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AI-Driven Genomic Surveillance Systems for Public Health Governance: An IoT-Integrated Framework for Smart Cities

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ABSTRACT

Rapid urbanization, climate-driven ecological changes, increased human mobility, and the accelerated evolution of infectious agents underscore the urgent need for next-generation, real-time public health intelligence systems in smart-city environments. Conventional surveillance approaches remain largely reactive, fragmented, and dependent on delayed laboratory reporting, limiting their effectiveness in densely populated urban settings. This paper proposes an AI-driven genomic surveillance system (AIGSS) that integrates IoT-enabled biosensing, distributed genomic sequencing, and predictive artificial intelligence models to support proactive public health monitoring and governance. Using the Issue Identification, Review, Methodology, Analysis, and Discussion (IRMAD) framework as a conceptual system design methodology, we develop a multi-layered surveillance architecture encompassing data acquisition, edge preprocess, AI-based genomic analytics, and governance-oriented decision support. The proposed framework is evaluated through simulation-based analysis and benchmarking against performance trends reported in existing surveillance systems. Results indicate that AI-enabled integration of genomic and IoT data has the potential to substantially reduce outbreak detection latency and improve variant classification performance when compared to traditional approaches. Rather than presenting real-world clinical validation, this study focuses on architectural feasibility, analytical workflow design, and governance implications. Beyond technical performance, the framework emphasizes ethical data governance, transparency, accountability, and equitable access, aligning genomic intelligence with smart-city public health objectives. This work contributes a scalable and policy-aware reference model for the convergence of AI, genomics, and IoT, providing a foundation for future empirical validation and deployment in urban public health surveillance systems.

Keywords: Genomic Surveillance, AI, IoT Biosensors, Public Health Governance, Smart Cities, IRMAD Framework.

INTRODUCTION

Governance of public health systems in the twenty-first century faces unprecedented challenges driven by emerging pandemics, accelerated global interconnectivity, rapid urbanization, and the continuous evolution of infectious agents. The COVID-19 pandemic exposed fundamental limitations in existing public health surveillance models, which remain heavily dependent on manual data entry, delayed laboratory confirmation, and fragmented genomic infrastructure (Gwinn et al., 2019). In densely populated urban environments, these limitations hinder timely detection and coordinated response to rapidly evolving health threats.

Genomic sequencing has become an essential component of modern epidemiology, enabling the identification of pathogen variants, characterization of mutation patterns, and analysis of evolutionary trajectories (Mardis, 2017). However, current genomic surveillance workflows are largely centralized, slow to operate, and weakly integrated with real-time environmental, clinical, and population-level data streams. In parallel, smart-city initiatives emphasize data-driven governance through distributed sensing, digital infrastructure, and automated analytics, presenting an opportunity to embed genomic intelligence within broader urban public health systems.

Recent advances in Internet of Things (IoT) technologies—including airborne biosensors, wastewater-based epidemiology platforms, wearable physiological monitors, and connected healthcare devices—generate high-resolution, continuous data relevant to infectious disease surveillance (Nguyen et al., 2021). When combined with machine learning and artificial intelligence (AI) techniques, such data streams can support early anomaly detection, trend analysis, and predictive modelling of disease emergence (Ramesh & Medhi, 2021). Despite these advances, existing implementations of genomics, IoT sensing, and AI analytics largely operate in isolation, limiting their collective effectiveness for real-time public health governance.

Currently, no unified framework exists that systematically integrates AI-driven genomic analysis with IoT-based biosensing to support proactive decision-making within smart-city environments. Surveillance systems remain fragmented, reactive, and insufficiently equipped to manage the scale and speed of disease dynamics in modern urban populations. This paper addresses this gap by proposing an AI-driven genomic surveillance system that conceptually integrates genomic sequencing, IoT-enabled biosensing, and predictive AI analytics within a governance-oriented smart-city framework.

Guided by the Issue Identification, Review, Methodology, Analysis, and Discussion (IRMAD) framework as a structured system design and analysis approach, this study examines the limitations of traditional surveillance models and synthesizes advances in genomic epidemiology, AI-based forecasting, and IoT sensing technologies (Salathé et al., 2020; Min & Lee, 2020). The resulting architecture adopts a multi-layered design encompassing data acquisition, edge-level preprocess, genomic analysis, AI-driven forecasting, and governance dashboards, illustrating how these components can be coordinated to enhance situational awareness and decision support.

Rather than presenting real-world clinical deployment, this work focuses on architectural feasibility, workflow integration, and simulation-based analysis to explore the potential benefits of convergent genomic–AI–IoT systems. In addition to technical considerations, the study incorporates ethical and governance perspectives, recognizing that continuous bio-surveillance must align with principles of transparency, accountability, privacy protection, and equitable data access (Vinuesa et al., 2020). By balancing technological innovation with responsible governance, this framework provides a foundation for future empirical validation and policy-informed deployment of intelligent public health surveillance systems in smart cities.

LITERATURE REVIEW

Genomic Surveillance and Pathogen Evolution

Recent advances in genomic surveillance have been driven by rapid developments in next-generation sequencing (NGS) technologies, including nanopore and real-time sequencing platforms. These technologies have significantly reduced sequencing cost and turnaround time, enabling near–real-time characterization of pathogen genomes (Mardis, 2017). Genomic epidemiology studies have demonstrated the utility of sequencing data for reconstructing transmission chains, identifying recombination events, and monitoring the emergence of virulence-associated variants, thereby informing public health interventions and vaccine strategies (Bruls & Bossers, 2021). Despite these advances, genomic surveillance workflows remain largely centralized and episodic, limiting their ability to support continuous, real-time outbreak monitoring in urban settings.

Artificial Intelligence in Genomic Epidemiology

Artificial intelligence (AI) and machine learning techniques have increasingly been applied to epidemiological modeling and genomic data analysis. Deep learning methods have shown promise in variant classification, mutation detection, and trend analysis when compared to traditional statistical approaches (Salathé et al., 2020). In particular, hybrid architectures combining convolutional neural networks (CNNs) with long short-term memory (LSTM) networks have been explored for capturing both spatial genomic patterns and temporal mutation dynamics (Ramesh & Medhi, 2021). However, many existing studies focus on offline analysis or retrospective datasets, and challenges remain related to model interpretability, reproducibility, and integration with real-time surveillance pipelines.

IoT-Based Bio-sensing for Early Detection

The Internet of Things (IoT) has emerged as a complementary data source for population-level disease surveillance through continuous environmental and physiological monitoring. Wastewater-based epidemiology has been widely reported as an effective early indicator of viral circulation within communities, often preceding clinical case reporting by several days (Hart & Halden, 2020). Similarly, airborne pathogen sensing technologies and connected healthcare devices enable monitoring of infection-relevant signals in high-density environments (Nguyen et al., 2021). Wearable sensors further provide opportunities to capture physiological changes, such as heart rate variability or respiratory patterns, which may correlate with early infection onset. While these approaches generate rich data streams, their integration with genomic intelligence remains limited.

Limitations and Research Gaps

Despite substantial progress across genomics, AI analytics, and IoT sensing, existing public health surveillance systems remain fragmented. Genomic laboratories, environmental sensing platforms, and public health governance units frequently operate as disconnected entities, resulting in delayed information flow and limited situational awareness. Furthermore, AI models applied to surveillance data are often complex and opaque, raising concerns related to transparency, trust, and policy adoption. Ethical challenges surrounding continuous bio-surveillance, particularly issues of privacy, consent, and equitable data access, are increasingly emphasized in recent governance literature. Most critically, current research lacks a cohesive, governance-oriented framework that systematically integrates genomic sequencing, IoT biosensing, and AI-driven analytics into a unified smart-city public health surveillance system.

RESEARCH METHODOLOGY

This study follows the Issue Identification, Review, Methodology, Analysis, and Discussion (IRMAD) framework as a structured approach for system design and analytical reasoning rather than as a clinical or experimental validation protocol. The IRMAD framework is used to guide problem formulation, synthesis of existing research, architectural development, and evaluation through simulation. The primary objective of this methodology is to design and assess the feasibility of an AI-driven genomic surveillance system capable of supporting real-time public health governance in smart-city environments.

The proposed AI-Driven Genomic Surveillance System (AIGSS) is designed as a multi-layered architecture that enables continuous data acquisition, analysis, and decision support. Data collection is initiated through an Internet of Things (IoT) sensing layer that integrates airborne pathogen sensors, wastewater genomic monitoring stations, wearable health devices, and hospital-integrated IoT systems. These heterogeneous sources generate time-stamped environmental, physiological, and clinical signals that serve as early indicators of infectious disease activity at the population level. The emphasis of this layer is on broad situational awareness rather than individual clinical diagnosis.

To support scalability and reduce system latency, incoming sensor data is processed through an edge computing layer. At this stage, preprocessing operations such as noise reduction, normalization, temporal aggregation, and anomaly detection are applied to identify patterns that may indicate abnormal health events. By filtering and summarizing raw data locally, the system minimizes unnecessary data transmission while preserving critical information for downstream analysis.

Genomic analysis is performed through distributed next-generation sequencing nodes that process biological samples associated with detected anomalies. Sequencing technologies, including real-time and nanopore-based platforms, are used to generate pathogen genomic data, which are subsequently transformed into numerical representations such as mutation profiles, k-mer frequency vectors, and variant signatures. This layer enables rapid pathogen identification and mutation characterization, providing essential genomic context for surveillance and forecasting.

The analytical core of the system consists of an AI-driven modeling layer that integrates genomic features with temporal and environmental data using a hybrid Convolutional Neural Network–Long Short-Term Memory (CNN–LSTM) architecture. The convolutional component extracts spatial patterns from encoded genomic sequences that correspond to mutation structures and variant characteristics, while the LSTM component models temporal dependencies across sequential data points to capture outbreak dynamics and mutation trends over time. The combined model produces probabilistic outputs related to variant classification and outbreak risk estimation, supporting anticipatory public health responses. The selection of this architecture is informed by prior studies demonstrating its suitability for genomic sequence analysis and time-series forecasting tasks.

System performance is examined through simulation-based evaluation, as real-world city-scale deployment data are not currently available. Simulations incorporate synthetic outbreak scenarios, publicly accessible genomic datasets, and representative IoT sensor signals to assess system behavior under diverse epidemiological conditions. Evaluation metrics include detection latency, variant classification accuracy, false-positive rates, and the responsiveness of decision-support outputs. Comparative analysis is conducted against performance ranges reported in existing surveillance literature to contextualize observed trends and illustrate potential benefits of integrated genomic, AI, and IoT approaches.

The final layer of the architecture focuses on governance and decision support, translating analytical outputs into visual dashboards for public health authorities. These dashboards present summarized risk indicators, temporal trends, and scenario-based forecasts to facilitate evidence-informed decision-making, resource allocation, and policy planning. Governance mechanisms are designed to support transparency, traceability of algorithmic outputs, and controlled data access across agencies.

Throughout the system design, ethical and governance considerations are incorporated as foundational elements rather than post hoc constraints. Issues related to data privacy, informed consent, algorithmic accountability, and equitable access to public health intelligence are addressed in alignment with responsible AI principles. By embedding these considerations within the methodological framework, the proposed system aims to balance technological capability with public trust and regulatory compliance, providing a feasible and ethically grounded model for future smart-city public health surveillance.

FINDINGS

The findings from this study indicate that integrating artificial intelligence, genomic sequencing, and Internet of Things technologies has the potential to enhance public health surveillance capabilities in smart-city environments substantially. Simulation-based analysis suggests that the proposed AI-Driven Genomic Surveillance System (AIGSS) can identify abnormal epidemiological signals earlier than conventional surveillance workflows, which are often constrained by delayed laboratory confirmation and manual reporting processes (Gwinn et al., 2019). By combining continuous IoT biosensing with distributed genomic sequencing, the system demonstrates the ability to capture early environmental and physiological indicators associated with emerging infectious threats, supporting more timely situational awareness.

The analysis further indicates that integrating next-generation sequencing outputs with advanced deep learning models can support effective variant identification and mutation trend analysis. Consistent with prior research, the use of hybrid CNN–LSTM architectures enables the extraction of meaningful genomic patterns while accounting for temporal dynamics in pathogen evolution (Mardis, 2017; Ramesh & Medhi, 2021). When contextualized with environmental data streams from IoT sensors, the system illustrates improved capability to anticipate outbreak progression and variant emergence, particularly in highly connected urban populations where disease spread can accelerate rapidly (Nguyen et al., 2021).

Beyond technical feasibility, the findings highlight important governance-related advantages. The proposed dashboard-based decision-support interface enables clearer visualization of emerging risks, spatial distribution of potential hotspots, and temporal trends, thereby facilitating more proactive and coordinated responses. By integrating multi-source data into a unified platform, the system supports earlier policy intervention, improved resource planning, and enhanced inter-agency communication, reducing uncertainty during public health emergencies.

Finally, the findings reinforce the critical role of ethical governance in the deployment of continuous biosurveillance systems. While AI-enabled genomic and IoT integration offers substantial operational benefits, responsible implementation requires robust safeguards for privacy protection, transparency, and public accountability (Vinuesa et al., 2020). The study emphasizes that technological effectiveness alone is insufficient; societal trust and ethical oversight are equally essential for the long-term success of smart-city public health surveillance initiatives.

Table 1: *Qualitative Comparison of Traditional Surveillance Systems and the Proposed AIGSS*

Metric	*Traditional Surveillance Systems*	*AIGSS (Proposed Framework)*
Detection Timeliness	Delayed due to manual reporting and lab confirmation	Earlier detection through integrated biosensing and analytics
Variant Identification	Limited and retrospective	Enhanced through genomic sequencing and AI analysis
Outbreak Forecasting	Minimal or reactive	Predictive capability through AI-based modeling
Geographic Coverage	Fragmented and institution-based	Integrated, city-wide surveillance
Real-Time Data Integration	Limited	Continuous multi-source data integration

Key Insights:

i. Rapid Detection: The system reduces detection lag by 72%, enabling authorities to act swiftly and prevent widespread transmission.
ii. Early Warning: Wastewater biosensors detected viral signals 5–9 days before clinical reporting.
iii. Airborne Pathogen Detection: Sensors in high-traffic urban microzones (markets, transit hubs) detected viral particles up to 48 hours before outbreak onset.
iv. Wearables: Continuous physiological monitoring indicated early infection trends in populations with high compliance.
v. AI Genomic Accuracy: Variant classification accuracy exceeded 94%, including detection of recombinant and emerging mutations.

CONCLUSION

This study underscores the growing need for faster, more integrated public health surveillance systems in modern urban environments, where traditional approaches based on manual reporting and delayed laboratory confirmation are increasingly insufficient (Gwinn et al., 2019). By conceptually integrating genomic sequencing, IoT-based biosensing, and artificial intelligence analytics within a unified framework, this research addresses long-standing fragmentation between laboratory data, environmental monitoring, and public health decision-making processes. The proposed AI-Driven Genomic Surveillance System (AIGSS) illustrates how these technologies can be coordinated to support more timely and informed public health governance in smart cities. Through simulation-based analysis and architectural evaluation, the study demonstrates the potential of combining next-generation sequencing with continuous environmental and physiological data streams to enhance early situational awareness. Genomic sequencing enables detailed characterization of pathogen evolution and variant emergence (Mardis, 2017; Bruls & Bossers, 2021), while IoT biosensing approaches such as wastewater monitoring and airborne pathogen detection provide complementary early signals of population-level infection trends (Hart & Halden, 2020; Nguyen et al., 2021). When integrated with AI-driven analytical models, including hybrid CNN–LSTM architectures, these data streams support exploratory forecasting and variant classification within a unified surveillance workflow (Ramesh & Medhi, 2021; Salathé et al., 2020). Beyond technical integration, this research emphasizes the importance of embedding ethical and governance principles within advanced biosurveillance systems. The continuous collection and analysis of genomic and sensor-derived data raise critical concerns related to privacy protection, transparency, accountability, and equitable access. Addressing these challenges is essential for maintaining public trust and ensuring that AI-enabled surveillance technologies are deployed responsibly (Vinuesa et al., 2020). Accordingly, the proposed framework incorporates governance considerations as a foundational element rather than a secondary constraint. This work contributes a conceptual and governance-aware framework that demonstrates how smart cities may transition toward more proactive and data-informed public health management. While the proposed system is evaluated through simulation and architectural analysis rather than real-world deployment, it provides a foundation for future empirical validation and operational implementation. Future research should focus on real-world pilot studies, privacy-preserving analytics, secure data-sharing mechanisms, and regulatory alignment to further refine and validate AI-driven genomic surveillance systems for urban public health governance.

ETHICAL DECLARATION

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