International Journal of Multidisciplinary Research and Growth Evaluation.

# Quantum Machine Learning Algorithms for Real-Time Epidemic Surveillance and Health Policy Simulation: A Review of Emerging Frameworks and Implementation Challenges

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## Article Info

**ISSN (online):** 2582-7138
**Volume:** 05
**Issue:** 03
**May - June 2024**
**Received:** 12-04-2024
**Accepted:** 13-05-2024
**Published:** 20-06-2024
**Page No:** 1100-1108

**Abstract**
This review explores the integration of quantum machine learning (QML) algorithms into real-time epidemic surveillance systems and health policy simulation frameworks. As conventional machine learning models face scalability and interpretability challenges with high-dimensional epidemiological data, QML offers a transformative paradigm by leveraging quantum computing principles to enhance pattern recognition, data compression, and forecasting precision. The study examines emerging QML architectures and their application to real-time tracking of infectious diseases, anomaly detection in public health datasets, and dynamic modeling of transmission patterns. Additionally, it assesses the role of QML in simulating the impact of health interventions, policy shifts, and behavioral dynamics on epidemic trajectories. Emphasis is placed on multi-modal data integration from genomics, environmental monitoring, and mobility trends to refine predictive accuracy. Key implementation challenges—such as quantum decoherence, algorithmic instability, regulatory constraints, and limited access to quantum hardware—are critically analyzed. The paper concludes by proposing a roadmap for the adoption of hybrid quantum-classical frameworks and policy-informed computational modeling to strengthen global epidemic preparedness and responsive health governance.

**DOI:** **https://doi.org/10.54660/.IJMRGE.2024.5.3.1100-1108**

**Keywords:** Quantum Machine Learning, Epidemic Surveillance, Health Policy Simulation, Predictive Modeling, Public Health Informatics, Hybrid Quantum-Classical Systems

## 1. Introduction

### 1.1 Background on Epidemic Surveillance Systems

Epidemic surveillance systems are undergoing a paradigm shift from reactive, manual frameworks to real-time, technology-enabled models. Traditional approaches—rooted in static laboratory reports and case registries—often face latency, underreporting, and poor data integration (Ijiga *et al.*, 2024). With the proliferation of electronic health records (EHRs), mobile health data, genomic platforms, and mobility sensors, public health surveillance must now handle vast, heterogeneous data streams requiring advanced analytical tools.

Quantum machine learning (QML), which leverages principles of quantum mechanics such as entanglement and superposition, offers computational advantages for such high-dimensional, nonlinear epidemiological data.

Its potential to improve transmission modeling, early outbreak detection, and contact tracing systems has been increasingly recognized (Ayanponle *et al*., 2024). The integration of QML into public health platforms enables simultaneous analysis of complex variables like behavioral patterns, environmental signals, and policy interventions with unprecedented speed and accuracy.

As Ijiga *et al*. (2024) argue, the resilience of epidemic surveillance is contingent not only on analytical accuracy but also on the system's ability to detect adversarial risks in data streams. This includes safeguarding against manipulation, bias, and privacy violations. Complementarily, Ayanponle *et al*. (2024) highlight that ethical considerations—such as fairness, transparency, and access—must be embedded in QML-powered health frameworks to ensure equitable deployment across diverse populations. These combined perspectives underpin the growing call for a hybrid epidemiological architecture: one that fuses technical innovation with social accountability.

### 1.2 The Need for Advanced Predictive Technologies in Public Health

The COVID-19 pandemic highlighted the inadequacy of conventional modeling tools in forecasting real-time outbreak dynamics. Classical machine learning models, although useful for specific disease predictions, falter when confronted with rapidly evolving, large-scale public health crises. The interplay of demographic, behavioral, mobility, and environmental variables requires scalable and adaptive models that can learn from sparse, high-dimensional, and often noisy data sources (Ayanponle *et al*., 2024).

Quantum machine learning presents a promising evolution in this context. By encoding information in quantum states and using quantum entanglement for correlation extraction, QML enables superior pattern recognition and generalization compared to classical methods. This is especially valuable in real-time outbreak surveillance, where early detection and intervention modeling can determine mortality and morbidity outcomes (Ijiga *et al*., 2024).

Ayanponle *et al*. (2024) stress that predictive public health technologies must also account for socio-economic disparity, behavioral variability, and data accessibility challenges. QML systems, if properly architected, can incorporate such social determinants of health within disease progression simulations, ensuring more inclusive and ethically grounded forecasting tools. Moreover, advances in federated quantum computing and edge deployment strategies offer opportunities to democratize access to such tools even in resource-constrained settings.

Thus, the need for advanced predictive technologies is not solely a technical matter but a policy imperative. Integrating QML into public health infrastructure enhances preparedness, fosters data equity, and enables evidence-based responses at local, national, and global levels.

### 1.3 Overview of Quantum Computing and Its Relevance to Machine Learning

Quantum computing introduces an alternative paradigm in computation, using quantum bits or "qubits" that operate in superposition and can be entangled. These features allow quantum systems to evaluate multiple probabilistic states simultaneously, offering exponential gains in processing power for specific classes of problems (Idoko *et al*., 2024). In the realm of machine learning, quantum-enhanced algorithms promise better optimization and representation learning, particularly in contexts involving non-convex objective functions and high-dimensionality.

Quantum machine learning (QML) combines quantum mechanics with classical learning architectures. Algorithms such as the Variational Quantum Classifier (VQC), Quantum Support Vector Machine (QSVM), and Quantum Principal Component Analysis (QPCA) are being tailored for real-world applications including drug discovery, genomics, and increasingly, epidemiology (Ijiga *et al*., 2024). These models can enable richer and faster identification of infection patterns, anomaly detection in biosurveillance, and prediction of healthcare resource utilization.

In a recent study, Ijiga *et al*. (2024) explored the use of adversarial machine learning for improving robustness in cyber-epidemiological models, laying groundwork for QML-enhanced defense mechanisms. Similarly, Ayanponle *et al*. (2024) advocate that the deployment of quantum systems in health must be guided by human-centric design principles, emphasizing fairness, reproducibility, and ethical risk assessment.

Although current quantum systems are constrained to NISQ devices, the momentum in quantum cloud platforms—like IBM Q and Google Sycamore—is rapidly increasing. These infrastructures now make it feasible for researchers and public health institutions to experiment with QML models for epidemiological data.

### 1.4 Purpose and Scope of the Review

This review explores the intersection of QML, real-time epidemic surveillance, and health policy simulation. The purpose is to evaluate the feasibility, advantages, and implementation challenges of integrating QML into digital health ecosystems for pandemic preparedness and proactive governance. While classical models have made substantial contributions, they remain inadequate for modeling multi-scalar, nonlinear, and uncertain epidemiological systems (Imoh *et al*., 2024).

The scope includes: (1) a review of quantum computing foundations and their alignment with public health goals; (2) an examination of QML applications in real-time outbreak modeling; (3) use of QML for simulating health policy impacts under uncertainty; and (4) a critical assessment of technical, ethical, and infrastructural barriers. Ijiga *et al*. (2024) underscore the need for integrating behavioral science and threat intelligence in QML development to strengthen resilience in public health systems. Ayanponle *et al*. (2024) emphasize the importance of equity-centered frameworks to ensure that emerging technologies enhance, rather than hinder, access and trust in health services.

By drawing from interdisciplinary research and case-based analysis, this paper aims to inform the development of next-generation surveillance architectures—ones that are intelligent, explainable, ethically compliant, and resilient. The findings will be relevant to policymakers, quantum scientists, epidemiologists, and data engineers collaborating to build pandemic-resilient systems.

## 2. Quantum Machine Learning: Foundations and Capabilities

### 2.1 Fundamentals of Quantum Computing for Machine Learning

Quantum computing exploits principles such as superposition and entanglement to perform computations across multiple states simultaneously. Unlike classical bits, quantum bits or *qubits*can represent both 0 and 1, thereby offering exponential parallelism. This property makes quantum computing highly promising for optimization and learning tasks, especially those dealing with complex and high-dimensional data spaces (Idoko *et al*., 2024).

Quantum Machine Learning (QML) applies quantum operations to machine learning workflows, enabling new forms of model architecture and data encoding. Hybrid quantum-classical approaches are currently the most practical, allowing quantum circuits to handle transformation and learning tasks while classical systems manage pre- and post-processing. These architectures are particularly relevant in health contexts where epidemiological data includes diverse modalities like genomics, clinical signals, and behavioral metrics (Imoh *et al*., 2024).

Ijiga *et al*. (2024) emphasize the importance of leveraging QML in adversarial environments such as cyber-epidemiology, where threats to data integrity and confidentiality can compromise ah1surveillance accuracy. Likewise, Ayanponle *et al*. (2024) stress the necessity of embedding fairness, transparency, and ethical oversight in quantum algorithm deployment. Together, their perspectives support the case for quantum computing not only as a technical upgrade, but also as a foundation for secure and inclusive public health intelligence systems.

### 2.2 Types of QML Algorithms: Quantum SVMs, QNNs, and VQAs

Quantum-enhanced models mimic traditional machine learning structures but employ quantum circuits to encode data and optimize learning parameters. Key models under current development include:

- **Quantum Support Vector Machines (QSVMs):** These leverage quantum kernels to separate data with greater flexibility in high-dimensional Hilbert spaces.
- **Quantum Neural Networks (QNNs):** Built from parameterized quantum gates, QNNs support supervised learning tasks through variational optimization.
- **Variational Quantum Algorithms (VQAs):** These include classifiers and regressors trained on quantum states using hybrid optimizers.

Each of these algorithms has significant implications for public health modeling. QSVMs, for instance, can improve clustering of disease phenotypes; QNNs can track transmission dynamics; and VQAs can enhance policy impact simulations in resource-constrained settings (Idoko *et al*., 2024).

Ijiga *et al*. (2024) argue that these architectures offer resilience in noisy and adversarial environments—ideal for real-time surveillance systems that must operate amid uncertain and fast-evolving data. Ayanponle *et al*. (2024) reinforce the need for explainable and auditable quantum systems, especially in sensitive health applications, to maintain public trust and regulatory compliance.

### 2.3 Advantages of QML Over Classical ML in High-Dimensional Data Contexts

Classical ML models experience scalability bottlenecks when applied to large, complex, and interdependent health datasets. Epidemiological modeling, which often involves real-time data from clinical, environmental, and social sources, exemplifies this challenge. QML can mitigate such issues by embedding data into high-dimensional quantum states, enabling more efficient pattern recognition and decision-making (Idoko *et al*., 2024).

Quantum feature encoding allows QML to detect nonlinear relationships among input variables that would otherwise require extensive manual engineering in classical systems. Moreover, quantum algorithms can accelerate iterative optimization tasks, reducing the training time for models used in pandemic forecasting and public health decision support (Imoh *et al*., 2024).

In cyber-health contexts, Ijiga *et al*. (2024) demonstrated that QML reduces both detection latency and false positive rates in threat modeling compared to classical deep learning approaches. Ayanponle *et al*. (2024) caution that computational benefits must be balanced with equity, ensuring that quantum advances do not widen the digital divide or exacerbate algorithmic bias.

### 2.4 Current Platforms and Toolkits for QML Deployment

Several platforms now support QML experimentation and development. IBM Qiskit, Google Cirq, and Amazon Brak*et al*low quantum circuit design, execution, and hybrid ML workflows. Libraries like PennyLane and TensorFlow Quantum enable seamless integration of quantum functions with classical deep learning pipelines, a configuration particularly useful for health informatics researchers (Imoh *et al*., 2024).

These platforms support cloud-based access to quantum hardware and simulators, allowing scalable deployment of models for policy simulation and outbreak modeling. As hardware advances, these environments are expected to transition from academic prototyping to operational public health infrastructure (Idoko *et al*., 2024).

Ijiga *et al*. (2024) recommend combining quantum platforms with behavioral modeling and threat intelligence to build robust surveillance architectures. Ayanponle *et al*. (2024) advise that policymakers and technologists collaborate early in the development process to create socially responsive and auditable QML systems that enhance both predictive capability and public accountability.

## 3. Real-Time Epidemic Surveillance Frameworks Using QML

### 3.1 Integration of QML in Real-Time Epidemiological Monitoring

Real-time epidemiological monitoring requires the processing of vast, heterogeneous data sources including syndromic surveillance reports, mobility data, environmental indicators, and digital health records. Quantum Machine Learning (QML) offers advanced capabilities to process and analyze these data streams with higher efficiency and precision compared to classical systems. By embedding these inputs into quantum states and exploiting parallel computation, QML frameworks can model latent outbreak dynamics with minimal delay (Ijiga *et al*., 2024).

QML-enabled surveillance systems can support continuous learning from streaming data, thereby improving the timeliness of outbreak detection and the specificity of alerts (Ayanponle *et al*., 2024). For instance, quantum-enhanced classifiers can be used to rapidly identify unusual spatiotemporal clusters, enabling early containment interventions. These systems also allow for probabilistic modeling of disease emergence across regions with poor data availability, a critical advantage in low-resource settings (Imoh *et al*., 2024).

Emerging frameworks often rely on hybrid classical-quantum pipelines where data preprocessing and visualization are handled classically, while quantum circuits manage high-dimensional pattern recognition. Platforms such as IBM Qiskit and TensorFlow Quantum allow implementation of such architectures, providing scalable access to quantum resources (Idoko *et al*., 2024). Additionally, Ayanponle *et al*. (2024) stress the necessity of embedding ethical safeguards in surveillance systems to protect privacy and prevent misuse. Integrating QML in real-time surveillance not only accelerates detection but also enhances interpretability and responsiveness, especially in volatile epidemic contexts.

### 3.2 Multi-Modal Health Data Fusion: Genomics, Mobility, and EHRs

Public health surveillance has become increasingly reliant on multi-modal datasets encompassing genomics, electronic health records (EHRs), social media feeds, and mobility networks. Each of these data types provides unique insights into disease dynamics, and their integration can significantly improve the fidelity of predictive models. QML is well-suited to handle this complexity due to its superior dimensionality reduction capabilities and entanglement-based feature fusion (Imoh *et al*., 2024).

Using QML, it is possible to unify structured and unstructured data sources within a single computational model, enabling the synthesis of genetic susceptibility data with clinical symptoms, exposure histories, and movement patterns. Such integration is essential for modeling diseases with multifactorial transmission pathways like COVID-19 and dengue. QML-based variational circuits can learn correlations that span across data modalities, improving both the precision and generalizability of surveillance outputs (Idoko *et al*., 2024).

Ijiga *et al*. (2024) demonstrate how adversarial QML frameworks enhance the robustness of these fusion models against noisy or incomplete data, which is common in outbreak settings. Moreover, Ayanponle *et al*. (2024) emphasize that multi-modal QML must be deployed with equity-focused data governance, ensuring that marginalized communities are not systematically excluded from predictive systems. The convergence of QML and multi-modal analytics thus represents a critical leap in developing adaptive, comprehensive epidemic surveillance infrastructures.

### 3.3 QML-Enabled Outbreak Detection and Transmission Modeling

Traditional outbreak detection models depend on statistical thresholds and rule-based alerts, which are often reactive and unable to accommodate novel patterns. QML-based systems, by contrast, use quantum-enhanced learning algorithms to detect anomalies in real-time with greater sensitivity and lower false positive rates. Quantum classifiers and unsupervised clustering algorithms can identify subtle deviations from normal disease patterns that may precede outbreaks (Ijiga *et al*., 2024).

Quantum Boltzmann Machines (QBMs) and Quantum Convolutional Neural Networks (QCNNs) are particularly effective in modeling transmission pathways, including indirect environmental vectors and behavioral covariates. These models simulate multiple infection scenarios simultaneously, enabling proactive intervention planning. When deployed within federated health networks, QML facilitates collaborative learning without direct data sharing, preserving privacy and accelerating regional response coordination (Ayanponle *et al*., 2024).

Transmission modeling with QML allows for the incorporation of real-time mobility data, vaccination rates, and genomic mutations into compartmental models like SEIR (Susceptible-Exposed-Infectious-Recovered). This dynamic capability enhances forecasting and supports nuanced decision-making in rapidly evolving health emergencies (Imoh *et al*., 2024). The integration of QML into public health surveillance not only increases analytic depth but also offers a scalable pathway to digital preparedness in the face of future pandemics.

### 3.4 Case Studies and Simulated Use Scenarios

Several pilot studies and conceptual frameworks have explored the integration of QML in epidemic surveillance. For example, simulated models based on quantum variational circuits have demonstrated success in forecasting hospital capacity demands and local transmission hotspots during simulated influenza outbreaks (Idoko *et al*., 2024). These use cases underscore the potential for QML to augment existing health infrastructure with intelligent decision-support systems.

In another study, quantum-enhanced anomaly detection models were used to analyze emergency department visit logs, successfully flagging early respiratory disease clusters that classical models had missed (Imoh *et al*., 2024). Such simulations suggest that QML can be a valuable augmentation tool for syndromic surveillance, particularly in identifying atypical clinical presentations or novel pathogens.

Ayanponle *et al*. (2024) propose integrating QML frameworks within mobile health platforms to support decentralized data acquisition and on-device inference. This strategy would allow communities in underserved areas to benefit from real-time insights without requiring constant internet connectivity. Ijiga *et al*. (2024) further advocate for cloud-based orchestration of quantum workloads, enabling centralized health agencies to dynamically update risk models and simulate intervention policies. These examples illustrate the viability and versatility of QML in varied epidemiological scenarios, demonstrating its role in building adaptive, resilient health systems.

## 4. Quantum-Driven Health Policy Simulation and Decision Support

### 4.1 Predictive Modeling of Health Policy Outcomes with QML

Quantum machine learning (QML) provides the computational foundation for simulating complex health policy scenarios under conditions of uncertainty and limited data. Unlike deterministic classical models, QML algorithms can process probabilistic distributions of outcomes, enabling the simulation of real-world interventions across diverse population segments (Ijiga *et al*., 2024). This is particularly important in public health where behavioral, demographic, and environmental variables interact in non-linear ways.

Using quantum-enhanced classifiers and regressors, policymakers can evaluate multiple intervention strategies—such as phased vaccination rollouts, lockdown thresholds, or resource allocation policies—and quantify their respective impacts in real-time. Ayanponle *et al*. (2024) emphasize the need for these simulations to be not only technically accurate but ethically sound, with safeguards to avoid exacerbating systemic health disparities.

When applied to historical and streaming data from mobile health applications, QML allows dynamic recalibration of policy outcomes. For example, QML can simulate counterfactual scenarios to determine the best timing for mobility restrictions or the effects of varying levels of public compliance. Idoko *et al*. (2024) and Imoh *et al*. (2024) further demonstrate how QML accelerates convergence in high-dimensional policy models compared to classical tools, enhancing both the precision and interpretability of results.

QML's value in policy modeling lies in its adaptability—offering real-time feedback, scenario testing, and robust predictive insight to support agile, data-driven governance.

### 4.2 Scenario Planning for Vaccination Strategies and Resource Allocation

Scenario planning is a core function of public health strategy, particularly in pandemic preparedness and response. QML can vastly improve this process by simulating thousands of vaccination distribution permutations across geographic and demographic spectra, helping policymakers choose strategies that minimize inequity and maximize impact (Ayanponle *et al*., 2024).

Quantum-enhanced generative models are well-suited for simulating how variations in vaccine supply chains, population movement, and age-based prioritization affect overall immunity thresholds. Ijiga *et al*. (2024) propose QML models integrated into federated databases to evaluate regional vaccine efficacy and real-time demand forecasting. These simulations reduce reliance on rigid supply schedules and allow for responsive, equitable allocation strategies.

The integration of QML into digital twin platforms further supports personalized vaccination planning. By modeling hypothetical population behavior in digital environments, policymakers can test incentive mechanisms, public outreach strategies, and targeted interventions (Idoko *et al*., 2024).

Imoh *et al*. (2024) show that QML-powered logistic optimization can improve cold-chain management and reduce waste in vaccine storage and delivery. This quantum-enhanced capacity for decision optimization ensures that vaccination campaigns are not only effective but sustainable under resource constraints.

### 4.3 Optimization of Public Health Interventions Using QML

Optimization problems in public health—ranging from resource deployment to scheduling interventions—often involve a large number of interacting constraints. QML enables rapid resolution of such problems through quantum annealing and variational optimization (Ijiga *et al*., 2024). These tools allow decision-makers to identify intervention combinations that maximize impact while minimizing cost, delay, or public resistance.

One key application is in contact tracing, where QML can optimize cluster analysis to identify high-risk transmission zones and recommend real-time mobility controls. Similarly, QML supports triage optimization in hospitals by predicting resource demand and pre-positioning supplies accordingly (Ayanponle *et al*., 2024).

Idoko *et al*. (2024) provide examples of QML models being used to optimize rural health delivery routes and personnel deployment. Such optimization has downstream effects on health equity, improving service accessibility for remote populations. As Imoh *et al*. (2024) suggest, this is particularly relevant for regions with fragmented healthcare infrastructure.

Ultimately, the use of QML in optimization supports data-driven public health operations that are agile, resilient, and tailored to contextual realities.

### 4.4 Socioeconomic and Behavioral Factors in QML-Based Policy Models

Incorporating behavioral and socioeconomic variables into policy models enhances the realism and fairness of public health simulations. QML allows multidimensional modeling of factors such as income distribution, digital access, compliance behavior, and misinformation exposure—variables that strongly influence policy effectiveness (Ayanponle *et al*., 2024).

QML's ability to represent complex correlations enables cross-sectoral modeling where healthcare, education, and employment data inform integrated policy design. For example, models can evaluate how food insecurity affects vaccine hesitancy or how school closures impact child mental health and long-term morbidity (Ijiga *et al*., 2024).

Idoko *et al*. (2024) argue that integrating behavioral nudges and policy interventions into QML systems provides decision-makers with tools for socially responsive governance. Imoh *et al*. (2024) further support the idea of using quantum-enhanced models to simulate differential impacts across income brackets or ethnic groups.

Embedding social determinants in QML-based frameworks ensures that interventions are not only technically sound but also ethically and socially valid. These insights are crucial for crafting equitable policies that foster long-term public trust and systemic resilience.

## 5. Challenges, Opportunities, and Future Directions

### 5.1 Technical Barriers: Quantum Hardware Limitations and Algorithmic Stability

Despite the promise of QML in public health, technical barriers continue to limit its wide-scale deployment. Quantum hardware remains in the Noisy Intermediate-Scale Quantum (NISQ) era, where decoherence, gate fidelity, and error correction pose substantial challenges. These constraints hinder the reliability and scalability of QML models in production environments. Moreover, variational quantum algorithms often suffer from issues such as barren plateaus and instability during training, making them difficult to generalize across diverse datasets. Bridging these gaps requires ongoing innovation in quantum error mitigation, hybrid algorithm development, and access to high-quality qubit architectures through cloud-based services.

### 5.2 Ethical, Legal, and Interoperability Considerations

Deploying QML within public health systems raises several ethical and regulatory concerns. The opacity of quantum models complicates explainability and auditability, especially in high-stakes decision-making scenarios such as triage and resource allocation. Privacy preservation remains critical, especially when integrating behavioral and genomic data into predictive frameworks. Additionally, existing legal frameworks do not yet accommodate the nuances of quantum computation in health data processing. Interoperability with classical health information systems and compliance with global data protection standards will be essential to ensuring that QML-based systems are adopted responsibly and sustainably.

### 5.3 Hybrid Quantum-Classical Approaches and Cloud-Based Deployment

One pathway to near-term QML adoption lies in hybrid quantum-classical models, where classical preprocessing and post-analysis are integrated with quantum computational cores. These models are particularly suitable for current hardware capabilities and offer a practical means to achieve quantum advantage incrementally. Cloud-based quantum computing services enable researchers and health institutions to prototype, deploy, and scale QML workflows without direct access to quantum machines. This democratization of quantum resources accelerates the research-to-implementation pipeline and supports multi-institutional collaborations across national health agencies, universities, and private-sector partners.

### 5.4 Strategic Recommendations for Research and Policy Integration

To unlock the full potential of QML in epidemic surveillance and health policy modeling, strategic investments are needed in quantum workforce development, ethical AI governance, and interdisciplinary research. Public health agencies should establish partnerships with quantum labs and academic institutions to foster translational innovation. Government-led pilot programs can help evaluate QML effectiveness in real-world settings while developing standards for interpretability and ethical safeguards. Incorporating QML into digital health strategies will require alignment with national priorities for technology infrastructure, data equity, and global health diplomacy.

### 5.5 Final Remarks on the Role of QML in Future Public Health Systems

Quantum Machine Learning is poised to revolutionize how societies monitor, predict, and respond to public health threats. Its ability to integrate high-dimensional data, simulate policy scenarios, and optimize interventions offers unmatched potential for precision governance. While barriers to adoption remain, the convergence of quantum science, machine learning, and digital health creates fertile ground for innovation. With thoughtful policy design, ethical foresight, and sustained investment, QML can play a transformative role in strengthening global health systems and preparing for future pandemics.

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