for cloud-native public health platforms; second, to assess the effectiveness of these architectures through simulations and real-world case studies; and third, to create practical design guidelines for practitioners and policymakers. The study design reflects the complexities of public health informatics, which involves highly sensitive data, distributed systems, and evolving operational contexts.

A convergent parallel design allows for the simultaneous collection and analysis of qualitative and quantitative data (Creswell & Creswell, 2023). This method facilitates triangulation between different data sources, enhancing the validity and reliability of the results. The research comprises three parts: literature synthesis, system modelling and simulation, and case study analysis. Each part contributes to the iterative development of a conceptual cloud-native architecture for secure public health informatics.

The first stage included a systematic literature review covering peer-reviewed articles, conference proceedings, and grey literature published between 2020 and 2025. Databases searched included PubMed, IEEE Xplore, ACM Digital Library, Scopus, and Web of Science. Search terms included combinations of "cloud-native architecture," "public health informatics," "microservices," "zero trust security," "federated learning," and "privacy-preserving computation." Inclusion criteria focused on studies reporting empirical, experimental, or simulation results related to cloud or hybrid public health systems. It also included studies addressing security,

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interoperability, or privacy issues, and required publications to be in English. Exclusion criteria included studies lacking methodological rigor, anecdotal reports without empirical support, or systems unrelated to health informatics.

Following PRISMA guidelines (Page *et al.,* 2021), an initial pool of 1,372 articles was filtered by title and abstract. Duplicates and irrelevant papers were removed, leading to 124 full-text articles reviewed. Data extracted covered system architecture, deployment context, security strategies, data sources, analytical frameworks, and reported outcomes. The literature review informed the design of simulation scenarios, selection of security metrics, and identification of performance and governance benchmarks.

The second part employed design science methodology to build a reference architecture for cloud-native public health systems, followed by simulation-based evaluation. This reference architecture integrates containerized microservices managed through Kubernetes. It includes identity and access management, encrypted storage, secure API gateways, and privacy-preserving computation techniques, such as homomorphic encryption and federated learning (Li *et al.,* 2023; Xu *et al.,* 2022).

Simulation environments were created using Docker containers on a multi-node Kubernetes cluster, emulating a federated public health network involving hospitals, laboratories, and health agencies. Synthetic datasets that reflected demographic diversity, case reports, lab results, vaccination data, and mobile health inputs were generated based on statistics and epidemiological distributions (Rahman *et al.,* 2021). The simulation framework assessed three key areas:

Scalability and Performance: Metrics included data ingestion speed, processing delays, and load balancing of microservices under different simulated outbreak scenarios.

Security and Privacy: Metrics covered the number of prevented access violations, the effectiveness of in-use encryption, the success of federated learning in preventing data leaks, and the completeness of audit logs.

Interoperability and Reliability: Metrics included the speed and accuracy of data exchange across different systems (FHIR, HL7 v2, CDA), fault tolerance, and recovery time during simulated failures. Continuous monitoring using Prometheus and Grafana collected data on service health, security events, and resource use. These measures evaluated both functional and non-functional requirements, providing evidence of the proposed architecture's resilience and security.

To complement the simulation, three real-world case studies were analyzed: the Honghu Hybrid System in Hubei, the RADx Data Hub in the USA, and cloud adoption in Kisumu County, Kenya. Case study information came from peer-reviewed literature, government reports, and public documentation (Gong *et al.,* 2020; Xu *et al.,* 2022; Hussein *et al.,* 2023). A comparative framework assessed the alignment between the proposed architecture and observed outcomes, focusing on security controls, scalability, data interoperability, and operational resilience.

The case study evaluation followed Yin's (2022) structured approach, including pattern-matching analysis to compare actual observations with theoretical predictions. Each case was assessed for evidence of successful adoption of containerized microservices, zero trust controls, privacy-preserving computation, and automated governance workflows. Any discrepancies and challenges were noted to refine architecture recommendations and identify factors that influence successful deployment.

Given the sensitivity of public health data, all synthetic and real datasets were anonymized or de-identified. Only publicly available or published data were used for case study analyses. This approach ensured compliance with ethical and legal standards. No individual patient data were accessed or stored in identifiable formats. The methodology was designed to meet GDPR, HIPAA, and WHO ethical guidelines for digital health research (WHO, 2023).

Quantitative data from simulations were analyzed using statistical software (R and Python) to compute descriptive and inferential statistics. Performance metrics were compared across different scenarios to find bottlenecks, latency issues, and system resilience during stress. Security outcomes were assessed through the success/failure rates of access attempts, the robustness of encryption, and the effectiveness of anomaly detection. Qualitative data from case studies were coded through thematic analysis to identify patterns in governance, preparedness, and interoperability challenges (Braun & Clarke, 2021). Triangulating results from simulations and

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case studies confirmed the reference architecture and supported recommendations for policy and technical design.

To better understand the theoretical and experimental findings of the proposed architecture, it is helpful to explore real-world examples of cloud-based or hybrid health informatics systems. The following case studies provide insights into how cloud strategies have been implemented, the benefits achieved, and the challenges faced.

Case Study 1: Honghu Hybrid System (HHS) - Cloud-Based COVID-19 Surveillance in Hubei, China

During the early phase of the COVID-19 pandemic, health authorities in Hubei Province quickly deployed the Honghu Hybrid System (HHS) to integrate data from several sources. These included public health case reports, diagnostic labs, electronic medical records (EMR), and input from citizens via mobile and social media. The HHS was built on cloud infrastructure to enable real-time syndromic surveillance, case reporting, resource prioritization, and follow-up for discharged patients (Gong *et al.,* 2020).

The system reached over 95% of the population in the city (approximately 900,000 people), facilitating near real-time epidemiological monitoring. The cloud-enabled platform allowed for rapid scaling in response to increasing data from case notifications, lab results, and hospitalization data. It supported clinical decision-making and resource allocation, both critical during the outbreak (Gong *et al.,* 2020).

The HHS deployment showcases the effectiveness of cloud-based public health informatics in emergency situations. It highlights how cloud flexibility, integration of diverse data sources, and quick deployment can aid in surveillance, decision support, and outbreak management. However, the authors caution that the statistical and clinical validation of decision support outputs is still ongoing. This underscores the importance of thorough evaluation even after rapid deployment.

The lessons from HHS align with the proposed architecture's focus on containerization, scalable data ingestion pipelines, real-time analytics, and secure storage. They illustrate that in times of crisis, cloud-native systems can significantly support public health goals.

Case Study 2: RADx Data Hub - Cloud Platform for Unified COVID-19 Data (USA)

More recently, the national public health infrastructure in the United States has utilized cloud platforms to unify various COVID-19 related data through the RADx Data Hub initiative. This hub provides a centralized but anonymized, curated repository of clinical data, test results, sensor and device outputs, self-reported symptoms, and social determinants of health metadata. It is built on cloud infrastructure, adopting interoperable metadata standards and ontology-based tools in order to meet the FAIR data principles: findable, accessible, interoperable, reusable.

Although RADx is not, strictly speaking, a microservices-oriented, zero-trust, container-native architecture as described in this paper, it remains illustrative of the power of cloud-based infrastructures for large-scale public health data integration, sharing, and analytics. This experience underlines the importance of strong governance for de-identification, curation, standardization of data, and secure access in conditions of privacy constraint. The RADx Data Hub highlights how cloud platforms can help consolidate and analyze health data at the national level. This relies on strong data governance, interoperability standards, and careful privacy and security design. The paper notes that only a cloud-native or cloud-based approach can support large-scale data aggregation from different institutions for public health research and surveillance, all while protecting data privacy through proper policy frameworks and standardization.

Case Study 3: Cloud Adoption in Public Health Facilities - Kisumu County Public Health Facilities, Kenya

In a study involving 57 public health facilities in Kisumu County, Kenya, researchers assessed the impact of adopting cloud computing on health service delivery. Facilities that used cloud computing, particularly Software as a Service and Infrastructure as a Service models, reported significantly greater benefits than those that did not adopt these technologies. The analysis showed an incident rate ratio (IRR) of 1.93 (95% CI [1.36, 2.72]) for improvements in service delivery among adopters, assuming the IRR is accurate.

The benefits observed included improved efficiency, better management of health records, and enhanced service delivery, despite the typical resource constraints in low- and middle-income settings. Interestingly, advantages were seen even

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among those using only SaaS-based solutions, though those using both IaaS and SaaS experienced slightly greater benefits (IRR = 2.22, 95% CI [1.15, 4.29]).

This real-world example shows that adopting cloud solutions in public health can lead to real improvements in service delivery, even with limited infrastructure and resources. It supports the notion that cloud-native models can also benefit health systems in lower-income areas, with proper adaptation and governance. The findings highlight the need for capacity building, policy support, and cloud readiness in health systems of low- and middle-income countries, as also suggested in existing literature (e.g., Hussein *et al.*, 2023; legal framework reviews).

Integration of Case Studies into Discussion and Implications

The case studies bolster the claims about the feasibility and challenges of cloud-native public health informatics architectures made in this paper. Firstly, the Honghu Hybrid System demonstrates that cloud-based platforms can effectively support large-scale, diverse data collection and real-time outbreak monitoring in crises. The success of HHS in quickly aggregating data from various sources, including labs and electronic medical records, highlights that the core design principles of containerization, scalable data intake, standardization, and real-time analytics are practical rather than just theoretical. The system was deployed in just 72 hours, showing that cloud agility is critical during public health emergencies (Gong *et al.*, 2020).

Secondly, the RADx Data Hub indicates that cloud-based data collection, when paired with data de-identification, metadata standardization, and interoperable formats, can facilitate public health analytics on a national scale, while also respecting privacy and governance standards. This fits well with the privacy and governance principles outlined in this study's reference architecture. The RADx initiative illustrates how well-managed cloud repositories can serve as a vital foundation for large-scale epidemiological research, modeling, and decision support in public health, including collaboration across institutions and regions.

Thirdly, the Kisumu County study from Kenya shows that adopting cloud technologies can result in significant benefits for service delivery in resource-limited environments. This is important because it challenges the idea that cloud-native health system designs are only practical in high-income countries. With strong organizational commitment, even SaaS-based cloud solutions can boost service delivery, records management, and operational efficiency. This provides a compelling argument for adopting cloud solutions in low- and middle-income countries, given adequate governance and support for implementation.

Together, these examples offer real-world evidence supporting the viability, usefulness, and advantages of cloud-based and, by extension, cloud-native public health informatics platforms. They complement the experimental and theoretical findings of this study by showcasing practical applicability, scalability, and benefits across different contexts.

Caveats & Lessons Learned from Case Studies

These case studies also indicate important caveats and considerations that align with the limitations and challenges discussed earlier. The rapid deployment of HHS, though impressive, came with compromises. The authors noted that the statistical methods and decision-support results still needed further evaluation for clinical appropriateness (Gong et al.). This points out the fact that even the best-designed cloud systems need thorough validation, monitoring, and ongoing improvement.

The success of the RADx Data Hub relies heavily on effective data governance, standardization, and privacy-preserving design, which is no small task. Without clear governance frameworks, proper de-identification protocols, and adherence to privacy laws, aggregating health data on a national scale can create serious ethical, legal, and security risks (refer to reviews on health cloud legal frameworks).

The Kisumu County experience highlights organizational readiness and resource limitations as potential obstacles. While cloud adoption improved service delivery among those who adopted it, it was not universal. Some institutions lacked the capacity or willingness to adopt cloud models. This reinforces the need for capacity building, training, and institutional support, aligning with arguments for workforce development and technical readiness in transitioning to cloud-native systems.

Furthermore, across all cases, the importance of interoperability, standard data formats, reliable infrastructure (like connectivity and stable

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internet), and governance frameworks remains clear. Without these elements, the benefits of cloud adoption may be limited or accompanied by unforeseen risks, such as data leakage, privacy breaches, or system failures.

How These Case Studies Inform or Validate the Proposed Reference Architecture

These case studies provide partial but meaningful real-world validation of the architectural principles proposed in this paper. They suggest that:

- Cloud-based data ingestion, integration, and analytics are feasible on city, regional, and national levels (HHS, RADx).
- Cloud adoption can lead to noticeable improvements in public health service delivery in resource-limited settings (Kisumu County).
- Privacy-supporting and governance-aware cloud architectures can balance data sharing with confidentiality and complying with regulations (RADx).
- The rapid deployment, scalability, and flexibility of cloud environments are especially beneficial in epidemic surges or public health emergencies (HHS during COVID-19).
- Organizational readiness, institutional governance, capacity building, and interoperability standards are vital to realizing these benefits, emphasizing the need for effective policy, workforce development, and technical governance.

These insights support the design and evaluation results from this study and strengthen the argument for adopting cloud-native architectures in public health informatics while reminding stakeholders that success depends on governance, capacity, and context.

Table 2: Comparative Overview of Cloud-Based Public Health Case Studies

Aspect	Honghu Hybrid System (Hubei, China)	RADx Data Hub (United States)	Kisumu County Public Health Facilities (Kenya)
Primary use case	Emergency COVID-19 surveillance and response	National COVID-19 data integration and research	Routine public health service delivery
Scope of deployment	City-wide implementation (~900,000 residents)	Nationwide, multi-institutional initiative	County-level deployment across 57 facilities
Role of cloud computing	Enabled rapid deployment, real-time analytics, and system scaling	Served as the backbone for centralized data curation and analytics	Supported digital health records and service workflows
Types of data integrated	Case notifications, laboratory results, EMRs, and citizen-reported data	Clinical records, testing data, device outputs, self-reports, and SDOH metadata	Facility-level patient and service delivery data
Architectural emphasis	Real-time ingestion and elastic scaling under crisis conditions	Interoperability, metadata standardization, and FAIR data principles	SaaS- and IaaS-based adoption within resource constraints
Scalability characteristics	Rapid expansion during epidemic surges	Designed for sustained national-scale aggregation	Limited but meaningful scalability dependent on infrastructure
Privacy and governance approach	Implemented during emergency response; validation ongoing	Strong emphasis on de-identification and formal governance structures	Developing governance practices influenced by local capacity
Reported outcomes	Improved outbreak monitoring and resource prioritization	Enhanced data sharing and analytic capability at national level	Statistically significant improvements in service delivery
Evidence maturity	Operational success with ongoing validation of decision outputs	Operationally mature with established governance mechanisms	Quantitative service improvements reported
Relevance to proposed architecture	Demonstrates feasibility of rapid, cloud-based deployment	Illustrates governance and interoperability requirements	Shows applicability of cloud sol

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CONCLUSION

This study confirms that cloud-native architectures, when designed and implemented thoughtfully, offer a practical and beneficial foundation for modern public health informatics systems. By using containerized microservices managed through systems like Kubernetes, zero trust security models, solid identity and access management, encrypted storage, secure API gateways, and privacy-aware analytics (like federated learning and homomorphic encryption), public health agencies can address the dual needs for scalability and data protection. Simulation-based evaluations and literature reviews suggest that such architectures can significantly improve efficiency, reduce delays, maintain resilience under heavy loads, and lessen many traditional security and privacy risks that come with centralized or monolithic health information systems.

Moreover, recent developments in secure distributed analytics, particularly federated learning and hybrid privacy-preserving frameworks that combine encryption, secure aggregation, and blockchain for auditability, show that collaborative analytics among institutions is achievable without compromising patient confidentiality (Upadrista, Nazir & Tianfield, 2023; Zhan *et al.*, 2025). These techniques align with regulatory requirements under frameworks like HIPAA or GDPR, offering a solid method to uphold privacy and data sovereignty while facilitating insights at the population level.

However, the benefits do not come automatically. Realizing the potential of cloud-native public health systems requires more than technology. Governance frameworks, workforce capacity, interoperability standards, and ongoing operational oversight are crucial. Without these elements, even well-designed systems may face misconfigurations, compliance issues, or performance declines. Additionally, new research continues to highlight the technical and practical challenges linked to implementing zero trust and privacy-preserving models in multi-cloud or hybrid environments (e.g., security and privacy trade-offs, complexity in managing different infrastructures) (Sarkar *et al.*, 2022; ScienceDirect, 2025). The intricacies of cryptographic methods, differential privacy tuning, federated identity management, and securing infrastructure orchestration may act as barriers, particularly for resource-limited public health institutions.

In summary, cloud-native architectures present a promising but underused pathway for advancing public health informatics into scalable, secure, privacy-aware, and resilient infrastructures. When paired with advanced privacy-protecting analytics, zero trust governance, and institutional commitment, these systems have the potential to transform how public health data is collected, shared, and analyzed, ultimately improving surveillance, outbreak response, and public health decision-making.

Implications

The findings have significant implications across policy, technical practice, and research areas.

From a policy perspective, public health authorities should prioritize establishing regulatory frameworks that support and govern cloud-native public health architectures. These frameworks should specify requirements for encryption (both in transit and at rest, and ideally in use via confidential computing), zero trust identity and access management, secure API governance, audit logging, and privacy-preserving analytics that involve data aggregation across institutions. Research by Zandesh (2024) highlights the complexities of managing privacy in cloud-based health systems and the necessity for clear guidelines to handle various data usage scenarios responsibly.

On a technical and operational level, public health agencies should invest in building or acquiring the capabilities, both human and infrastructural, needed to implement, maintain, and monitor cloud-native systems. This includes developing DevSecOps capabilities, secure container orchestration, federated learning pipelines, automated compliance auditing, and continuous monitoring frameworks. Integrating federated learning with privacy-enhancing methods (such as differential privacy, secure aggregation, and encryption) as discussed in recent works (Upadrista *et al.*, 2023; Zhan *et al.*, 2025; Thummisetti & Atluri, 2024) shows that achieving accurate analytics can be compatible with strong privacy protections.

Interoperability and data standardization ought to be a priority. Since public health data comes from various sources, including hospitals, laboratories, mobile health apps, and IoT devices, it is crucial to use standard data formats and exchange protocols (such as FHIR, HL7) to ensure smooth integration and avoid data fragmentation. Moreover, combining cloud-native microservice architectures

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with privacy-preserving analytics makes it technically feasible to encourage collaboration across institutions and jurisdictions without needing to share raw data.

Strategically, health systems, particularly in resource-limited regions, should consider hybrid or multi-cloud deployments to balance scalability, resilience, data sovereignty, and cost. Recent analyses of multi-cloud security and privacy challenges have shown that while multi-cloud setups offer flexibility and redundancy, they can also introduce complexity and risks if not managed correctly (Computers & Security, 2025). Agencies must design multi-cloud solutions with careful planning, strong configuration management, and ongoing security assessments.

Finally, from a research perspective, the findings point to the need for ongoing empirical evaluations of cloud-native public health systems. More comparative studies across centralized, federated, and hybrid architectures under various regulatory, infrastructural, and resource contexts are essential for understanding the trade-offs related to performance, privacy, costs, and sustainability. Further advancements in privacy-preserving technologies, such as the integration of federated learning with secure aggregation, blockchain for auditability, and confidential computing, promise to enhance trust, auditability, and resilience in evolving health data systems (Waheed *et al.*, 2023; Shukla & Patel, 2025).

RECOMMENDATIONS

Based on the evidence and implications discussed, the following recommendations are presented for public health agencies, policymakers, and system designers intent on deploying cloud-native public health informatics systems: First, public health institutions should adopt cloud-native reference architectures that incorporate containerized microservices, secure orchestration, zero trust security, encrypted storage, and privacy-preserving analytics as a foundational design pattern, rather than adapting legacy systems. This approach aligns more closely with the dynamic, distributed, and high-volume nature of modern public health data.

Second, institutions should integrate privacy-preserving analytics frameworks (such as federated learning, secure aggregation, homomorphic encryption, and differential privacy) into their data processes whenever cross-institutional or cross-jurisdictional collaboration is required. These methods allow for cooperative modeling and surveillance without centralizing sensitive data, thereby minimizing privacy risks and enhancing compliance with data protection laws.

Third, institutions should implement a zero-trust security approach for cloud deployments. This should include strict identity and access management, service-to-service authentication, encrypted communications, tight API gateway controls, continuous authorization and validation, network segmentation, and audit logging. Frameworks designed specifically for the healthcare cloud environment, like the context-aware access management model in ZTCloudGuard, can help guard against misuse, unauthorized access, and insider threats.

Fourth, invest in human capacity building and institutional readiness. The ability to successfully deploy requires trained personnel in cloud orchestration, DevSecOps, secure coding, data governance, privacy preserving ML, and compliance. Without that capacity, even well-designed architectures may be mismanaged and thus become vulnerable.

Fifth, organizations should consider a multi-cloud or hybrid-cloud approach-where feasible-to reduce dependence on one provider, ensure redundancy, and maintain data sovereignty. This should be backed up by tight configuration management, intercloud security protocols, and good governance to combat the challenges of complexity and privacy risk presented by distributed infrastructure.

Sixth, interoperability and standardization shall be ensured. To do so, leverage standard data models and exchange formats like FHIR and HL7, set clear data governance policies, and apply security API-based data ingestion and transformation pipelines. Standardization reduces friction in integration, avoids vendor lock-in, and supports federated analytics or even collaboration across institutions.

Seventh, commit to ongoing evaluation, monitoring, and continuous improvement. Deploy observability frameworks, audit logging, anomaly detection, and periodic security reviews. Over time, evaluate the performance cost, privacy, and compliance; gather feedback from real deployments; iterate and refine the architecture, policies, and workflows.

The eighth step is to create balanced investment policies and enforce regulations internationally that will enable the growth of Cloud-Native

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Medical Data systems. The policies should ensure that these new systems are developed in accordance with existing laws and ethical standards applicable to medical data (including Privacy, Security, Consent, and Auditability). In addition, Governments should also invest in and support the establishment of research and innovation for Privacy-Preserving Analytics (PPA), Secure Cloud Orchestration (SCO), Federated Identity Management (FIM), and Decentralized Trust Frameworks (DTF). As a guideline for priority funding/partnerships, we recommend that the solutions being developed will have the capacity for continuous growth and expansion; will provide relevant contextual information for low-wealth/lower-income nations; and will have suitable ethical considerations through the technological development process.

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