ACCSCIENCE PUBLISHING

Asian Journal of Water, Environment and Pollution

REVIEW ARTICLE

Wastewater-based epidemiology for early detection of viral outbreaks: Global evidence and insights from the Philippines

Ysaren Mae Paclauna[1†], Gabrielle Bennet Mancilla[1†], Onikka Bernice E. Jara[1], Jomar Adams Ganding[1*], Nancy Choon-Si Ng[2,3], and Shealtiel William S. Chan[4,5]

[1]Department of Medical Technology, School of Health Sciences, Mapúa University, Manila, Philippines

[2]Department of Medical Education, Sir Jeffrey Cheah Sunway Medical School, Faculty of Medical and Life Sciences, Sunway University, Petaling Jaya, Selangor, Malaysia

[3]Faculty of Education and Liberal Arts, INTI International University, Nilai, Malaysia

[4]Department of Biology, School of Health Sciences, Mapúa University, Manila, Philippines

[5]School of Chemical, Biological, and Materials Engineering and Sciences, Mapúa University, Manila, Philippines

[†]*These authors contributed equally to this work.*

***Corresponding author:**
Jomar Adams Ganding
(jaganding@mapua.edu.ph)

Citation: Paclauna YM, Mancilla GB, Jara OBE, Ganding JA, Ng NC-S, Chan SWS. Wastewater-based epidemiology for early detection of viral outbreaks: Global evidence and insights from the Philippines. *Asian Journal of Water, Environment and Pollution.* 2026;23(3):025460351. doi: 10.36922/AJWEP025460351

Received: November 13, 2025

Revised: January 8, 2026

Accepted: January 13, 2026

Published online: March 17, 2025

Abstract

The COVID-19 pandemic accelerated global interest in wastewater-based epidemiology (WBE) as a complementary public health surveillance tool, capable of capturing both symptomatic and asymptomatic infections and providing earlier warnings than clinical testing in many contexts. While most established WBE programs originate from highly developed, well-resourced settings, far less is known about how WBE can be realistically developed, governed, and sustained in countries with fragmented sanitation networks and uneven laboratory capacity. Using the Philippines as a case study, this article synthesizes published studies, registered initiatives, institutional reports, and emerging government and utility-led programs to characterize an evolving national WBE landscape. Philippine pilots demonstrate feasibility for SARS-CoV-2 and antimicrobial resistance surveillance, while also revealing technical limitations related to detection sensitivity, environmental degradation of signals, and challenges posed by low sewerage coverage. Regional experience from the Association of Southeast Asian Nations countries indicates that wastewater and environmental surveillance can be operationalized even in mixed or informal sanitation environments, reinforcing the potential relevance of WBE in comparable settings. Building on these insights, this study outlines policy and research priorities, including transitioning from COVID-specific to multi-pathogen platforms, adopting sanitation-appropriate sampling strategies, investing in regional laboratory hubs and quality assurance, linking WBE outputs to decision-support systems, strengthening governance and data stewardship, addressing ethics and equity, and securing sustainable financing. Together, these considerations position WBE as a promising but still developing pillar of One Health surveillance in the Philippines and similar lower–middle-income contexts.

Keywords: Association of Southeast Asian Nations; Environmental surveillance; One Health; Philippines; Wastewater-based epidemiology

1. Introduction

Viral outbreaks continue to threaten global health, and COVID-19 has exposed the limitations of surveillance systems that rely heavily on symptomatic clinical testing, contact tracing, and health facility reports. These approaches remain essential, but they are often constrained by delayed reporting, limited access to diagnostics, and under-detection of asymptomatic infections, particularly in low- and middle-income countries (LMICs).[1,2] Wastewater-based epidemiology (WBE) emerged during the pandemic as a powerful complementary tool, detecting SARS-CoV-2 RNA in sewage days to weeks before spikes in reported cases and hospitalizations.[3,4]

Since 2020, investments in WBE have transformed what was once a niche technique for poliovirus into a broader environmental surveillance platform. Programs across Europe, North America, Asia, and the Western Pacific now use WBE for multiple respiratory viruses, enteric pathogens, and antimicrobial resistance genes. Several countries have integrated wastewater data into dashboards that inform testing strategies, vaccination campaigns, and resource allocation.[5–8] The World Health Organization (WHO)'s 2024 guidance on wastewater and environmental surveillance (WES) explicitly positions WBE as a component of multi-pathogen surveillance, to be linked with routine communicable disease monitoring and health security plans.[9] Most existing global reviews[1,2,6], however, primarily focus on methodological advances, pathogen detection performance, and large-scale programs in highly sewered or well-resourced settings. Less attention has been given to how WBE can be realistically implemented, governed, and sustained in countries with fragmented sanitation systems, decentralized institutional structures, and uneven laboratory capacity.

Despite growing global adoption of WBE, its application in the Philippines remains at an early and exploratory stage. To date, wastewater surveillance efforts have been limited primarily to sentinel pilot studies, short-term research projects, and institution-led initiatives rather than nationwide deployment. In this study, the term "Philippine experience" does not imply a comprehensive national surveillance program or population-representative epidemiologic coverage. Instead, it refers to an emerging national landscape in which pilot studies, capacity-building initiatives, and early policy-oriented collaborations collectively illustrate how WBE is being explored, adapted, and constrained within the Philippine context. By explicitly situating WBE within the realities of an archipelagic LMIC setting, which is characterized by low sewerage coverage, climatic vulnerability, and complex governance arrangements, this study aims to complement global reviews by offering a context-sensitive synthesis with policy relevance. By synthesizing these early experiences alongside global lessons, this article seeks to identify context-specific opportunities, structural limitations, and pathways for scaling WBE in a lower–middle-income, archipelagic setting.

This study was developed through a structured narrative synthesis of published literature relevant to WBE in the Philippine context. A focused literature search was conducted utilizing the Scopus, PubMed, and the Directory of Open Access Journals databases. Search phrases consisted of various combinations of the following keywords: "wastewater-based epidemiology," "wastewater surveillance," "Philippines," "SARS-CoV-2," "antibiotic resistance," "enteric viruses," and "environmental virology." In addition, registered Philippine research initiatives and publicly available institutional reports were included to capture ongoing surveillance activities that may not yet be represented in the peer-reviewed literature.

2. Wastewater-based epidemiology

2.1. Global evolution of wastewater-based epidemiology

The origins of WBE trace back to well before the advent of modern virology. In the 19th century, John Snow's investigation of cholera in London demonstrated that a contaminated water pump could reveal underlying patterns of disease transmission within a community. His findings highlighted the capacity of shared water systems to reflect and shape population-level health risks. In the decades that followed, early efforts to detect poliovirus in sewage marked one of the first sustained applications of environmental surveillance. These studies showed that poliovirus could be detected in wastewater before increases in reported clinical cases, suggesting the potential of wastewater monitoring to anticipate outbreaks and support timely public health responses.[1]

The COVID-19 pandemic catalyzed an unprecedented global expansion of WBE. Proof-of-concept studies rapidly demonstrated SARS-CoV-2 RNA detection in raw wastewater[10,11] and many programs showed that viral loads in sewage correlated with case counts and hospitalizations, often with several days of lead time.[4,12] In Barcelona, SARS-CoV-2 was detected in wastewater 41 days prior to the first reported clinical cases, underscoring its potential as an early warning indicator.[3]

Water-based epidemiology methods typically involve composite sampling at wastewater treatment plants or sewer interceptors, sample concentration, and RNA extraction and quantification using reverse transcription quantitative polymerase chain reaction (RT-qPCR), increasingly complemented by high-throughput sequencing for variant tracking.[13,14] Advances in bioinformatics and lineage deconvolution, such as the HERCULES framework, have improved the ability to characterize viral populations and identify novel mutations directly from wastewater.[15] Alongside these technical advances, frameworks have emerged for integrating WBE into public health decision-making, exemplified by Arizona's WATERS program.[16]

These developments reposition WBE as a mainstream surveillance tool rather than a pandemic curiosity. However, converting pilot studies conducted during crises into sustainable, multi-pathogen systems requires attention to sampling strategy, network coverage, laboratory quality assurance, and—importantly—governance and communication.[17–19]

2.2. Emerging wastewater surveillance in the Philippines: Current initiatives and evidence

To contextualize WBE in the Philippines, we mapped existing and emerging wastewater surveillance activities that have generated, or are positioned to generate, population-level pathogen signals. Although only two initiatives have thus far produced peer-reviewed epidemiologic analyses of viral detection in wastewater, these studies represent only a subset of ongoing and developing efforts. Additional activities, such as antimicrobial resistance surveillance, utility-academic collaborations, and government-funded research programs, have contributed to the operational, methodological, and infrastructural foundations of WBE, but are primarily documented in institutional reports, registered research initiatives, and conference proceedings. Collectively, these efforts constitute an early but meaningful national surveillance landscape rather than isolated or ad hoc pilots.

Table 1 summarizes identified Philippine sentinel WBE sites based on published literature, registered research initiatives, institutional reports, and publicly disclosed utility–academic collaborations. Collectively, these nodes indicate an emerging national surveillance topology capable of supporting decentralized, regionally responsive wastewater-based pathogen monitoring.

Beyond viral surveillance, the Philippine WBE has also been applied to antimicrobial resistance monitoring. In several studies conducted in Metro Manila, wastewater from hospitals was analyzed, documenting the presence of clinically relevant extended-spectrum β-lactamase genes (blaCTX-M-1, blaCTX-M-9, blaTEM-1) in *Escherichia coli* isolates. These findings demonstrate the feasibility of wastewater-based antimicrobial resistance surveillance in urban Philippine settings.[20,21]

The limited number of peer-reviewed WBE studies in the Philippines reflects the nascency of the field rather than an absence of surveillance activity. Consequently, this study emphasizes institutional readiness, governance considerations, and feasibility constraints rather than national prevalence estimates or predictive performance metrics. As additional Philippine wastewater surveillance initiatives mature and generate peer-reviewed outputs, future syntheses will be better positioned to evaluate the epidemiologic validity and cost-effectiveness of these initiatives at scale.

3. Water-based epidemiology in a post-COVID world: Multi-pathogen and One Health dimensions

In the post-COVID period, WBE is being extended to a broader range of pathogens. Recent work has systematically reviewed WBE for influenza viruses, demonstrating good concordance between wastewater signals and clinical

Table 1. Identified sentinel and emerging wastewater-based epidemiology initiatives in the Philippines

Location	Institution	Status	Primary pathogen/markers	Year
Davao City	UP Mindanao	Pilot epidemiologic surveillance	SARS-CoV-2	2022
Metro Manila	UP NIH	Pilot epidemiologic surveillance	SARS-CoV-2	2021
Metro Manila (Hospital-based)	UP and FEU	Published AMR environmental surveillance	ESBL-producing *E. coli* (blaCTX-M, blaTEM)	2022–2023
Metro Manila	Manila Water/ADB/Emory University	Ongoing implementation	SARS-CoV-2	2023

Abbreviations: ADB: Asian Development Bank; AMR: Antimicrobial resistance; blaCTX-M: CTX-M beta-lactamase gene; blaTEM: TEM beta-lactamase gene; *E. coli*: *Escherichia coli*; ESBL: Extended-spectrum β-lactamase; FEU: Far Eastern University; NIH: National Institutes of Health (Philippines); RT-qPCR: Reverse transcription quantitative polymerase chain reaction; SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2; UP: University of the Philippines; WBE: Wastewater-based epidemiology.

surveillance, and highlighting its utility for tracking seasonal dynamics and the burden of vaccine-preventable diseases.[5,22,23] Wastewater surveillance for measles and Mpox has also been piloted, with encouraging sensitivity for detecting community transmission and potential use for early detection in settings with incomplete clinical reporting.[24]

Beyond respiratory viruses, WBE is now used for enteric viruses, antimicrobial resistance genes, and drug consumption patterns, framing wastewater as a multi-dimensional indicator of community health.[7,25,26] The WHO's WES guidance lists a broad set of candidate pathogens for wastewater surveillance—including coronaviruses, influenza, enteroviruses, hepatitis A and E, and multidrug-resistant organisms—and emphasizes that countries should prioritize based on burden, feasibility, and integration with existing systems.[9,27]

These developments align well with the One Health approach, which recognizes the interconnectedness of human, animal, and environmental health.[28,29] Wastewater and other human-impacted waters carry signals from households, healthcare facilities, livestock operations, and markets, capturing zoonotic pathogens and antimicrobial resistance emerging at the interface of human activity and the environment.[30] In such a framework, WBE becomes not only a mirror of human infection but also a sentinel for environmental contamination and zoonotic spillover, particularly relevant in rapidly urbanizing, flood-prone, and agriculturally intensive settings. Figure 1 illustrates how WBE operates within a One Health framework by capturing signals from human, animal, and environmental sources.

To operationalize multi-pathogen wastewater and environmental surveillance beyond COVID-19, LMIC programs need a pragmatic prioritization of targets aligned with disease burden, laboratory feasibility, and decision-

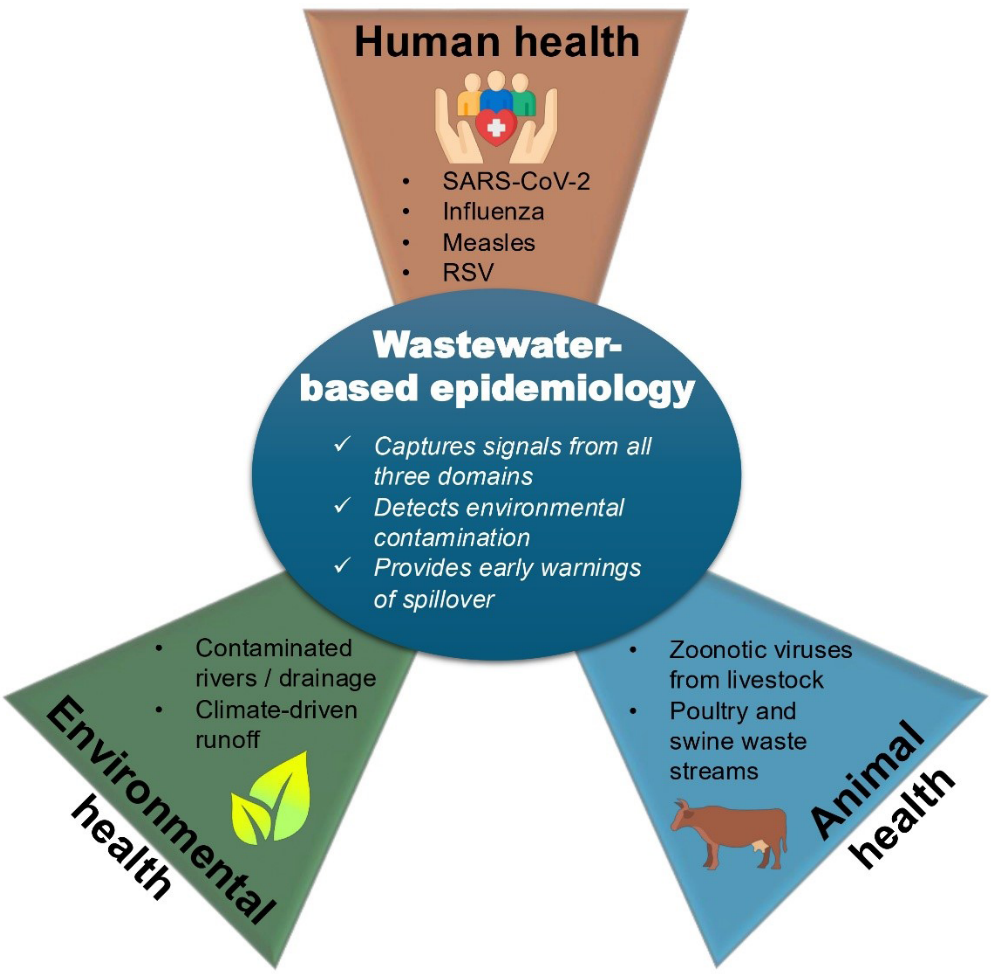

Figure 1. Multi-pathogen wastewater-based epidemiology within the One Health surveillance ecosystem

making. Table 2 summarizes candidate pathogens/targets commonly supported by current evidence and implementation guidance, along with recommended matrices, analytical approaches, and primary public health applications relevant to resource-constrained and mixed-sanitation contexts.

Table 2. Pathogens/targets for wastewater and environmental surveillance

Pathogen/target	Recommended matrix (Typical)	Primary laboratory approach	Primary public health use-case	Key feasibility considerations in LMICs	References
SARS-CoV-2 (RNA)	Influent wastewater; settled solids, where available	RT-qPCR; sequencing for variants; lineage deconvolution/analytics	Early warning; trend monitoring; variant tracking	Signal dilution in low-sewerage areas; inhibitors; transport time/temperature; need for QA/QC and normalization	3,4,9,10,12,14,15,19,32
Influenza A/B (RNA)	Influent wastewater	RT-qPCR (targeted assays); confirmatory methods as needed	Seasonal trend monitoring; support clinical surveillance when under-testing	Lower community prevalence can reduce detectability; assay harmonization and sampling frequency matter	5,22,23
Respiratory syncytial virus (RSV) (RNA)	Influent wastewater	RT-qPCR (often multiplexed with influenza)	Seasonal activity monitoring; pediatric surge anticipation (context-dependent)	Methods are still emerging; careful assay validation and interpretation are needed	22
Enteroviruses (including poliovirus) (RNA)	Influent wastewater; environmental waters where sewerage is limited	RT-qPCR; sequencing where feasible	Early detection and situational awareness; complement routine surveillance	Sampling representativeness in fragmented sanitation; logistics for cold-chain and timely processing	1,9,27
Hepatitis A/E (HAV/HEV) (RNA)	Influent wastewater; environmental waters in mixed sanitation settings	RT-qPCR	Early warning/trend monitoring in settings with limited clinical reporting	Environmental persistence varies; stronger need for standardized protocols and QA	9,27
Mpox (DNA)	Influent wastewater	Targeted PCR (DNA); confirmatory approaches	Early detection; community transmission monitoring	Target selection and event-driven deployment; ensure careful communication to reduce stigma	9,24
Measles (RNA)	Influent wastewater (pilot use)	RT-qPCR (targeted)	Early warning in under-diagnosed outbreaks (pilot-level)	Limited programmatic maturity; interpret as a supportive signal rather than a definitive incidence	9,24
AMR targets (e.g., ESBL genes; resistant Enterobacterales)	Hospital wastewater; influent wastewater, where feasible	Culture + AST; qPCR for genes; WGS/referral sequencing	AMR hotspot monitoring: an early signal of circulating resistance	Biosafety; heterogeneity of shedding; site selection (hospital vs community); requires clear governance for data use	20,21,30,36
Pharmaceutical consumption markers (selected APIs/metabolites)	Influent wastewater	Targeted chemical analytics (LC–MS/MS)	Community-level exposure/usage trends (non-infectious health intelligence)	High cost and technical requirements; limited lab availability; prioritize sentinel use	26
Integrated multi-pathogen panels (respiratory + enteric + AMR)	Wastewater + selected environmental waters	Multiplex RT-qPCR + sequencing where feasible	Broader situational awareness; preparedness; One Health surveillance integration	Requires careful prioritization, lab QA frameworks, and governance for actionability	8,9,27,29

Abbreviations: AMR: Antimicrobial resistance; API: Active pharmaceutical ingredient; AST: Antimicrobial susceptibility testing; ESBL: Extended-spectrum β-lactamase; HAV: Hepatitis A virus; HEV: Hepatitis E virus; LC–MS/MS: Liquid chromatography–tandem mass spectrometry; LMIC: Low- and middle-income country; QA/QC: Quality assurance/quality control; RT-Qpcr: Reverse transcription quantitative polymerase chain reaction; RSV: Respiratory syncytial virus; WGS: Whole-genome sequencing.

4. The Philippine experience: Opportunities and constraints

In the Philippines, WBE remains a nascent but growing movement, gaining prominence since the COVID-19 pandemic. A pilot study in Davao City demonstrated that SARS-CoV-2 RNA could be detected in wastewater in communities with moderate-to-high transmission risk, and highlighted how physico-chemical and hydrological factors influence viral signal decay.[31] More recently, Inson *et al.*[32] detected SARS-CoV-2 and Omicron variant RNA in wastewater from Metro Manila, with trends that broadly reflected community case patterns and underscored the feasibility of variant tracking.[32]

National institutions have begun to invest in WBE infrastructure. With the support of the Department of Science and Technology–Philippine Council for Health Research and Development (DOST–PCHRD), projects such as WAGAS and the broader AMDABiDSS-Health program have explored the integration of WBE and data analytics for community-level pathogen surveillance and genetic tracking.[33,34] These efforts have fed into tools like the DiWA application, which provides local government units (LGUs) with forecasting and scenario analysis for epidemic control.[35] Environmental surveillance for SARS-CoV-2 and antimicrobial resistance has also been piloted in Metro Manila, signaling growing recognition of wastewater as a surveillance asset.[36]

Despite the progress achieved so far, the Philippines continues to face several structural challenges that limit the broader use of WBE. Sewerage coverage remains low, and many households depend on on-site sanitation such as septic tanks or makeshift drainage systems. This is especially common in rural communities, peri-urban areas, and informal settlements, which makes it difficult to collect samples that truly represent the population.[37] In many regions, the absence of centralized wastewater treatment plants or the presence of fragmented systems managed by different utilities further complicates surveillance efforts. Laboratory facilities that can perform molecular testing and sequencing are primarily located in a few major cities, creating bottlenecks when programs attempt to expand beyond their initial pilot areas. Funding also tends to come from short-term or project-based sources, raising concerns about whether current initiatives can be sustained once external support ends.[33] A summary of the major constraints and the emerging opportunities for implementing WBE in the Philippines is presented in Figure 2.

At the same time, these challenges create opportunities for context-specific innovation. For example, sampling at strategic nodes in drainage canals, pumping stations, and small sewage treatment plants can provide pragmatic coverage in the absence of fully centralized sewer networks. Coupling WBE with LGU-level data platforms, such as DiWA, enables local actors to use wastewater signals for early warning, targeted clinical testing, and resource allocation. Embedding WBE within multi-sector coordination involving the Department of Health (DOH), Department of Environment and Natural Resources (DENR), DOST, and water utilities can also ensure that environmental and health data are jointly interpreted and acted upon.

4.1. Technical constraints, detection sensitivity, and risk of false negatives in Philippine settings

The Philippine pilot studies also underline important technical limitations that affect sensitivity and interpretation. In the Davao City pilot, SARS-CoV-2 RNA was successfully detected in community wastewater using RT-qPCR; however, formal analytical performance parameters, such as recovery efficiency, quantification accuracy, and assay limit of detection, were not established because genome standards were unavailable during the study. Viral loads were therefore reported qualitatively rather than quantitatively.[31] Similar early experiences in Manila focused primarily on demonstrating feasibility and variant detection rather than generating robust estimates of analytical sensitivity.[32] As a result, while detection was achievable, uncertainty remains around the minimum prevalence required for reliable wastewater signal identification in Philippine settings.

False negatives are also plausible in tropical, non-centralized wastewater systems, where RNA degradation and signal dilution are major risks. The Davao pilot documented that environmental and hydrological conditions, such as high temperatures, variable residence time, saline intrusion, tidal influence, and stormwater mixing, affected RNA stability and detectability; sites with greater seawater influence and prolonged transport were more prone to signal loss, and sampling at low tide was recommended to reduce dilution.[31] These findings are consistent with broader global experience, which shows that warm climates, intermittent flow, inhibitors, transport delays, and low community incidence can reduce detection probability and increase the risk of false negatives if sampling and storage protocols are not carefully managed. Taken together, these limitations indicate that Philippine WBE evidence should be interpreted cautiously at present and that future national implementation will require standardized protocols, quality assurance, and explicit estimation of recovery efficiency and detection limits to strengthen confidence in decision-making.

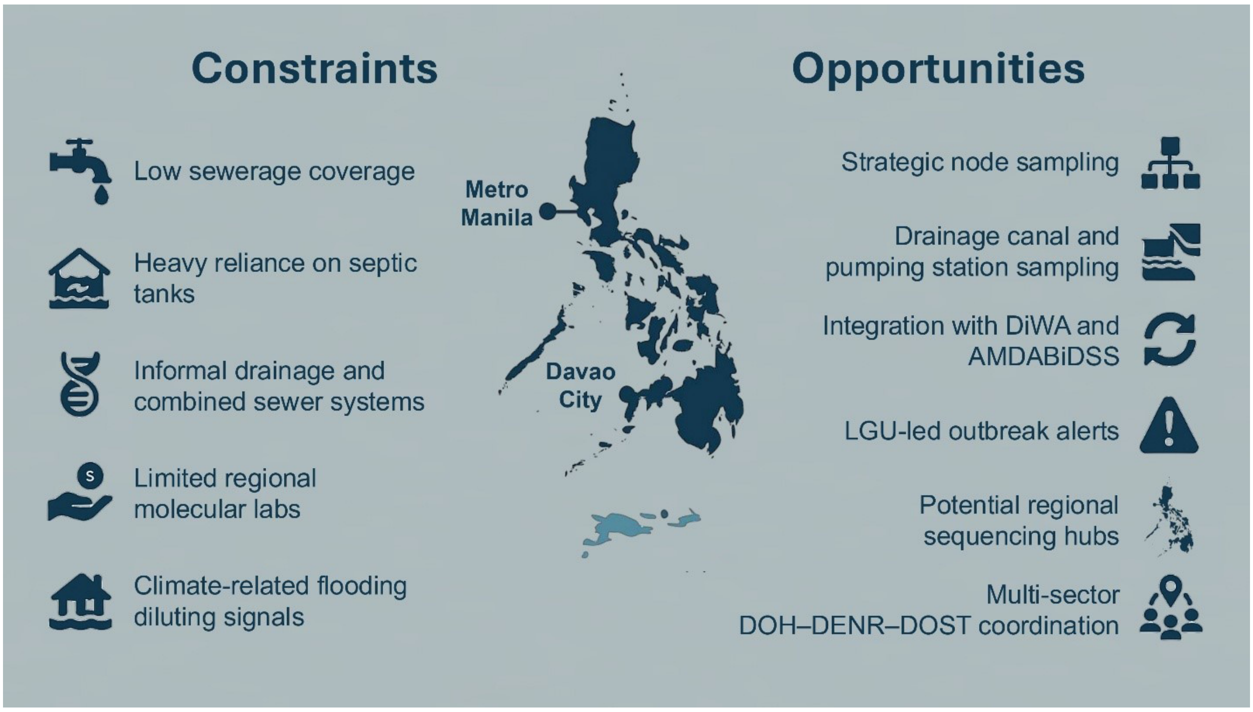

Figure 2. Structural constraints and emerging opportunities for wastewater-based epidemiology in the Philippines
Abbreviations: DENR: Department of Environment and Natural Resources; DOH: Department of Health; DOST: Department of Science and Technology; LGU: local government unit.

In LMIC and archipelagic contexts, sampling representativeness and signal stability are strongly shaped by sanitation infrastructure, hydrology, and operational constraints. Table 3 outlines sanitation-specific sampling nodes, major sources of bias and false negatives, and practical mitigation steps to support cautious interpretation and improve reliability when scaling WBE beyond highly sewered settings.

4.2. Positioning the Philippines in the Association of Southeast Asian Nations surveillance landscape

Regional experience with WES in Southeast Asia indicates that countries with varying levels of sanitation infrastructure have explored WBE as part of public health monitoring and early warning strategies. In Thailand, multiple studies have documented the detection of SARS-CoV-2 RNA in wastewater from cities. Influent samples from wastewater treatment plants in Bangkok have shown measurable viral RNA that correlates with epidemiological trends, providing early warning signals several weeks before increases in reported cases.[38] In Indonesia, community-level surveillance in Yogyakarta demonstrated that WBE can operate in formal and informal environments, with SARS-CoV-2 detected in wastewater across urban, semi-urban, and rural settings, reflecting COVID-19 incidence patterns over time.[39] Emerging work in Vietnam has also used environmental water sampling over extended periods to assess the persistence and prevalence of SARS-CoV-2 in non-clinical water bodies, suggesting the broader applicability of environmental surveillance in diverse Southeast Asian contexts.[40] Although these studies vary in scale, infrastructure context, and focal pathogens, they collectively demonstrate that the Association of Southeast Asian Nations countries with diverse sewerage and environmental conditions have operationalized wastewater or water-based surveillance, providing comparative insights that enrich the Philippine experience and emphasize the need for context-specific implementation strategies.

5. Policy and research priorities for low- and middle-income settings

Drawing on global experience and the Philippine case study, the key policy and research priorities for institutionalizing WBE in LMIC settings are summarized in Table 4. These priorities reflect technical, infrastructural, governance, and equity considerations necessary to transition WBE from pilot initiatives to sustainable public health surveillance systems.

The priorities reflect recurrent structural, technical, governance, and ethical challenges identified in global wastewater surveillance literature and are informed by

Table 3. Sanitation context-specific sampling options and interpretation risks for water-based epidemiology

Sanitation/ Network Context	Recommended sampling node(s)	Sampling mode (Pragmatic)	Main bias/uncertainty	Mitigation/QA actions	Interpretation note	References
Highly sewered, centralized WWTP catchment	WWTP influent; settled solids	24-h composite (preferred)	Less bias than other contexts, but still affected by inhibitors and variable shedding	Standardized concentration/ extraction; process controls; normalization; consistent frequency	Strongest setting for trend interpretation and correlation with cases/ hospitalizations	12,16,19
Partially sewered urban areas with fragmented networks	Sewer interceptors; pumping stations; selected trunk lines	Repeated grab samples (time-standardized) or short composites	Representativeness depends on node selection, intermittent flows, and spatial heterogeneity	Sentinel node mapping; replicate sampling; rainfall-aware interpretation; QA/QC	Best for directional trends and hotspot detection, not population-prevalence claims	19,41
Combined sewer–stormwater systems/monsoon-influenced drainage	Interceptors before major stormwater mixing; upstream nodes	Timed grabs pre-/post-rain; increased frequency during events	Dilution and wash-in effects; large temporal variability; increased false negatives at high flow	Rain-event metadata; avoid single-timepoint conclusions; standardize sampling windows	Interpret as an event-sensitive signal; use alongside syndromic/clinical data	19,31
Predominantly on-site sanitation (septic tanks) with low sewerage	Septic effluent discharge points; desludging hubs; communal drainage outfalls	Targeted grab sampling (sentinel)	Highly localized signal; unknown catchment size; variable residence time; degradation	Define catchment boundaries; repeat sampling; conservative thresholds; strong documentation	Use mainly for sentinel early warning and localized situational awareness	19,37
Coastal/tidal influence (saline intrusion, tidal mixing)	Upstream nodes before seawater influence; tide-standardized sites	Timed grab sampling (e.g., low tide)	Salinity and tidal mixing dilute/degrade signals; transport/ residence time affects detectability	Tide-standardize; rapid processing; cold-chain; replicate samples	Elevated risk of false negatives; treat non-detection cautiously	31
Hospital wastewater (AMR/high-risk pathogens)	Hospital outflow prior to mixing with municipal sewage	Frequent grabs (or short composites)	Enrichment bias (not community-representative); biosafety risks	Biosafety protocols; target-defined surveillance; clear governance and reporting	Appropriate for AMR hotspot monitoring and infection-control intelligence	20,21,36
Environmental waters (surface waters impacted by human activity)	Downstream of dense settlements/ markets; canals; rivers (context-specific)	Grab sampling (repeat over time)	High variability; dilution; contamination sources are less defined than sewers	Site stratification; repeated longitudinal sampling; environmental metadata	Complementary to WBE, where sewerage is limited, interpreted as environmental surveillance	9,40
Utility-public health integrated surveillance (decision-support linkage)	Nodes aligned with administrative decision areas (LGU-relevant catchments)	Routine schedule aligned with dashboards	Operational inconsistency can undermine actionability	Harmonized SOPs; reporting pathways; interoperability with analytics platforms	Highest value when signals are translated into action thresholds and response workflows	16,33,35

Abbreviations: AMR: Antimicrobial resistance; LGU: Local government unit; QA/QC: Quality assurance/quality control; SOPs: Standard operating procedures; WBE: Wastewater-based epidemiology; WES: Wastewater and environmental surveillance; WWTP: Wastewater treatment plant.

Table 4. Policy and research priorities for institutionalizing wastewater-based epidemiology in low- and middle-income settings

Priority area	Key challenge	Proposed action	Policy relevance
Sampling strategy	Low sewerage	Decentralized nodes	Urban and peri-urban
Laboratory capacity	Centralization	Regional hubs	Equity and speed
Governance	Fragmentation	Inter-agency memorandum of understandings	Sustainability
Ethics	Stigmatization	Communication protocols	Trust

empirical insights from the Philippine experience and comparable contexts. The proposed actions are intended to support the transition of WBE from pilot initiatives to sustainable public health surveillance systems.

5.1. The consolidation of COVID-19 capacity into multi-pathogen platforms

Rather than dismantling SARS-CoV-2 WBE infrastructure, governments should repurpose it to include influenza, enteric viruses, and antimicrobial resistance targets, guided by WHO's WES prioritization frameworks and local disease burden.[5,7,9]

5.2. The design of sewage- and sanitation-appropriate sampling strategies

In settings with limited sewer infrastructure, research should focus on optimizing sampling from septic tank effluents, drainage channels, and combined sewer–stormwater systems, as well as understanding how monsoon-driven flooding and climate variability affect signal dilution and persistence.[19,31]

5.3. Investments in regional laboratory hubs and quality assurance

Scaling WBE requires regional hubs capable of RT-qPCR and sequencing, supported by standardized protocols, external quality assessment, and data sharing mechanisms.[8,13] Evidence from decentralized surveillance networks demonstrates that multilayered laboratory networks with quality assurance frameworks improve detection consistency and public health responsiveness, especially where variability in laboratory outputs has been observed across sites.[41]

For the Philippines, as an archipelagic country, existing universities and DOH laboratories in the National Capital Region, Visayas, and Mindanao could be converted into regional hubs, as these institutions already possess biosafety level 2 laboratories and molecular platforms, minimizing capital investment and logistical delays. A phased hub model aligns with global guidance to strengthen laboratory networks by mapping existing assets, establishing referral pathways, and integrating quality management systems across tiers of public health laboratories.

In practical terms, capital costs for upgrading existing laboratories to support standardized wastewater testing (e.g., RT-qPCR instrumentation, cold-chain capacity, and biosafety enhancements) are likely to range from USD 150,000 to 300,000 per hub, based on documented costs for similar molecular surveillance capacity expansion in LMIC settings. Sequence capacity and advanced analytics could be phased in over two to three years through shared or referral arrangements to optimize both resources and workforce capacity.[42]

Quality assurance is essential to ensure reliable data across hubs. Participation in external quality assessment programs, such as those coordinated by WHO and other regional schemes, has been shown to improve competence and comparability of molecular detection results across laboratories.[43] Regular inter-laboratory comparison and standardized operating procedures will support harmonization and data sharing, enabling meaningful integration of wastewater signals into national surveillance and risk assessment frameworks.

Policymakers can operationalize this recommendation through a tiered implementation roadmap: (i) identify and designate anchor laboratories in key regions, (ii) harmonize WBE protocols and quality assurance frameworks under the stewardship of DOH and partner agencies, (iii) leverage existing data platforms for interoperability, and (iv) strengthen workforce training and supply chains to sustain hub operations over time.

5.4. The integration of water-based epidemiology with data analytics and decision support

Water-based epidemiology data are most valuable when linked to dashboards and modeling tools that translate signals into actionable insights for policymakers, as seen in Arizona's WATERS framework and the Philippines' AMDABiDSS/DiWA platforms.[16,33,35] Methodological work on thresholds, alert levels, and fusion with clinical and syndromic data is a key research frontier.[2,44]

5.5. Ethics, equity, and communication considerations

Wastewater data can inadvertently stigmatize specific communities if not communicated carefully. Perspectives from residents, local leaders, and marginalized groups should be incorporated into WBE design and reporting, and communication protocols should ensure that data are used to support, rather than penalize, high-risk areas.[18,29]

5.6. Governance, data ownership, and institutional coordination

Water-based epidemiology functions within the broader domain of WES, which the WHO defines as surveillance using sewage or human-impacted waters to supplement other surveillance modalities and inform public health action. According to the WHO's WES technical guidance, WES is intended to be integrated into multi-modal surveillance and response systems that involve public health, wastewater, water quality, and environmental sectors, rather than operating in isolation.[9]

Effective governance, therefore, depends on multi-agency coordination. In the Philippines, the DOH leads communicable disease surveillance and outbreak response, while the DENR regulates wastewater discharges and water quality through instruments such as the Philippine Clean Water Act. LGUs are responsible for implementing and enforcing on-site sanitation and local public health ordinances, while bodies such as the DOST support laboratory capacity building and research infrastructure that underpin analytical capabilities. The concept of integrating environmental data into public health systems, along with the institutional coordination required to achieve this, reflects international practice for expanding surveillance beyond clinical reporting and toward community-level indicators.

Models of integrated public health wastewater surveillance demonstrate that defined structures for communication, roles, and data use are necessary to support interpretation and action. For example, the Arizona WATERS framework describes how structured reporting pathways and collaborative committees enabled wastewater analyses to inform decision-making in a public health context by linking laboratory results with health agency response actions.[16] A broader literature on wastewater surveillance underscores that integrating environmental data streams with public health authorities enhances the ability to translate molecular measurements into epidemiologically meaningful information that can inform outbreak response.[18]

Regarding data stewardship and sharing, environmental surveillance generates operational analytical outputs at the laboratory or utility level, but the interpretation of aggregated trends for public health purposes is typically governed by health authorities or designated surveillance bodies. This reflects how sentinel environmental data, once de-identified and aggregated, are used to support situational awareness in other surveillance systems. Formalizing data sharing protocols and custodianship can be achieved through inter-agency agreements, memoranda of understanding, and standard operating procedures that clarify responsibilities, data access conditions, and mechanisms for quality assurance without requiring entirely new legislation.

Although there is no single Philippine statute specifically addressing WBE data governance, existing frameworks for wastewater management and environmental monitoring, such as effluent standards and discharge monitoring protocols mandated by the DENR, provide a foundation upon which cooperative data arrangements can be built. Continued dialog among DOH, DENR, DOST, LGUs, and utilities, supported by documented procedures for sample flow, data validation, and reporting, will be crucial for integrating WBE into routine surveillance and ensuring that technical capacity produces actionable public health intelligence.

5.7. Sustainable financing and governance frameworks

Ultimately, WBE needs to become an integral part of regular public health budgeting and day-to-day surveillance activities, rather than being treated as a temporary project. This requires clear and steady coordination among the health, environmental, and water sectors, ensuring that responsibilities are well understood and actions are aligned. Recent international guidance encourages countries to link wastewater surveillance with national systems for monitoring infectious diseases and preparing for future health threats. It also highlights the value of using early pilot efforts to guide long-term adoption, ensuring that lessons from real communities shape how wastewater surveillance becomes a stable part of public health practice.[6,9,27]

6. Conclusion

The COVID-19 pandemic demonstrated that WBE can supplement traditional surveillance by providing earlier, population-level signals of infectious disease transmission, particularly in settings where clinical testing capacity is constrained. In this study, the Philippine experience illustrates both the promise and the complexity of translating this potential into practice in a lower–middle-income, archipelagic context. Philippine pilot initiatives have demonstrated that viral and antimicrobial resistance signals can be detected in wastewater; however, they have also highlighted important limitations, including low sewerage coverage, variable environmental conditions, uneven laboratory capacity, and the absence of clear governance and data stewardship frameworks.

At the same time, these constraints have prompted context-appropriate innovation, including the exploration of decentralized sampling strategies, integration with local data analytics platforms, and a growing interest from national agencies in institutionalizing WBE beyond the COVID-19 pandemic. Experience from neighboring the Association of Southeast Asian Nations countries further demonstrates that WES can be operationalized in diverse infrastructural conditions, reinforcing the feasibility and regional relevance of Philippine efforts while underscoring the need for locally adapted approaches.

Looking ahead, the Philippines and similar LMIC settings will need to convert pilot enthusiasm into sustainable architecture. This will require prioritizing multi-pathogen surveillance, developing sampling strategies suited to mixed and non-sewered systems, investing in regional laboratory hubs and quality assurance, embedding WBE into decision-support tools, formalizing governance and data-sharing arrangements, addressing ethical and equity risks, and securing long-term financing. If these elements can be aligned, WBE can evolve from a pandemic experiment into a durable component of One Health surveillance—transforming wastewater from an overlooked by-product into a strategic public health resource that strengthens preparedness for future outbreaks and antimicrobial resistance threats.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Ysaren Mae Paclauna, Gabrielle Bennet Mancilla

Writing – original draft: Ysaren Mae Paclauna, Gabrielle Bennet Mancilla

Writing – review & editing: Nancy Choon-Si Ng, Onikka Bernice E. Jara, Jomar Adams Ganding, Shealtiel William S. Chan

Availability of data

Not applicable.

References

1. Medema G, Been F, Heijnen L, Petterson S. Implementation of environmental surveillance for SARS-CoV-2 virus to support public health decisions: Opportunities and challenges. *Curr Opin Environ Sci Health*. 2020;17:49-71.

   doi: 10.1016/j.coesh.2020.09.006

2. Chen C, Wang Y, Kaur G, *et al*. Wastewater-based epidemiology for COVID-19 surveillance and beyond: A survey. *Epidemics*. 2024;49:100793.

   doi: 10.1016/j.epidem.2024.100793

3. Chavarria-Miró G, Anfruns-Estrada E, Martínez-Velázquez A, *et al*. Time Evolution of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in Wastewater during the First Pandemic Wave of COVID-19 in the Metropolitan Area of Barcelona, Spain. Elkins CA, ed. *Appl Environ Microbiol*. 2021;87(7):e02750-20.

   doi: 10.1128/AEM.02750-20

4. Ocagli H, Zambito M, Da Re F, *et al*. Wastewater Monitoring During the COVID-19 Pandemic in the Veneto Region, Italy: Longitudinal Observational Study. *JMIR Public Health Surveill*. 2025;11:e58862-e58862.

   doi: 10.2196/58862

5. Viviani L, Vecchio R, Pariani E, *et al*. Wastewater-based epidemiology of influenza viruses: a systematic review. *Sci Total Environ*. 2025;986:179706.

   doi: 10.1016/j.scitotenv.2025.179706

6. Keshaviah A, Diamond MB, Wade MJ, *et al*. Wastewater monitoring can anchor global disease surveillance systems. *Lancet Glob Health*. 2023;11(6):e976-e981.

   doi: 10.1016/S2214-109X(23)00170-5

7. Association of Public Health Laboratories (U.S.), Centers for Disease Control and Prevention (U.S.). National Trends in Wastewater Surveillance 2023 Survey Report. Published online April 2024.

8. O'Reilly K, Wade M, Farkas K, *et al*. Analysis insights to support the use of wastewater and environmental surveillance data for infectious diseases and pandemic preparedness. *Epidemics*. 2025;51:100825.

   doi: 10.1016/j.epidem.2025.100825

9. World Health Organization. Wastewater and environmental surveillance for one or more pathogens: Guidance on prioritization, implementation and integration. World Health Organizationmedahmedgrahamchaga. Available from: https://www.who.int/publications/m/item/wastewater-and-environmental-surveillance-for-one-or-more-pathogens--guidance-on-prioritization--

implementation-and-integration [Last accessed on 13 Nov 2025]

10. Ahmed W, Angel N, Edson J, *et al*. First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: A proof of concept for the wastewater surveillance of COVID-19 in the community. *Sci Total Environ*. 2020;728:138764.

    doi: 10.1016/j.scitotenv.2020.138764

11. Bivins A, Greaves J, Fischer R, *et al*. Persistence of SARS-CoV-2 in Water and Wastewater. *Environ Sci Technol Lett*. 2020;7(12):937-942.

    doi: 10.1021/acs.estlett.0c00730

12. Graham KE, Loeb SK, Wolfe MK, *et al*. SARS-CoV-2 RNA in Wastewater Settled Solids Is Associated with COVID-19 Cases in a Large Urban Sewershed. *Environ Sci Technol*. 2021;55(1):488-498.

    doi: 10.1021/acs.est.0c06191

13. Prado T, Fumian TM, Mannarino CF, *et al*. Wastewater-based epidemiology as a useful tool to track SARS-CoV-2 and support public health policies at municipal level in Brazil. *Water Res*. 2021;191:116810.

    doi: 10.1016/j.watres.2021.116810

14. Fontenele RS, Yang Y, Driver EM, *et al*. Wastewater surveillance uncovers regional diversity and dynamics of SARS-CoV-2 variants across nine states in the USA. *Sci Total Environ*. 2023;877:162862.

    doi: 10.1016/j.scitotenv.2023.162862

15. Garcia I, Riis RK, Moen LV, Rohringer A, Madslien EH, Bragstad K. Unsupervised detection of novel SARS-CoV-2 mutations and lineages in wastewater samples using long-read sequencing. *BMC Genomics*. 2025;26(1):87.

    doi: 10.1186/s12864-025-11255-z

16. Brosky H, Prasek SM, Innes GK, *et al*. A framework for integrating wastewater-based epidemiology and public health. *Front Public Health*. 2024;12:1418681.

    doi: 10.3389/fpubh.2024.1418681

17. Bowes DA, Driver EM, Choi PM, Barcelo D, Beamer PI. Wastewater-based epidemiology to assess environmentally influenced disease. *J Expo Sci Environ Epidemiol*. 2024;34(3):387-388.

    doi: 10.1038/s41370-024-00683-w

18. Farkas K, Kaya D, Maal-Bared R, *et al*. Communicating wastewater-based surveillance data to drive action. *J Water Health*. 2025;23(9):1095-1108.

    doi: 10.2166/wh.2025.080

19. Tiwari A, Radu E, Kreuzinger N, Ahmed W, Pitkänen T. Key considerations for pathogen surveillance in wastewater. *Sci Total Environ*. 2024;945:173862.

    doi: 10.1016/j.scitotenv.2024.173862

20. Tolenada CPS, Dayrit GB. Presence of blaCTXM-1, blaCTXM-9, and blaTEM-1 Genes in Extended-spectrum β-lactamase-producing Escherichia coli Isolates from Hospital Wastewater. *Indones Biomed J*. 2023;15(5):278-287.

    doi: 10.18585/inabj.v15i5.2531

21. Tolenada CP, Dayrit G. W078 Clinically relevant antibiotic resistant enterobacteriaceae from hospital wastewater in metro manila, Philippines. *Clin Chim Acta*. 2022;530:S308-S309.

    doi: 10.1016/j.cca.2022.04.816

22. Geissler M, Berndt H, Herberger E, Wilms K, Dumke R. Methodic aspects of influenza and respiratory syncytial virus detection in raw wastewater and presence in treatment plants in southeastern Germany. *Sci Rep*. 2025;15(1):28194.

    doi: 10.1038/s41598-025-13998-x

23. Mancini P, Brandtner D, Veneri C, *et al*. Evaluation of Trends in Influenza A and B Viruses in Wastewater and Human Surveillance Data: Insights from the 2022–2023 Season in Italy. *Food Environ Virol*. 2025;17(1):6.

    doi: 10.1007/s12560-024-09622-2

24. Maloux H. Wastewater-based epidemiological surveillance (Yearly Report 2024). *Sciensano*. Published online May 2025. Available from: https://www.sciensano.be/fr/biblio/wastewater-based-epidemiological-surveillance-yearly-report-2024 [Last accessed on 2025 September 25].

25. Polo D, Quintela-Baluja M, Corbishley A, *et al*. Making waves: Wastewater-based epidemiology for COVID-19—Approaches and challenges for surveillance and prediction. *Water Res*. 2020;186:116404.

    doi: 10.1016/j.watres.2020.116404

26. Fontanals N, Marcé RM, Montes R, *et al*. Wastewater-based epidemiology to assess pharmaceutical consumption. Spanish perspective. *Sci Total Environ*. 2024;953:176108.

    doi: 10.1016/j.scitotenv.2024.176108

27. Shaw AG, Troman C, Akello JO, *et al*. Defining a research agenda for environmental wastewater surveillance of pathogens. *Nat Med*. 2023;29(9):2155-2157.

    doi: 10.1038/s41591-023-02457-7

28. O'Brien E, Xagoraraki I. A water-focused one-health approach for early detection and prevention of viral outbreaks. *One Health*. 2019;7:100094.

    doi: 10.1016/j.onehlt.2019.100094

29. Hill R, Stentiford GD, Walker DI, *et al*. Realising a global One Health disease surveillance approach: insights from wastewater and beyond. *Nat Commun*. 2024;15(1):5324.

    doi: 10.1038/s41467-024-49417-4

30. Xiao K, Zhang L. Wastewater pathogen surveillance based on One Health approach. *Lancet Microbe*. 2023;4(5):e297.

doi: 10.1016/S2666-5247(23)00039-3

31. Otero MCB, Murao LAE, Limen MAG, *et al*. Multifaceted Assessment of Wastewater-Based Epidemiology for SARS-CoV-2 in Selected Urban Communities in Davao City, Philippines: A Pilot Study. *Int J Environ Res Public Health*. 2022;19(14):8789.

    doi: 10.3390/ijerph19148789

32. Inson JGM, Malla B, Amalin DM, *et al*. Detection of SARS-CoV-2 and Omicron variant RNA in wastewater samples from Manila, Philippines. *Sci Total Environ*. 2024;919:170921.

    doi: 10.1016/j.scitotenv.2024.170921

33. Mundo DMND. Wastewater-Based Epidemiology and Data Analytics for Community-Level Pathogen Surveillance and Genetic Tracking: Proof-of-Concept. *Abstr Jt Conf Symp Health*. Published online November 12, 2024. Available from https://ojs.upmin.edu.ph/index.php/jcsh/article/view/47 [Last accessed on 13 Nov 2025].

34. WAGAS: Integrated Wastewater-Based Epidemiology and Data Analytics for Community-Level Pathogen Surveillance and Genetic Tracking: Proof-of-Concept. Philippine Council for Health Research and Development. Available from: https://www.pchrd.dost.gov.ph/ongoing_projects/wagas-integrated-wastewater-based-epidemiology-and-data-analytics-for-community-level-pathogen-surveillance-and-genetic-tracking-proof-of-concept/ [Last accessed on 13 Nov 2025].

35. Pinoy researchers develop application for disease forecasting, surveillance for LGUs. Philippine Council for Health Research and Development. 2022. Available from: https://www.pchrd.dost.gov.ph/news_and_updates/pinoy-researchers-develop-application-for-disease-forecasting-surveillance-for-lgus/ [Last accessed on 13 Nov 2025].

36. Salazar MA, Dalmacio LM, Orbecido A, *et al*. Strengthening health systems resilience using environmental surveillance for COVID-19 and antimicrobial resistance in the Philippines. *West Pac Surveill Response J*. 2022;13(2):46-49.

    doi: 10.5365/wpsar.2022.13.2.930

37. De Luna ME, Lacson M, Santos KG, Umali AJ, Bagasbas JO. A narrative review on wastewater-based epidemiology as a strategy for disease surveillance in the Philippines. *Biol Bachelors Theses*. Published online December 1, 2023. Available from: https://animorepository.dlsu.edu.ph/etdb_bio/56 [Last accessed on 2025 September 25].

38. Saita T, Thitanuwat B, Niyomdecha N, *et al*. Measuring SARS-CoV-2 RNA in Bangkok wastewater treatment plants and estimating infected population after fully opening the country in 2023, Thailand. *Sci Rep*. 2025;15(1):9663.

    doi: 10.1038/s41598-025-94938-7

39. Murni IK, Oktaria V, McCarthy DT, *et al*. Wastewater-based epidemiology surveillance as an early warning system for SARS-CoV-2 in Indonesia. *PLOS ONE*. 2024;19(7):e0307364.

    doi: 10.1371/journal.pone.0307364

40. Siri Y, Malla B, Thao LT, *et al*. Assessment of environmental factors influencing SARS-CoV-2 in Vietnam's surface water across two years of clinical data. *Sci Total Environ*. 2024;957:177449.

    doi: 10.1016/j.scitotenv.2024.177449

41. Iwu-Jaja C, Ndlovu NL, Rachida S, *et al*. The role of wastewater-based epidemiology for SARS-CoV-2 in developing countries: Cumulative evidence from South Africa supports sentinel site surveillance to guide public health decision-making. *Sci Total Environ*. 2023;903:165817.

    doi: 10.1016/j.scitotenv.2023.165817

42. Oliveira M, Prithiviraj B, Osuolale OO, *et al*. Integrated environmental surveillance: the role of wastewater, air, and surface microbiomes in global health security. *Water Emerg Contam Nanoplastics*. 2025;4(2).

    doi: 10.20517/wecn.2024.80

43. Meredith LW, Aboualy M, Ochola R, Ozel M, Abubakar A, Barakat A. Monitoring the quality of SARS-CoV-2 virus detection in molecular diagnostic laboratories in the Eastern Mediterranean Region during the COVID-19 pandemic. *Influenza Other Respir Viruses*. 2023;17(11):e13217.

    doi: 10.1111/irv.13217

44. Innes GK, Patton AN, Prasek SM, *et al*. Introduction to WBE case estimation: A practical toolset for public health practitioners. *Sci Total Environ*. 2025;980:179487.

    doi: 10.1016/j.scitotenv.2025.179487