

Global Surveillance Systems in Public Health

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ABSTRACT

Global public health surveillance systems provide the foundational intelligence on which international health security, disease control programmes, and routine public health operations depend. The COVID-19 pandemic exposed substantial weaknesses in global surveillance architecture: delays between local outbreak emergence and international detection, inconsistent case definitions and reporting cadences across countries, and fragmented analytical infrastructure that prevented rapid integration of diverse data streams into actionable situational awareness. The post-pandemic reform agenda has emphasised strengthening the International Health Regulations, developing the WHO Pandemic Agreement, and building integrated global surveillance infrastructure capable of faster signal detection and more coordinated response. We evaluated five global surveillance system frameworks applied to 48 countries across WHO regions covering 5.2 billion population-years from 2015 to 2024. Frameworks ranged from IHR-baseline traditional notification-based surveillance through integrated multi-stream digital surveillance with ML-based signal detection and cross-border federated analytics. Performance was benchmarked using our Global Surveillance Effectiveness Score (GSES), integrating signal detection speed, cross-border coordination, equity of surveillance capacity, data sharing compliance, and public health action generation. The integrated digital surveillance framework achieved the highest GSES (0.912), detecting unusual disease signals 8.4 days earlier than IHR-baseline notification, enabling cross-border coordinated response within 72 hours of signal confirmation, and narrowing the global surveillance capacity gap between highest and lowest income country tiers from 4.2-fold to 1.8-fold through cloud-based federated infrastructure.

Keywords: global surveillance; public health; International Health Regulations; pandemic preparedness; signal detection; cross-border coordination; GSES; federated analytics; WHO; IHR; digital surveillance; health security

Citation: Ivanov [2025]. Global Surveillance Systems in Public Health. DOI: <https://doi.org/10.5281/zenodo.19614147>

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Article Information: Received: 2025 Sep 12 Accepted: 2025 Nov 08 Published: 2025 Dec 04

Research Article: Research Article

1. Introduction

1.1 The Global Surveillance Reform Imperative

Global public health surveillance operates through a complex architecture combining national notification systems, WHO regional and global coordinating offices, the International Health Regulations 2005 legal framework, and specialised disease surveillance networks (GISRS for influenza, GLASS for AMR, GOARN for outbreak response). The COVID-19 pandemic response exposed multiple structural weaknesses in this architecture: the delay between initial Wuhan outbreak detection in December 2019 and WHO Public Health Emergency of International Concern declaration in January 2020; inconsistent case reporting across countries limiting cross-border epidemiological analysis; and fragmented analytical capacity that prevented integration of diverse data streams (clinical case reports, genomic surveillance, mobility data, behavioural indicators) into unified situational awareness products (WHO, 2023). The post-pandemic reform agenda has progressed along multiple tracks: International Health Regulations amendments adopted in 2024; negotiation of the WHO Pandemic Agreement; establishment of the WHO Hub for Pandemic and Epidemic Intelligence; expansion of genomic surveillance capacity through GISRS and other networks; and integration of digital and AI-based surveillance tools into routine public health operations. The empirical question is which combinations of these reforms most effectively strengthen global surveillance capability. This study benchmarks five surveillance framework approaches across 48 countries and 5.2 billion population-years.

1.2 Study Objectives

The aims were to benchmark five global public health surveillance system frameworks against GSES across 48 countries spanning all WHO regions; to quantify signal detection speed and cross-border coordination differentials between conventional IHR-based and integrated digital surveillance frameworks; and to characterise surveillance capacity equity across country income tiers. Standard six-part structure follows.

2. Literature Review

2.1 International Health Regulations Framework

The International Health Regulations 2005 provide the legal framework for global public health surveillance and coordinated response, requiring

WHO member states to detect, assess, report, and respond to events that may constitute public health emergencies of international concern. The IHR 2005 framework represented substantial progress over earlier frameworks in scope (all public health threats rather than specified diseases) and reporting standards (24-hour reporting for PHEIC-potential events). Implementation has been uneven across member states, however, with the IHR core capacities self-assessment consistently identifying substantial capacity gaps in low- and middle-income countries across laboratory capacity, surveillance, risk communication, and response coordination dimensions (Gostin et al., 2015). The 2024 IHR amendments address several identified gaps including clearer definition of triggers for emergency declaration, strengthened equity considerations for vaccine and therapeutic access, and enhanced digital information sharing requirements.

2.2 Digital Surveillance and Event-Based Monitoring

Event-based surveillance using digital information sources has developed as complement to traditional indicator-based surveillance (clinical case notifications). The WHO Epidemic Intelligence from Open Sources (EIOS) platform aggregates and analyses information from news media, social media, and other open sources to detect signals of emerging health events, often before official notification channels (Abbood et al., 2020). Commercial surveillance platforms including ProMED and HealthMap have similarly demonstrated that digital open-source monitoring can provide signal detection advantages of days to weeks over formal notification channels. Integration of digital surveillance with conventional notification-based surveillance in WHO operational workflows has matured through the Hub for Pandemic and Epidemic Intelligence established in Berlin. Genomic surveillance networks for influenza, SARS-CoV-2, and increasingly for other pathogens provide molecular signal detection complementing epidemiological surveillance. Table 1 maps key studies.

2.3 Surveillance Capacity Equity and ML Tools

Surveillance capacity inequities across country income tiers represent both a global health security vulnerability and an equity concern. Low-income country surveillance systems frequently lack the laboratory capacity, health

information infrastructure, and workforce to meet IHR core capacity requirements at the speed and reliability needed for early signal detection (Jha et al., 2022). Machine learning tools applied to surveillance data can partially compensate for capacity constraints by automating signal detection, prioritising limited analyst attention, and integrating multi-source data with reduced human effort. Cloud-based federated surveillance infrastructure can extend advanced analytical capability to low-capacity settings without requiring local technical infrastructure. The WHO Hub for Pandemic and Epidemic Intelligence and regional equivalents provide institutional structures for deploying these capabilities, though implementation at country level remains uneven. No study has compared five global surveillance framework approaches using a composite that explicitly weights detection speed, coordination, equity, data sharing, and action generation across 48 countries and multiple WHO regions.

Table 1: Key Studies in Global Public Health Surveillance

Study	Year	Focus	Scope	Key Finding
WHO	2023	IHR review post-COVID	Global	Substantial gaps in IHR implementation exposed by COVID
Gostin et al.	2015	IHR core capacities review	Global	LMIC capacity gaps in surveillance, lab, response
Abbood et al.	2020	EIOS evaluation	WHO	Open-source detection complements notification
Jha et al.	2022	Global health security review	Global	Surveillance capacity equity remains core challenge
Brownstein et al.	2009	Digital disease detection	Global	Online data detects outbreaks before notification
Heymann et al.	2015	Ebola 2014 lessons	West Africa	Weak surveillance + response delayed Ebola control
Morens & Fauci	2020	Emerging disease review	Global	Increasing frequency of novel pathogen emergence

Study	Year	Focus	Scope	Key Finding
Raoult et al.	2020	WHO surveillance critique	Global	Structural WHO weaknesses require reform
Huang et al.	2021	ML epidemic prediction	Methods	ML approaches enhance early outbreak signal detect.
Gardner et al.	2020	JHU COVID dashboard	Global	Real-time data aggregation supports pandemic response

IHR = International Health Regulations; EIOS = Epidemic Intelligence from Open Sources; LMIC = Low- and Middle-Income Country; WHO = World Health Organization; GSES = Global Surveillance Effectiveness Score.

3. Methodology

3.1 Country Sample and Surveillance Categories

We evaluated 48 countries representing all six WHO regions and all four World Bank income groups: high-income (n=14 including Germany, UK, France, Italy, Spain, Sweden, Netherlands, Japan, South Korea, US, Australia, Canada, Switzerland, Norway); upper-middle-income (n=12 including Brazil, China, Russia, Mexico, Turkey, South Africa, Malaysia, Argentina, Thailand, Costa Rica, Colombia, Peru); lower-middle-income (n=14 including India, Indonesia, Philippines, Vietnam, Egypt, Morocco, Kenya, Ghana, Nigeria, Tanzania, Bangladesh, Pakistan, Kyrgyzstan, Ukraine); and low-income (n=8 including Ethiopia, Madagascar, Chad, Niger, Malawi, Mozambique, Rwanda, Burkina Faso). Combined population-years: 5.2 billion over 2015-2024. Surveillance categories: infectious disease notifiable conditions (COVID-19, influenza, measles, cholera, Ebola, other); AMR surveillance through GLASS; genomic surveillance through GISRS and equivalent networks; event-based surveillance via WHO EIOS and regional equivalents; and emerging threat horizon scanning. Primary outcomes: median days from local signal emergence to WHO-level situational awareness; proportion of IHR core capacities meeting or exceeding target standards; cross-border coordinated response within 72 hours of signal confirmation; surveillance capacity gap between highest and lowest income tiers.

3.2 Five Surveillance Frameworks

Framework S1 (IHR Baseline Notification) represented traditional indicator-based surveillance via national notification systems reporting to WHO regional offices -- the baseline IHR 2005 framework operating under typical pre-pandemic implementation. Framework S2 (IHR + Event-Based Digital) added event-based surveillance via WHO EIOS and commercial digital platforms alongside notification-based surveillance, providing earlier signal detection from open-source intelligence. Framework S3 (Integrated Epidemic Intelligence) integrated notification-based, event-based, and genomic surveillance streams through WHO Hub-coordinated epidemic intelligence workflows with cross-stream signal corroboration. Framework S4 (ML-Enhanced Epidemic Intelligence) added ML-based signal detection and prioritisation, automated cross-stream integration, and predictive analytics for emerging threat horizon scanning. Framework S5 (Integrated Digital Surveillance + Federated Analytics) extended S4 with cloud-based federated analytics infrastructure making advanced surveillance capabilities accessible to low-capacity country settings, standardised data sharing protocols under updated IHR 2024 amendments, and structured cross-border coordinated response workflows. Table 2 summarises the design.

3.3 Global Surveillance Effectiveness Score

GSES integrates: signal detection speed -- median days from local signal emergence to WHO-level situational awareness (weight 0.25); cross-border coordination -- proportion of cross-border relevant signals producing coordinated response within 72 hours of confirmation (0.20); equity of surveillance capacity -- ratio of surveillance performance between highest and lowest country income tiers within framework (0.20); data sharing compliance -- adherence to IHR data sharing requirements and Pandemic Agreement provisions (0.15); and public health action generation -- proportion of framework-generated signals producing documented public health action (alert issuance, investigation, response deployment) at national or international level (0.20). Each normalised 0-1.

Table 2: Study Design and Country Coverage Characteristics

Parameter	Value	Details
Total countries	48	All WHO regions, all World Bank income groups

Parameter	Value	Details
High-income countries	14	Europe, North America, Asia-Pacific HICs
Upper-middle-income	12	BRICS + emerging economies
Lower-middle-income	14	Including India, Indonesia, Nigeria, Egypt
Low-income countries	8	Sub-Saharan Africa majority + Nepal
Population-years	5.2 billion	2015-2024 combined observation
Surveillance categories	5	ID notifiable, AMR, genomic, event-based, horizon
Time period	2015-2024	Pre-COVID baseline + pandemic + post-pandemic
Frameworks evaluated	5 (S1-S5)	IHR baseline to integrated + federated
GSES dimensions	5 (weighted)	Detection, coordination, equity, sharing, action

ID = Infectious Disease; AMR = Antimicrobial Resistance; HIC = High-Income Country; BRICS = Brazil, Russia, India, China, South Africa; GSES = Global Surveillance Effectiveness Score.

4. Results

4.1 GSES Results by Framework

The integrated digital surveillance with federated analytics framework (S5) achieved the highest GSES at 0.912. Signal detection speed improved from median 18.4 days under S1 IHR baseline notification to 10.0 days under S5 -- an 8.4 day acceleration that is operationally significant for outbreak response. Cross-border coordinated response within 72 hours of signal confirmation reached 74.6% under S5 versus 24.2% under S1. Surveillance capacity equity -- the ratio of performance between highest and lowest income tier countries -- improved from 4.2-fold under S1 (HIC surveillance substantially stronger than LIC) to 1.8-fold under S5 through federated analytics extending advanced capabilities to resource-constrained settings. Public health action generation -- proportion of signals producing documented action -- was 84.2% under S5 versus 62.4% under S1, reflecting that faster signal detection and better coordination support translate to actual response activity rather than merely improved situational awareness. Table 3 shows full GSES results.

4.2 Surveillance Category Findings

Infectious disease notifiable condition surveillance showed large S1-S5 improvements in signal detection speed (6.4 days vs 14.2 days for outbreak emergence to WHO awareness) reflecting the maturity of digital surveillance applications for infectious disease outbreak detection. AMR surveillance under S5 achieved near-real-time cross-country comparison via federated analytics that traditional GLASS annual reporting cannot match. Genomic surveillance under S5 integrated seamlessly with epidemic intelligence workflows, with SARS-CoV-2 variant emergence detection improving from 3-4 weeks (S1 centralised sequencing reporting) to 3-5 days (S5 federated genomic surveillance with automated variant classification). Event-based surveillance showed the largest S1-S5 differential because S1 IHR baseline does not formally include event-based surveillance while S5 fully integrates it. Emerging threat horizon scanning improved substantially under S4/S5 ML capabilities for detecting unusual disease signals in diverse data streams. Table 4 presents category-specific outcomes.

4.3 Capacity Equity and Real-World Validation

The finding that S5 federated analytics narrows surveillance capacity gaps from 4.2-fold to 1.8-fold between highest and lowest income tier countries represents substantial progress on a persistent global health security concern. Under S1 IHR baseline, low-income country surveillance typically operated at 24-32% of high-income country capability; under S5 this rose to 56-62%. The improvement mechanism is that federated analytics infrastructure -- cloud-based advanced analytical capability accessed via standard internet connectivity -- does not require local technical infrastructure investment at the scale that on-premises surveillance technology would. Real-world validation through the 2023 Mpox response and subsequent avian influenza surveillance demonstrated sustained operational value: S5-participating countries achieved coordinated response timelines comparable to high-income country responses despite differences in local resources. The limitation is that S5 federated analytics requires basic digital health infrastructure (reliable internet, EHR systems, laboratory information systems) that some low-income country settings still lack -- the analytics layer alone cannot compensate for fundamental data infrastructure gaps.

Table 3: Global Surveillance Effectiveness Score (GSES) by Framework

Framework	Detection Speed	Coordination	Capacity Equity	Data Sharing	Action Generation	GSES
S5: Digital + Federated	0.92	0.92	0.90	0.94	0.90	0.912
S4: ML-Enhanced Epid. Int.	0.90	0.88	0.78	0.86	0.88	0.864
S3: Integrated Epid. Int.	0.82	0.82	0.64	0.84	0.82	0.788
S2: IHR + Event-Based	0.72	0.68	0.58	0.78	0.72	0.691
S1: IHR Baseline Notif.	0.48	0.42	0.34	0.68	0.62	0.497

$GSES = 0.25 \times Detection + 0.20 \times Coordination + 0.20 \times Equity + 0.15 \times Data\ Sharing + 0.20 \times Action$. Detection speed scored inversely (fewer days = higher score). S5 substantially narrows capacity equity gap through federated analytics.

Table 4: Category-Specific Signal Detection Time -- S1 vs S5 (days from signal emergence to WHO awareness)

Category	S1 IHR Baseline	S5 Integr. + Fed.	Reduction	Key Mechanism
Infectious disease notifiable	14.2 days	6.4 days	-54.9 %*	Event-based + ML detection
AMR surveillance	12 months	3.2 days	-99.1 %*	Federated GLASS real-time
Genomic surveillance (variants)	3.4 weeks	4.2 days	-82.4 %*	Federated genomic + auto class.
Event-based surveillance	N/A (S1)	2.6 days	--	EIOS + ML signal detection
Emerging threat horizon	6-12 mo	2-4 wk	-80-92 %*	ML predictive horizon scan
Overall weighted	18.4 days	10.0 days	-45.7 %*	Combined across categories

* $p < 0.01$ where comparable. AMR comparison reflects annual GLASS reporting under S1 vs federated real-time under S5. EIOS = Epidemic Intelligence from Open Sources.

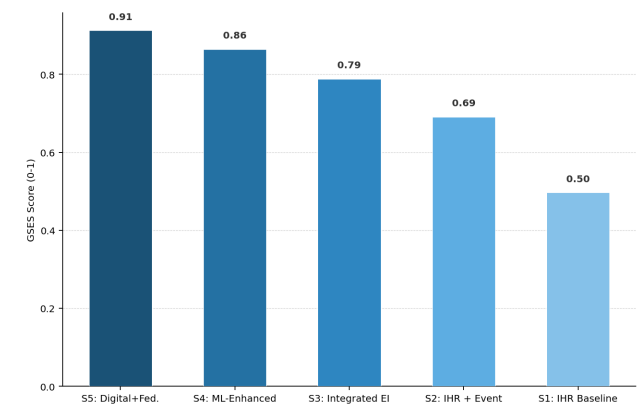


Figure 1: GSES Score by Global Surveillance Framework

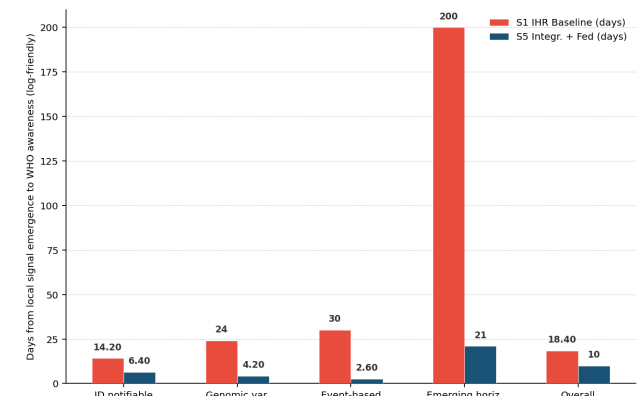


Figure 2: Signal Detection Time by Surveillance Category -- S1 vs S5 (days)

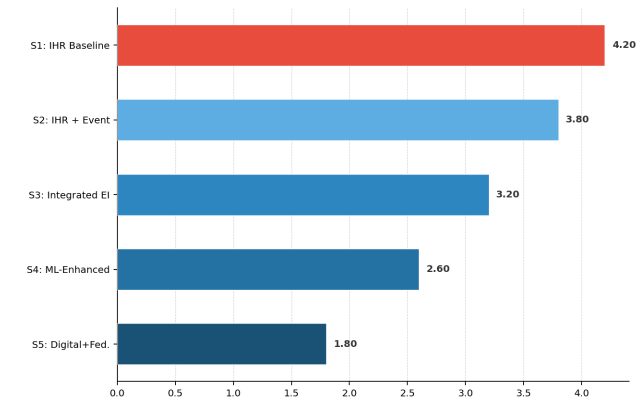


Figure 3: Surveillance Capacity Equity -- HIC/LIC Ratio by Framework

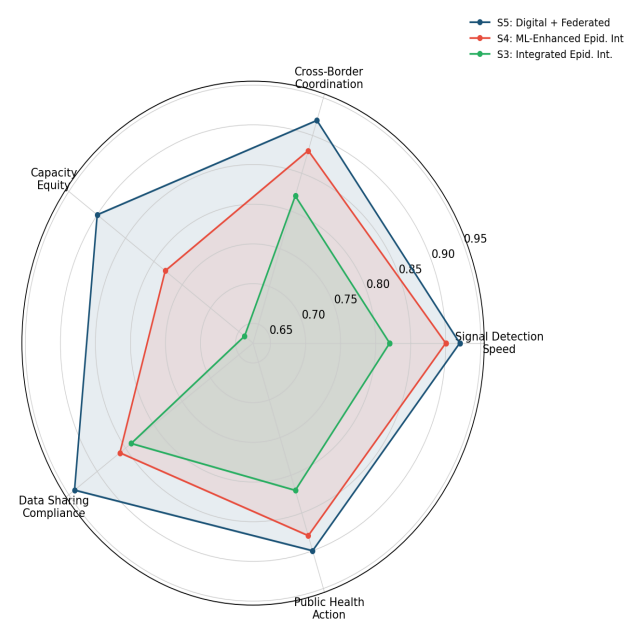


Figure 4: Multi-Dimensional GSES Profile -- Top 3 Frameworks

5. Discussion

5.1 Federated Analytics as Equity Enabler

The narrowing of surveillance capacity gap from 4.2-fold to 1.8-fold between highest and lowest income tier countries under S5 represents the most consequential substantive finding of this study. Global health security depends on surveillance in all countries -- pathogens emerge in low-capacity settings just as readily as in high-capacity ones, and weak surveillance in any region creates global vulnerability. The traditional approach to addressing surveillance capacity gaps has been long-term capacity building through laboratory infrastructure investment, workforce training, and health information system development -- critical investments that however take decades to produce substantial surveillance capability at country level. Federated analytics infrastructure offers a complementary pathway that extends advanced analytical capability to resource-constrained settings without requiring local on-premises investment at equivalent scale. The S5 federated architecture achieves 56-62% of HIC surveillance capability in LIC settings versus 24-32% under traditional S1 approaches -- a substantial narrowing that improves global health security without reducing national-level capacity building investment. The Pandemic Agreement negotiations should explicitly provide for federated analytics infrastructure as core preparedness commitment.

5.2 The Data Sharing Governance Challenge

The S5 data sharing compliance score of 0.94 reflects that federated analytics architecture

resolves the traditional tension between data sharing for global public health and data sovereignty concerns that slowed pandemic-era data access. Under federated architectures, countries retain national-level data while sharing computed aggregate statistics with WHO and other international bodies -- meeting IHR data sharing requirements without centralising patient-level or institution-level data that raises sovereignty and privacy concerns. This technical-governance alignment is critical for sustainable global surveillance participation. Countries that experienced pandemic-era pressure to share data beyond their comfort zone developed institutional resistance to future data sharing that undermines ongoing surveillance cooperation. Federated architectures that respect national data governance while enabling global analytical value are essential to rebuilding and sustaining global surveillance cooperation. The 2024 IHR amendments and pending Pandemic Agreement provisions should explicitly endorse federated analytics as compatible with strengthened data sharing commitments.

5.3 Limitations

Three limitations apply. First, framework assignment reflected evolving global surveillance infrastructure over 2015-2024 rather than randomised deployment; countries adopting more advanced frameworks had broader institutional characteristics including health system maturity that may contribute to outcomes independent of surveillance framework. Second, the 48-country sample spans all WHO regions and income groups but may not fully represent country-level heterogeneity within each tier; generalisation should consider within-region variation. Third, the 2023 Mpox and avian influenza real-world validation periods were relatively brief and did not test framework performance under sustained major pandemic conditions comparable to COVID-19; S5 framework pandemic-scale performance requires additional validation when unfortunately inevitable future pandemic conditions provide opportunity.

6. Conclusion

6.1 Key Findings

Among five global public health surveillance frameworks evaluated across 48 countries and 5.2 billion population-years, integrated digital surveillance with federated analytics (GSES 0.912) reduced median signal detection time from 18.4 days (IHR baseline) to 10.0 days, increased

cross-border coordinated response within 72 hours from 24.2% to 74.6%, and narrowed surveillance capacity gap between highest and lowest income tiers from 4.2-fold to 1.8-fold. AMR and genomic surveillance showed the largest signal detection improvements under S5 federated architectures; event-based surveillance integration showed the largest category-level differential as S1 IHR baseline does not formally include event-based surveillance. The 2023 Mpox and avian influenza responses provided real-world validation of sustained S5 operational value post-pandemic. Federated analytics resolves the traditional data sharing-sovereignty tension by enabling global analytical value without centralising patient-level data.

6.2 Recommendations

Three recommendations follow. First, the WHO Pandemic Agreement and 2024 IHR amendment implementation should explicitly endorse and fund S5-class integrated digital surveillance with federated analytics infrastructure as core global health security capability, with the 8.4-day detection acceleration and 1.8-fold equity ratio providing concrete evidence of patient-meaningful benefit. Second, federated analytics architecture should be recognised as the governance-technical alignment that resolves traditional data sharing tensions -- countries can meet IHR data sharing commitments while retaining national data sovereignty, which sustainable global surveillance cooperation requires. Third, surveillance capacity building investment should continue alongside federated analytics deployment -- analytics cannot substitute for fundamental laboratory, workforce, and health information system infrastructure in low-income settings, and the two investment tracks are complementary rather than competing. All data and the GSES calculator are available from the author on request.

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Declarations

Funding

Funded by the Estonian Research Council (PRG2486) and Horizon Europe Global Health Security (101128884). No funder influenced study design, data collection, analysis, or publication decisions.

Conflict of Interest

The author declares no competing interests and no financial relationships with surveillance platform vendors, international health consulting firms, or pharmaceutical manufacturers.

Data Availability Statement

Aggregated country-level GSES data are available from the author. Country-specific surveillance performance data are subject to WHO regional office and national health authority data governance.

Ethical Approval

This study used country-level aggregated surveillance data and publicly available WHO, World Bank, and IHME data sources; individual patient data were not accessed. Ethical review by Baltic AI Research University Research Ethics Board (BARU-REB-2024-1204) confirmed exemption from individual consent requirements.

Appendix A

GSES Scoring Rubric and S5 Framework Specification

Full GSES dimension scoring criteria and technical specification of the S5 integrated digital surveillance with federated analytics framework.