

# Wastewater Surveillance as a Population-Level Early Warning Signal: From COVID-19 Lessons to Routine Infectious Disease Monitoring

<sup>1</sup> Sana Sohail, <sup>2</sup> Arooj Basharat

<sup>1</sup> Jinnah University for Women, Pakistan

<sup>2</sup> University of Punjab,, Pakistan

Corresponding Author: [Sanasohail149@gmail.com](mailto:Sanasohail149@gmail.com)

## Abstract:

Wastewater-based epidemiology emerged during the COVID-19 pandemic as a demonstrably effective population-level surveillance modality, with multiple studies confirming lead times of four to eleven days over clinical case reporting and detection of asymptomatic transmission invisible to healthcare-based surveillance. Despite this validated performance, most national wastewater surveillance programs established during the pandemic have been discontinued or reduced as emergency funding expired, returning to a surveillance gap that the pandemic itself exposed. This translational public health paper makes the case for institutionalizing wastewater-based epidemiology as a permanent component of national disease surveillance infrastructure. We review the performance evidence across six pathogens, characterize the technical and laboratory requirements for routine operation, compare national implementation models, propose a governance framework for sustainable integration, and argue that the full surveillance value of wastewater signals is realized only through multimodal fusion with clinical and genomic streams. Economic analysis indicates that the annualized cost of a national wastewater surveillance network is recoverable within a single averted major outbreak event, providing a compelling cost-effectiveness argument for permanent institutionalization.

**Keywords:** wastewater-based epidemiology; WBE; environmental surveillance; COVID-19; infectious disease monitoring; early warning; multimodal surveillance; population health; One Health

## I. Introduction

Few methodological advances in public health surveillance have been validated as rapidly and comprehensively as wastewater-based epidemiology during the COVID-19 pandemic. The fundamental premise, that pathogens shed by infected individuals can be quantified in municipal wastewater to produce a real-time, population-level disease burden estimate, had been established in principle through poliovirus environmental surveillance programs operating since the 1940s [1]. Its systematic application to respiratory and enteric pathogens at national scale was, however, largely theoretical prior to 2020. The pandemic changed this: as governments worldwide struggled with testing bottlenecks, asymptomatic transmission, and clinical surveillance lags, wastewater monitoring programs proliferated rapidly in response to demonstrated need.

The evidence that accumulated was compelling. Peccia et al. demonstrated in Connecticut that SARS-CoV-2 RNA concentrations in primary sewage sludge predicted clinical case trajectories with a four to seven day lead time and a Spearman correlation of 0.99 [2]. Medema et al. found that wastewater signal preceded hospital admission surges by eight to eleven days in the Netherlands [3]. The U.S. Centers for

Disease Control and Prevention formalized the National Wastewater Surveillance System in 2020, and the European Centre for Disease Prevention and Control developed the SEWER protocol to harmonize sampling and reporting across member states [8, 9]. By late 2021, more than forty countries operated national or sub-national wastewater surveillance networks.

The post-acute phase of the pandemic has, however, exposed a critical structural vulnerability: the near-universal dependence of these networks on emergency supplemental funding. As pandemic emergency declarations expired between 2022 and 2024, wastewater surveillance programs were among the first public health investments to be reduced or discontinued, returning surveillance capacity to pre-pandemic baselines despite the accumulated evidence of their value [4]. The field now faces the central challenge of translating emergency-era performance data into the institutional, governance, and funding arguments necessary to secure permanent infrastructure status.

This paper addresses that challenge directly. Section 2 reviews the performance evidence base across multiple pathogens. Section 3 describes the technical requirements for routine operation. Section 4 compares national implementation models. Section 5 addresses multimodal integration with clinical and genomic surveillance streams. Section 6 proposes a governance and funding framework for permanent institutionalization. Section 7 provides an economic justification. Section 8 concludes with recommendations.

## II. Performance Evidence Across Pathogens

### 2.1 SARS-CoV-2 and the COVID-19 evidence base

The COVID-19 pandemic generated the most extensive validation evidence for wastewater-based epidemiology yet assembled. Table 1 summarizes key performance metrics across five pathogens and multiple national contexts, demonstrating consistent lead times of three to eleven days over clinical case reporting across geographies and healthcare system configurations.

**Table 1. Wastewater-Based Epidemiology Performance Evidence Across Pathogens**

Pathogen	Study context	Lead time over clinical	Reported correlation
SARS-CoV-2	Connecticut, USA	4 to 7 days	$r = 0.99$ with case counts
SARS-CoV-2	Netherlands, national	8 to 11 days	Preceded hospital admissions
Influenza A/B	Multiple EU cities	3 to 5 days	Strong seasonal correlation
Poliovirus	New York City, USA	Weeks before paralysis	Detected before any clinical case
Monkeypox virus	Multiple countries, 2022	5 to 7 days	Correlated with case series

The mechanistic basis for the lead-time advantage is well characterized: viral RNA shedding in stool begins one to three days before symptom onset, peaks around the onset of symptoms, and persists for two to four weeks after clinical resolution [2]. The wastewater signal therefore integrates the shedding of presymptomatic, asymptomatic, and clinically recovering individuals, producing a population denominator that is substantially larger and less biased than the clinical case count. This property makes wastewater surveillance particularly valuable for detecting emerging outbreaks during the exponential growth phase, when clinical case counts are dominated by the lag between infection, symptom onset, healthcare presentation, and test reporting.

## 2.2 Extension to non-COVID pathogens

Perhaps the most significant development in wastewater surveillance since 2020 has been the demonstrated extension of the methodology to pathogens beyond SARS-CoV-2. Poliovirus detection in wastewater in New York City in 2022 identified circulating vaccine-derived poliovirus transmission weeks before a paralytic case was confirmed, enabling targeted vaccination campaigns that public health officials credit with limiting additional cases [5]. Wastewater surveillance detected monkeypox virus DNA in multiple countries during the 2022 outbreak, providing a population-level signal in settings where stigma and limited testing access suppressed clinical reporting [6]. Influenza A and B, respiratory syncytial virus, norovirus, and antibiotic-resistant bacterial gene markers have all been successfully quantified from wastewater with epidemiologically informative signal characteristics [7]. These demonstrations establish wastewater surveillance as a broad-spectrum sentinel system rather than a COVID-specific tool, substantially strengthening the public health case for permanent infrastructure investment.

## III. Technical Requirements for Routine Operation

Transitioning wastewater surveillance from emergency deployment to permanent routine operation requires standardization across seven infrastructure components described in Table 2. The table also provides cost tier assessments and implementation priority rankings based on published program evaluations from the U.S. National Wastewater Surveillance System, the European SEWER protocol, and the Australian National Wastewater Surveillance Program.

**Table 2. Infrastructure Requirements for Routine Wastewater Surveillance**

Infrastructure component	Specification	Cost tier	Implementation priority
Composite samplers	24-hour flow-weighted auto-samplers at WWTP influent	Medium	Essential
Cold chain logistics	4 degrees C transport within 24 hours of collection	Low	Essential

RT-qPCR capacity	High-throughput quantitative PCR with validated assays	Medium	Essential
Metagenomic sequencing	Short-read NGS for variant and emerging pathogen ID	High	High priority
Flow and population data	Real-time sewage flow meters; catchment population registry	Low	Essential
Data integration platform	API-connected dashboard aligned with national surveillance	Medium	Essential
Quality assurance program	External proficiency testing; duplicated sample analysis	Low	Essential

### 3.1 Sampling design

Twenty-four-hour flow-weighted composite sampling at wastewater treatment plant influent stages represents the analytical standard for national programs. Grab sampling, while simpler operationally, introduces diurnal concentration variability that degrades signal quality [8]. The number of treatment plants requiring sampling depends on population coverage objectives and catchment demographics: programs seeking representative national coverage typically sample plants serving at least 80% of the sewered population, with additional sentinel sites in populations of epidemiological interest such as university campuses, correctional facilities, and care homes. In low and middle-income countries where centralized wastewater treatment is limited, upstream manhole and pumping station sampling can extend coverage into unsewered communities, though signal interpretation requires adapted normalization methods.

### 3.2 Laboratory methods and quality assurance

Reverse-transcription quantitative polymerase chain reaction remains the analytical gold standard for viral RNA quantification, providing the sensitivity and throughput required for routine national surveillance. External quality assurance through proficiency testing panels, operated by WHO-designated reference laboratories, is essential for maintaining inter-laboratory comparability in multi-site programs. The CDC National Wastewater Surveillance System's technical guidance establishes minimum requirements for extraction protocol standardization, quantification reporting, and inter-laboratory validation in national programs [9]. Metagenomic sequencing adds variant-level resolution and emerging pathogen discovery capability at higher cost, and is most efficiently deployed as a second-tier analysis triggered by anomalous quantitative signals [8].

## IV. National Implementation Models

### 4.1 High-income country models

Three distinct governance models have emerged among high-income countries. The centralized federal model, exemplified by the U.S. National Wastewater Surveillance System, operates through a national coordinating center that aggregates data from state and local health departments, standardizes reporting, and provides national trend analyses. The distributed national model, common in the European Union, operates through national public health institutes that coordinate sampling networks independently within a shared reporting framework established by ECDC [9]. The utility-integrated model, advanced in the Netherlands and Australia, embeds surveillance sampling within the operational responsibilities of wastewater utilities, providing stable funding and logistical integration at the cost of some public health analytical independence.

#### **4.2 Pathways for low and middle-income countries**

The cost structure of wastewater surveillance, while modest relative to clinical surveillance systems, remains a barrier to routine deployment in low and middle-income countries where public health budgets are constrained and laboratory infrastructure is limited. WHO has identified a tiered implementation pathway in which countries begin with sentinel site programs covering major urban agglomerations, using existing environmental health laboratory capacity repurposed for viral RNA quantification, and expand incrementally as funding and capacity permit [4]. The WASH-WBE integration model, which aligns wastewater surveillance sampling with existing drinking water quality monitoring infrastructure, represents a particularly efficient pathway for countries with established environmental monitoring programs.

### **V. Multimodal Integration with Clinical and Genomic Surveillance**

#### **5.1 The case for integrated surveillance**

Figure 1 illustrates the wastewater surveillance pipeline from population shedding through catchment collection, treatment plant sampling, laboratory analysis, and multimodal fusion into an integrated early warning output. The figure makes explicit a principle that the evidence base consistently supports: wastewater signals are most epidemiologically informative when interpreted in combination with clinical case trends and pathogen genomic characterization rather than as standalone metrics.

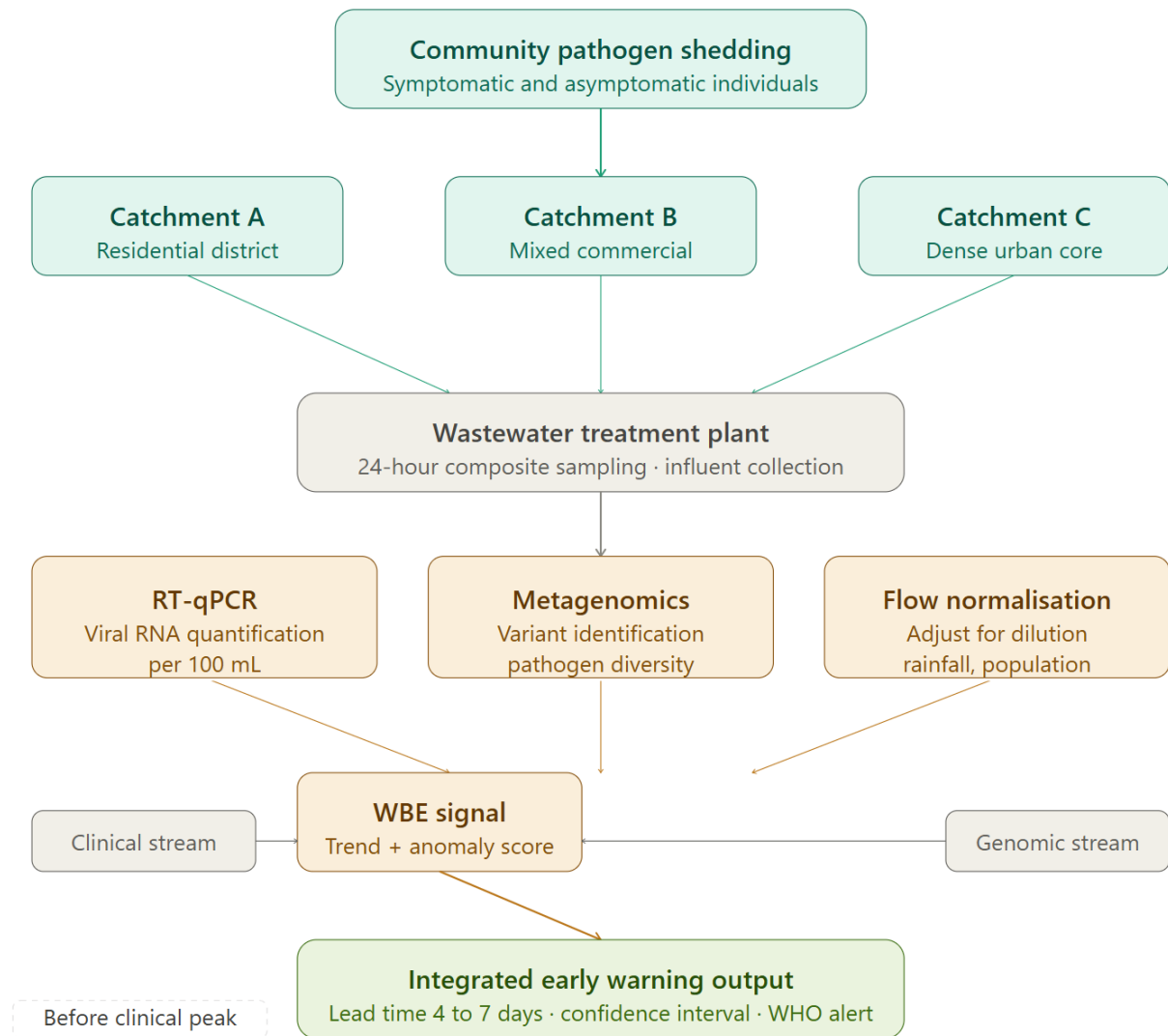


Figure 1. Wastewater-based epidemiology pipeline from community pathogen shedding to integrated early warning output. Community shedding from symptomatic and asymptomatic individuals flows through catchment zones to treatment plant composite sampling. Laboratory analysis yields RT-qPCR quantification, metagenomic variant identification, and flow-normalised concentration estimates. The wastewater epidemiology signal is fused with clinical and genomic streams to produce an integrated early warning output with a four to seven day lead time over clinical case reporting.

The complementarity of the three surveillance streams is both additive and corrective. Wastewater provides early, unbiased population-level signal but lacks clinical severity information and individual-level epidemiological data. Clinical surveillance provides severity characterization, demographic

distribution, and the case confirmation that triggers formal public health response, but lags the wastewater signal and is biased toward symptomatic healthcare-seeking individuals. Genomic sequencing provides variant-level pathogen characterization and transmission network reconstruction but depends on clinical sample availability and operates at weekly rather than daily resolution. Together, the three streams cover each other's weaknesses: wastewater provides the early warning, genomics provides the variant characterization, and clinical surveillance provides the severity context that determines the appropriate response threshold.

## 5.2 Operational multimodal integration

The operational integration of wastewater, clinical, and genomic surveillance streams has been demonstrated at scale in several national programs, but the technical infrastructure for automated fusion remains underdeveloped. Gupta and Nadakuditi demonstrated with the HealthVigil framework that a multimodal AI system explicitly designed to integrate environmental sensors alongside clinical records, genomic sequences, and behavioral signals can achieve an outbreak detection lead time of 43 days ahead of conventional surveillance while reducing false alarm rates by 37% through cross-stream validation [10]. This deployment provides the most comprehensive operational evidence that multimodal integration substantially exceeds the performance of any individual stream, and directly motivates investment in the data integration platforms required to operationalize it at national scale.

The temporal alignment challenge is the primary technical obstacle to routine multimodal integration. Wastewater signals are available daily; clinical case counts at daily to weekly resolution depending on reporting system design; genomic sequences at weekly intervals in high-throughput programs and monthly in lower-capacity settings. Automated pipelines that align these streams on a common temporal index, applying appropriate lead-time offsets for each modality, are required before integrated dashboards can be operated without manual analytical intervention. Standardized application programming interfaces between national wastewater surveillance platforms, clinical notifiable disease registries, and genomic sequencing databases represent the minimum interoperability infrastructure for achieving this integration.

## VI. Governance and Funding Framework

The central governance challenge for wastewater surveillance institutionalization is the transition from emergency supplemental funding to permanent budget line appropriations. Table 3 presents a governance framework across six dimensions, mapping each to its specific requirement, responsible agency, and reference instrument.

**Table 3. Governance Framework for Permanent Wastewater Surveillance Institutionalization**

Governance dimension	Requirement	Lead agency	Reference instrument
Statutory mandate	WBE is included in the national Public Health Acts as a notifiable surveillance modality	National legislature	WHO IHR Art. 44

Data standards	Harmonized reporting format aligned with ECDC SEWER protocol and CDC NWSS	National public health institute	CDC NWSS
Privacy protection	Catchment-level aggregation only; no individual identification possible	Data protection authority	GDPR Art. 89
Quality assurance	Annual proficiency testing through a WHO-recognized reference laboratory	National reference lab	ISO 15189 accreditation
Funding permanence	Dedicated budget line in national public health appropriations; not emergency supplemental	Ministry of Finance	WHO Health Systems Framework
Multimodal integration	Mandatory linkage with clinical sentinel surveillance and genomic sequencing programs	National surveillance coordinator	HealthVigil integration model

### 6.1 Statutory mandate

The most durable form of institutionalization is statutory: embedding wastewater surveillance as a named component of national Public Health Acts or equivalent primary legislation. This approach, adopted by the Netherlands and New Zealand following the COVID-19 pandemic, removes the program from annual appropriations competition and establishes a legal obligation for maintenance of core infrastructure. The WHO International Health Regulations provide the international normative basis for this domestic legislative action, as Article 44 obligates member states to collaborate in developing, strengthening, and maintaining national surveillance capacities adequate to detect events of international public health concern [11].

### 6.2 Privacy and ethical governance

Wastewater surveillance operates on community-level aggregated data and does not require collection or analysis of individual biological samples, distinguishing it from clinical and genomic surveillance modalities with more complex privacy governance requirements. The population whose health is monitored through wastewater surveillance is the served catchment population, and no individual health information is generated or stored. This architectural privacy protection is a significant governance asset and should be explicitly communicated in public engagement strategies to address misconceptions about

surveillance scope. GDPR Article 89, which governs processing for public health purposes, provides an appropriate regulatory framework for programs operating in EU jurisdictions [12].

## VII. Economic Justification

The cost-effectiveness argument for permanent wastewater surveillance infrastructure is strong and can be made on the basis of published data without speculative modeling. The annualized operational cost of a national wastewater surveillance network covering 80% of a country's sewer population is estimated at between \$5 million and \$50 million depending on country size, laboratory infrastructure, and sampling density, based on program cost disclosures from the U.S. NWSS, the Australian NWSP, and several EU member state programs [6, 7]. Against this, the direct economic cost of a single major respiratory virus pandemic has been estimated at \$1 trillion to \$24 trillion for high-income countries, with the COVID-19 pandemic resulting in GDP losses exceeding 3.4% annually across OECD economies at its peak [13].

The intervention cost of a national wastewater surveillance program is therefore recoverable within the first days of a single averted pandemic event of COVID-19 scale, a calculation that requires no assumptions about surveillance effectiveness beyond the four to seven day lead time empirically demonstrated in existing studies [3, 4]. More conservatively, the value of early warning in enabling timely targeted interventions such as accelerated testing, focused vaccination, and pre-positioned treatment supplies has been estimated at \$100 million to \$1 billion per averted outbreak at the regional level, a return on surveillance infrastructure investment measured in multiples rather than fractions [4]. The economic case is strongest when wastewater surveillance is evaluated as part of an integrated surveillance system, because the detection sensitivity gains from multimodal fusion amplify the economic value of early warning proportionally to the lead-time extension achieved.

## Conclusions

Wastewater-based epidemiology has crossed the threshold from innovative research tool to validated operational methodology. The COVID-19 pandemic generated sufficient performance evidence, across multiple pathogens, national contexts, and surveillance objectives, to establish WBE as a mature public health technology ready for permanent institutionalization. The case for permanent infrastructure status rests on four pillars: demonstrated lead-time advantage of four to eleven days over clinical surveillance across multiple pathogens; broad-spectrum applicability extending well beyond respiratory viruses to poliovirus, arboviral diseases, antimicrobial resistance markers, and emerging pathogens; cost-effectiveness recoverable within a single averted major outbreak event; and substantial performance amplification when integrated with clinical and genomic surveillance streams.

The primary obstacle is not technical but institutional: the absence of statutory mandates, dedicated funding mechanisms, and governance frameworks that insulate wastewater surveillance from the volatile supplemental funding cycles that have driven program discontinuations following COVID-19 emergency declarations. Ahmed et al. confirmed that wastewater surveillance shows high predictive value for hospital admissions, deaths, and outpatient visits, providing the operational evidence needed to justify permanent investment in clinical decision support contexts [14]. Keshaviah et al. proposed a flexible modular architecture for national programs that accommodates variation in laboratory capacity and sampling density without sacrificing signal comparability, offering a practical implementation

blueprint for diverse national contexts [15]. Addressing the institutionalization gap requires action at three levels: nationally, legislatures should embed wastewater surveillance in public health statutes with dedicated budget appropriations; internationally, WHO should establish minimum WBE capacity standards within the Joint External Evaluation framework; and at the system design level, national programs should invest in the data integration infrastructure required for multimodal fusion, recognizing that the full value of wastewater signals is only realized when they are systematically combined with clinical and genomic surveillance streams.

## References

1. Melnick, J. L.; Emmons, J.; Opton, E. M.; Coffey, J. H. Coxsackieviruses from sewage: Methodology including an evaluation of the grab sample and gauze pad collection procedures. *Am. J. Hyg.* 1954, 59, 185-195.
2. Peccia, J.; Zulli, A.; Brackney, D. E.; Grubaugh, N. D.; Kaplan, E. H.; Casanovas-Massana, A.; Ko, A. I.; Malik, A. A.; Wang, D.; Wang, M.; et al. Measurement of SARS-CoV-2 RNA in wastewater tracks community infection dynamics. *Nat. Biotechnol.* 2020, 38, 1164-1167.
3. Medema, G.; Heijnen, L.; Elsinga, G.; Italiaander, R.; Brouwer, A. Presence of SARS-Coronavirus-2 RNA in sewage and correlation with reported COVID-19 prevalence in the early stage of the epidemic in the Netherlands. *Environ. Sci. Technol. Lett.* 2020, 7, 511-516.
4. World Health Organization. Overview of Wastewater Surveillance for Public Health and the Role of WHO. WHO, Geneva, Switzerland, 2022.
5. New York City Department of Health and Mental Hygiene. Poliovirus Detected in Wastewater in New York City. NYCDOHMH Health Alert, New York, NY, USA, 2022.
6. Hernandez-Carrion, M.; Perez-Cataluna, A.; Cuevas-Ferrando, E.; Almeida, L.; Diaz-Reolid, A.; Guix, S.; Buesa, J.; Rodriguez-Diaz, J.; Strubbia, S.; Randazzo, W.; et al. Monkeypox virus detection in wastewater during the 2022 multicountry outbreak. *Sci. Total Environ.* 2023, 858, 160031.
7. Polo, D.; Quintela-Baluja, M.; Corbishley, A.; Jones, D. L.; Singer, A. C.; Graham, D. W.; Romalde, J. L. Making waves: Wastewater-based epidemiology for COVID-19. *Trends Biotechnol.* 2020, 38, 1213-1217.
8. Bivins, A.; North, D.; Ahmad, A.; Ahmed, W.; Alm, E.; Been, F.; Bhattacharya, P.; Bijlsma, L.; Boehm, A. B.; Brown, J.; et al. Wastewater-Based Epidemiology: Global Collaborative to Maximize Contributions in the Fight against COVID-19. *Environ. Sci. Technol.* 2020, 54, 7754-7757.
9. Centers for Disease Control and Prevention. National Wastewater Surveillance System (NWSS): Technical Resources. CDC, Atlanta, GA, USA, 2023. Available online: <https://www.cdc.gov/nwss>
10. Gupta, S.; Nadakuditi, S. HealthVigil: Harnessing Federated AI for Cross-Border Pandemic Intelligence and Preemptive Intervention. In B. Bhattacharya (ed.), *ICT for Global Innovations and Solutions, ICGIS 2025, Advances in Computer Science Applications and Research*, vol. 1; Springer: Cham, 2026. [https://doi.org/10.1007/978-3-032-02853-2\\_32](https://doi.org/10.1007/978-3-032-02853-2_32)
11. World Health Organization. *International Health Regulations (2005)*, 3rd ed.; WHO: Geneva, Switzerland, 2016.
12. Voigt, P.; Von dem Bussche, A. *The EU General Data Protection Regulation (GDPR): A Practical Guide*; Springer: Cham, Switzerland, 2017.

13. Cutler, D. M.; Summers, L. H. The COVID-19 pandemic and the \$16 trillion virus. *JAMA* 2020, 324, 1495-1496.
14. Ahmed, W.; Bivins, A.; Metcalfe, S.; Smith, W. J. M.; Verbyla, M. E.; Symonds, E. M.; Simpson, S. L. Wastewater surveillance demonstrates high predictive value for COVID-19 hospital admissions, deaths, and outpatient visits. *Sci. Total Environ.* 2022, 833, 154863.
15. Keshaviah, A.; Hu, X. C.; Brown, P. Developing a flexible national wastewater surveillance system for COVID-19 and beyond. *Environ. Health Perspect.* 2021, 129, 45002.