Wastewater monitoring can anchor global disease surveillance systems

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To inform the development of global wastewater monitoring systems, we surveyed programmes in 43 countries. Most programmes monitored predominantly urban populations. In high-income countries (HICs), composite sampling at centralised treatment plants was most common, whereas grab sampling from surface waters, open drains, and pit latrines was more typical in low-income and middle-income countries (LMICs). Almost all programmes analysed samples in-country, with an average processing time of 2·3 days in HICs and 4·5 days in LMICs. Whereas 59% of HICs regularly monitored wastewater for SARS-CoV-2 variants, only 13% of LMICs did so. Most programmes share their wastewater data internally, with partnering organisations, but not publicly. Our findings show the richness of the existing wastewater monitoring ecosystem. With additional leadership, funding, and implementation frameworks, thousands of individual wastewater initiatives can coalesce into an integrated, sustainable network for disease surveillance—one that minimises the risk of overlooking future global health threats.

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Introduction

Despite decades of funding being directed into global infectious disease surveillance, and warning signs that came from both traditional and non-traditional data sources, much of the world was caught off-guard by the rapid spread of SARS-CoV-2 globally.[1,2] The pandemic would potentially have unfolded differently if there had been a dedicated surveillance system that was on constant alert, continuously transmitting information about existing and emerging pathogens circulating across the globe. With such a system in place, experts would have identified SARS-CoV-2 far more quickly. Even if pandemic spread was inevitable, health-care systems could have better prepared for the fallout with more advanced notice, saving countless lives.

Wastewater monitoring is an approach to disease surveillance that offers a foundation for providing early warnings for known and novel health threats via cost-effective, objective measures of health obtained from non-invasive, anonymous community-level sampling. Although wastewater monitoring programmes have greatly increased in number as public health officials across the globe realised the benefits of such data to inform pandemic management, recognised frameworks for global disease surveillance have yet to be developed and adopted. Lessons from the Global Polio Eradication Initiative and smallpox eradication programmes make clear that global coordination, adaptable toolkits, and data-sharing standards are crucial components of a successful global health programme.[3]

Outside of polio eradication efforts, the current wastewater ecosystem remains disjointed, largely because monitoring emerged in a grassroots manner, often driven by local and regional needs to rapidly assess SARS-CoV-2 circulation. Programmes operating in isolation or within small, informal networks, particularly those in low-income and middle-income countries (LMICs), are not visible to the wider wastewater community. Although progress has been made to highlight global wastewater monitoring efforts,[4–6] a comprehensive view of programmes' methods, analytical approaches, and data sharing practices is absent.

Here, we present the results of a survey of 43 countries to characterise the landscape of global wastewater monitoring. We summarise the range of approaches used for implementation and provide information to support the development of an integrated wastewater monitoring network.

Methods

After a virtual roundtable hosted in April, 2022, to discuss the realised value of wastewater-based epidemiology, The Rockefeller Foundation partnered with Mathematica and the UK Health Security Agency to conduct an international wastewater survey. A 20-question online survey was built in SurveyMonkey and emailed to a convenience sample of roundtable attendees from 46 countries (appendix pp 1–2). Respondents that completed the survey and had monitored wastewater for SARS-CoV-2 were included in the analysis. When multiple people from a country completed the survey (typically representing different localised programmes), responses were combined into a single country-level record by either averaging or taking the maximum value across responses (depending on the variable type and summary statistic of interest). To assess how implementation features vary by resource availability, we compared responses between programmes in high-income countries (HICs) and LMICs, using data from the World Bank on countries' 2022 gross domestic product.[7]

See **Online** for appendix

Results

Coverage

Representatives of wastewater monitoring programmes in 43 countries (16 LMICs, 27 HICs) spanning six continents completed the survey. Programmes monitored anywhere from less than 1% to 100% of the country's total population, with an average in-country coverage of 41% (figure). Monitoring was more likely to

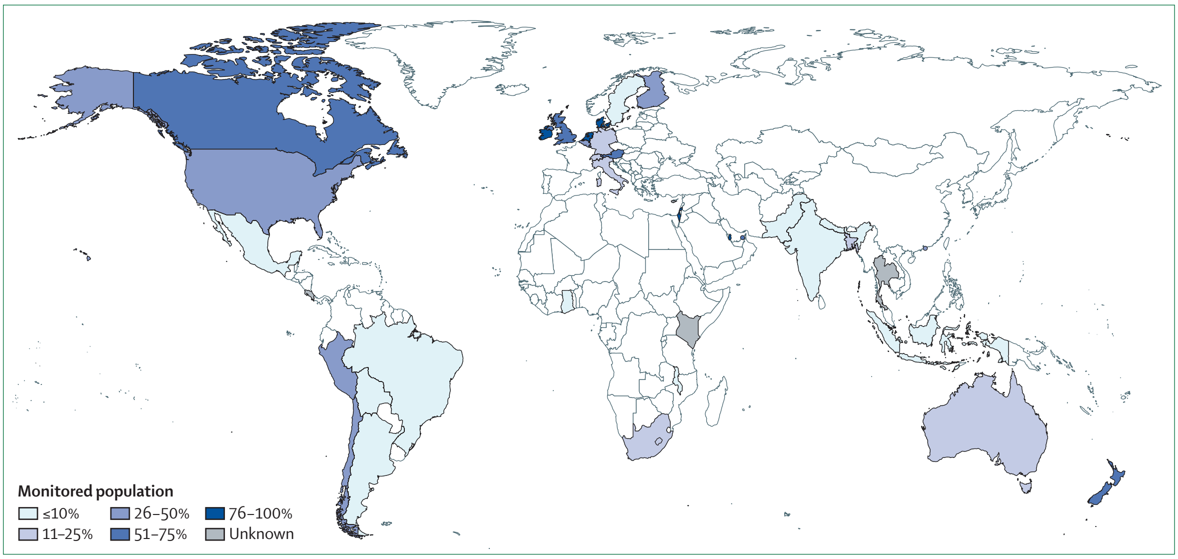

Figure: **Population coverage of wastewater monitoring programmes in surveyed countries**
This map shows the percentage of a country's population that was monitored through wastewater testing for the 43 (shaded) countries that responded to the wastewater survey.

cover urban areas, with 32 (74%) of 43 programmes reporting that less than 20% of the population monitored was non-urban (rural, suburban, or peri-urban). Most surveyed countries (11 [69%] of 16 LMICs, 25 [93%] of 27 HICs) had monitored wastewater for SARS-CoV-2 for more than 1 year, and some (two [13%] LMICs, 16 [59%] HICs) were also regularly monitoring wastewater for viral variants (table).

Sampling

Wastewater monitoring programmes worldwide use different implementation approaches to meet their communities' needs. Whereas in HICs, almost all samples are collected from centralised wastewater treatment plants (65%) or manholes located across the sewershed (34%), wastewater sampling in LMICs occurs at several locations that include wastewater treatment plants (30%) and manholes (20%), but also surface waters (22%), open drains (15%), pit latrines (7%), and other locations (7%). On average, LMICs routinely collected roughly half as many samples as HICs (appendix p 3).

The type of wastewater sampling used also varied between HICs and LMICs. Composite sampling (the automated collection of multiple time-weighted or flow-weighted subsamples during a defined period—typically 24 hours) was more commonly used in HICs (26 [96%] of 27) than LMICs (four [25%] of 16). By contrast, grab sampling (the collection of a small quantity of wastewater or primary settled sludge at a single point in time, usually around peak flow periods, to provide a snapshot of the target analyte) was more prevalent in LMICs (12 [75%]) than HICs (11 [41%]). Passive sampling, which involves the deployment of a diffusive material, such as gauze or a swab, into the wastewater matrix for an extended period, was used by roughly a third of HICs and LMICs.

Analysis

To quantify SARS-CoV-2 viral concentrations in wastewater, 41 (95%) of 43 countries surveyed used reverse transcription quantitative polymerase chain reaction, and only a minority (one [6%] of 16 LMICs, ten [37%] of 27 HICs) used digital droplet PCR. The SARS-CoV-2 target gene(s) measured in wastewater were similar between HICs and LMICs: more than two-thirds of countries surveyed targeted the N1 region, roughly half targeted the N2 region (often in combination with the N1 region), and almost a third targeted the E region (table). Almost all countries surveyed (16 [100%] of LMICs, 24 [89%] of HICs) analysed their wastewater samples in-country, with an average laboratory processing time of 4·5 days in LMICs (range: 0·5–14·0 days) and 2·3 days in HICs (range 0·5–7·0 days). A greater share of HICs (18 [67%]) than LMICs (five [31%]) reported adjusting viral concentrations to account for daily variation in wastewater flow rate, the contributing population size, or both.

Data sharing

Although most countries surveyed (14 [87%] of 16 LMICs, 27 [100%] HICs) share their wastewater data in some capacity, most do not share the data publicly. For example, we noted that 19 (70%) HICs and six (38%) LMICs uploaded their wastewater data to a data dashboard or repository, but only ten (37%) HICs and five (31%) LMICs reported uploading their data to a public or open-access platform. Among the LMICs surveyed, other channels were more commonly used for data sharing (by six [38%] LMICs), including reports or emails for internal data sharing to improve the situational awareness of health authorities.

Even though only about a third of countries surveyed share their wastewater data publicly, almost all were willing and able to share aggregate data with organisations such as The Rockefeller Foundation, Mathematica, and the UK Health Security Agency to increase the visibility of wastewater monitoring for public health globally (with three [19%] of 16 LMICs and nine [33%] of 27 HICs also willing to share raw data).

Discussion

Findings from our global survey clearly show that a wastewater monitoring ecosystem is potentially poised to anchor and advance disease surveillance worldwide.[8] Although our survey cannot fully capture all global experiences with wastewater monitoring, because of the small sample size and reliance on convenience sampling, the stark differences we observed across country income groups suggest that we were able to capture actionable information for the design of adaptable implementation frameworks, funding initiatives, and global data sharing mechanisms.

To further advance and unify wastewater monitoring programmes, considering the successes and lessons learned from past global health initiatives is helpful. For example, holistic approaches, such as WHO's One Health agenda, which offers a vision for a globally interconnected surveillance system, suggest that three core attributes are needed to realise the potential of wastewater surveillance: 1) global and country-level leadership, 2) financial investment, and 3) unifying but flexible implementation frameworks.[9]

Leadership from influential multinational organisations has proven helpful in substantially reducing the burden of diseases of global concern, such as measles and poliovirus. Such leadership is essential to ensure buy-in from national governments; develop multi-year strategic plans; and create blueprints for implementation that promote rigorous standards and quality assurance practices across the wastewater monitoring continuum.[10,11] Because of the diversity of sanitation systems globally, our results support a tiered governance structure that includes advocates at the highest levels, but also regional and local entities to promote community-specific adaptation and monitoring.[12]

Substantial financial investments are also needed to sustain wastewater monitoring into the future. Many wastewater programmes currently rely on donor funding, grants, or short-term government aid,[13] putting them at risk of ending as global COVID-19 funding declines. Funding for wastewater monitoring should be flexibly allocated to account for diverse programme needs, infrastructure, and priorities. Funds should support research and innovation, as well as activities that increase capacity, such as hands-on training of health and water professionals, and mapping of the locations and service populations of sanitation systems.[14] Large organisations, such as the World Bank, are making unprecedented investments in pandemic preparedness, presenting a unique window of opportunity for an intentional investment in the field.[15]

To advance wastewater monitoring for public health, we present considerations for a set of frameworks to inform adaptive sampling, flexible testing, enhanced data reporting, and ethical monitoring.

	LMICs (n=16)	HICs (n=27)
Genomic targets measured by lab		
N1	69%	70%
N2	50%	48%
N unspecified	13%	19%
E	31%	30%
S	0	15%
Orf	19%	26%
Other	13%	19%
Laboratory method for SARS-CoV-2 measurement		
qPCR	94%	96%
ddPCR	6%	37%
Other	13%	7%
Method used to monitor SARS-CoV-2 variants		
PCR	50%	74%
Genomic sequencing	75%	85%
Not applicable (variants not monitored)	50%	0
Frequency of testing for SARS-CoV-2 variants		
Just a few samples	13%	7%
More than few samples, but not regularly	13%	15%
Regularly	13%	59%
Not reported	13%	19%
Not applicable (variants not monitored)	50%	0

This table shows the variety of approaches that wastewater monitoring programmes use to detect or quantify the SARS-CoV-2 virus in wastewater, or both. Respondents could select more than one response for questions about the genomic targets measured and laboratory methods used. For frequency of testing, percentages might add up to more than 100% due to rounding. ddPCR=digital droplet PCR. HICs=high-income countries. LMICS=low-income and middle-income countries. qPCR=quantitative PCR.

Table: **Characteristics of wastewater testing methods**

Adaptive sampling

Best practices are needed to inform how to tailor wastewater sampling in the face of financial or feasibility constraints. Rather than designing a sampling strategy around pre-specified approaches (eg, using composite sampling at fixed locations), implementers should consider how to dynamically adapt sampling locations and approaches based on community demographics (to maintain sight lines to populations who are at high risk and clinically or socially vulnerable), informational needs (the type, structure, and cadence of data needed for decision making), and infrastructural features (which can affect sewage travel times, and thus the stability of biomarkers).

Flexible testing panels

Increasing the capacity of laboratories worldwide to develop assays for novel pathogens or variants, or to apply Next Generation Sequencing technology, should be a priority area of investment for global disease surveillance. Similarly, investments in artificial intelligence applications for meta-genomic wastewater sequencing can enhance our ability to detect novel pathogens. Together, these approaches can provide insight into changing threats and the composition of complex microbial communities,[16,17] and are far timelier and cheaper than sequencing clinical samples.[18] Recent investments, such as those made by the Africa Centres for Disease Control and Prevention for the Africa Pathogen Genomics Initiative, are encouraging, but more funding of pathogen-agnostic methods can better prepare communities to respond to dynamic pathogenic threats.

Enhanced reporting to improve situational awareness

To facilitate rigorous site-to-site comparisons of wastewater metrics, many researchers are assessing different approaches to normalisation and exploring the creation of standardised indices.[18–21] Even if wastewater data cannot be standardised, there is great value in making them publicly available, since information on detectability and within-site changes can be strategically harnessed in different phases of a threat.[21] At the beginning of an outbreak, mapping changes in presence or absence at several sites can reveal where the threat is located and how it is spreading. As the threat accelerates, alerts that separate signal (sustained surges in concentrations) from noise (routine sample-to-sample fluctuation) can be applied to within-site biomarker concentrations.[22] As the threat decelerates, integrating within-site changes in biomarker concentration and detectability with traditional public health metrics can clarify when threat levels are stably low. In each of these scenarios, wastewater data are most useful if they are collected repeatedly across several sites in a region, consolidated into a single platform, integrated with established data sources, and shared publicly. Although efforts have been made to create public data repositories,[23,24] such as the Wastewater SPHERE, the information posted is typically confined to metadata. Having raw biomarker and sequencing results available globally, and in the public domain, will not only facilitate tracking risks in near real time, but can also increase public health awareness and community resilience.[25]

Ethical monitoring

At present, no comprehensive guidelines have been established to promote the ethical practice of wastewater monitoring. The results from our survey indicate that a global advisory panel of diverse experts from countries across all income groups should be engaged to inform how to adapt guidelines to different local contexts and capabilities. At a minimum, guidance documents should cover communicating with the public, engaging and protecting vulnerable populations, and facilitating data sharing. For communicating with the public, public messaging should be transparent, highlight the advantages and limitations of wastewater data, and summarise how it can complement existing data. Messaging toolkits should provide sample language that illustrates how to reduce the risk of stigmatising communities, particularly those with vulnerabilities stemming from socioeconomic status, race, or religion.[26,27]

To protect vulnerable populations, clear guidance is needed on how to develop inclusive sampling strategies that preserve privacy and reduce the risk of information bias that creates disproportionate harms to specific populations. For instance, if wastewater monitoring is primarily done in high-density urban areas, public health actions that impose mobility restrictions based on the data could unduly affect racial or minority ethnic groups.[28] Local communities should be involved in all stages of wastewater programming, from planning site collection to implementing interventions.[29] Because most wastewater treatment systems and sewage collection sites are public, the community should be privy to the information generated from them. Guidance on how to do risk-benefit assessments of data sharing as sample sizes decrease can help ensure that individual privacy is not at risk.[28]

Conclusion

As the world re-commits to improving global disease surveillance systems, countries must consider the role of innovative approaches such as wastewater monitoring to overcome shortcomings that the COVID-19 pandemic revealed. Although some countries are scaling back wastewater monitoring, others have expanded its use to identify re-emerging and ongoing health threats, including cholera, mpox (formerly known as monkeypox), influenza, typhoid, and antimicrobial resistance. Because of the nuanced and multifaceted approaches to implementing wastewater monitoring globally, researchers, practitioners, and public health institutions must consider trade-offs in the design and delivery of theoretically optimal versus practically feasible approaches as they introduce, expand, and develop standards for wastewater monitoring. Finally, with additional leadership and investments to connect disparate efforts and develop adaptable implementation frameworks, the many individual wastewater initiatives that now exist can coalesce into an integrated, sustainable network for disease surveillance that minimises the risk of overlooking or underestimating future emerging global health threats.

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Contributors

AK, MBD, and MJW conceived of the project, with input from SS; AK and MBD designed the survey, with input from MW; MBD built and fielded the online survey instrument; AK cleaned the data, with input from MD; AK analysed the survey data and developed data summaries and visualisations; MBD coordinated the project; SVS supervised the project; AK, MBD, and SVS drafted the original manuscript; AK, MBD, MJW, and SS reviewed and edited the final manuscript; MBD and SS acquired funding for the project; and AK, MBD, MJW, and SVS contributed resources for the project. AK and SVS directly accessed and verified the underlying data reported in the manuscript. All authors read and approved the final version of the manuscript. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

AK received funding from The Rockefeller Foundation to support this work; MBD and SVS were employees of The Rockefeller Foundation at the time of this study. All other authors declare no competing interests.

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