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REVIEW

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Preparing public health systems for the quantum revolution: Challenges and opportunities

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ABSTRACT

Wastewater-Based Epidemiology (WBE) has emerged as a transformative tool for monitoring community health by analyzing biological and chemical markers in sewage. This approach provides a non-invasive, cost-effective, and near real-time means to assess public health trends, including the spread of infectious diseases, drug consumption patterns, and antimicrobial resistance. This mini-review outlines the core principles and methodologies of WBE, such as sample collection strategies, biomarker selection, and analytical techniques like quantitative PCR (qPCR) and liquid chromatography–mass spectrometry (LC-MS/MS). Key public health applications are discussed, with emphasis on WBE's role during the COVID-19 pandemic, as well as in monitoring opioids and AMR genes. Case studies from global WBE initiatives demonstrate the utility of this approach in informing timely policy decisions and community-level responses. Despite its promise, WBE faces challenges related to data standardization, ethical concerns, and infrastructure limitations. Looking ahead, the integration of WBE with digital health tools and AI presents significant opportunities for advancing global disease surveillance and strengthening future public health systems.

KEYWORDS

Wastewater-based epidemiology (WBE); Antimicrobial resistance; Monitoring; Pathogen detection; qPCR and LC-MS/MS analysis

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Introduction

Epidemiology, the study of disease distribution and determinants within populations, is fundamental to public health. It informs policies and interventions aimed at preventing and controlling diseases. Traditional public health surveillance methods, such as clinical reporting and laboratory testing, focus on individual cases and often rely on symptomatic individuals seeking medical attention. While effective, these methods can be limited by delays in reporting, underdiagnosis, and resource constraints [1].

In recent years, Wastewater-Based Epidemiology (WBE) has emerged as a complementary approach to traditional surveillance. WBE involves analyzing municipal wastewater for biological and chemical markers excreted by individuals, providing aggregated data on community health. This method offers a non-invasive, cost-effective means to monitor public health trends in near real-time. By detecting pathogens, pharmaceuticals, and other biomarkers in sewage, WBE can provide early warnings of disease outbreaks and other public health concerns [2,3].

The importance of WBE has been highlighted during the COVID-19 pandemic. Studies have demonstrated that SARS-CoV-2 RNA can be detected in wastewater, often before clinical cases are reported, allowing for earlier intervention and resource allocation. Beyond infectious diseases, WBE has applications in monitoring substance use, antimicrobial resistance, and exposure to environmental contaminants. Its ability to provide comprehensive, community-level data makes it a valuable tool for public health authorities [4].

The objectives of WBE in modern health monitoring include [5,6]:

- Early detection of disease outbreaks, enabling prompt public health responses.
- Monitoring the prevalence and spread of infectious agents within communities.
- Assessing population-level exposure to drugs, chemicals, and environmental toxins.
- Evaluating the effectiveness of public health interventions and policies.

As urban populations grow and public health challenges become more complex, WBE offers a scalable and adaptable approach to health surveillance. Its integration into existing public health frameworks can enhance our ability to detect and respond to health threats, ultimately improving community health outcomes [7].

Principles and Methodology of Wastewater-Based Epidemiology

Wastewater-Based Epidemiology (WBE) relies on the systematic collection and analysis of wastewater samples to assess the health status of a population by detecting biomarkers excreted through human waste. Understanding the principles and methodology of WBE is essential for its effective application in public health surveillance [8].

Sample collection and types

The cornerstone of WBE is the collection of representative

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wastewater samples. Typically, samples are collected from influent streams entering wastewater treatment plants, which aggregate sewage from large urban populations. These influential samples provide a composite snapshot of the community's health status. Alternatively, samples can be collected from specific sewer catchment areas or smaller neighborhood sewer lines to localize data more precisely. Other types of samples include sludge, the semi-solid residue from wastewater treatment, which can harbor concentrated biomarkers and provide historical data. Sampling methods vary, including grab sampling, which captures a single snapshot at a point in time, and composite sampling, where multiple samples are collected over hours or days to provide an averaged representation. Composite sampling is generally preferred for reducing temporal variability and improving data reliability. The process typically involves several stages, from sample collection to public health decision-making (Figure 1) [8,9].

Biomarker selection

WBE targets a variety of biomarkers, including chemical substances and biological agents excreted by individuals. Common chemical biomarkers include metabolites of pharmaceuticals, illicit drugs, and environmental chemicals. Biological biomarkers often consist of pathogens such as viruses, bacteria, and antimicrobial resistance genes. For example, the SARS-CoV-2 virus, responsible for COVID-19, has been widely monitored in wastewater, providing valuable data on infection trends even before clinical cases rise. The selection of biomarkers depends on the public health question and the analytical capabilities available. Biomarkers must be stable in sewage, excreted in measurable quantities, and specific enough to provide meaningful data about the population. Depending on the target analyte, WBE can detect a wide variety of biomarkers (Table 1), including pathogens, drug metabolites, and antimicrobial resistance genes [10].

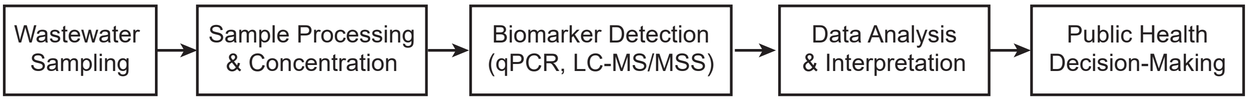

Figure 1. General workflow of wastewater-based epidemiology (WBE), including key steps from sampling to public health interpretation.

Table 1. Common biomarkers used in wastewater-based epidemiology.

Biomarker Type	Example(s)	Analytical Technique	Public Health Application
Viral pathogens	SARS-CoV-2, Poliovirus	qPCR, digital PCR	Infectious disease surveillance
Bacterial markers	AMR genes	qPCR, NGS	Antimicrobial resistance monitoring
Illicit drugs	Cocaine, Amphetamines	LC-MS/MS	Drug consumption and abuse tracking
Pharmaceuticals	Antibiotics, Painkillers	LC-MS/MS	Medication use patterns
Environmental contaminants	Heavy metals, pesticides	ICP-MS, GC-MS	Toxic exposure assessment

Analytical techniques

After collection, samples undergo processing and analysis using advanced techniques. For chemical biomarkers, liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) is a gold-standard method due to its high sensitivity and specificity for detecting a broad spectrum of compounds at low concentrations. For biological markers, quantitative polymerase chain reaction (qPCR) is widely employed to detect and quantify specific DNA or RNA sequences of pathogens, such as SARS-CoV-2. Other methods include digital PCR, next-generation sequencing (NGS), and immunoassays, each providing unique advantages depending on the target and required resolution. Sample concentration steps, such as filtration and centrifugation, are often necessary to enhance detection sensitivity [11,12].

Data interpretation and population estimation

Interpreting WBE data involves translating the measured concentrations of biomarkers into estimates of community health metrics. This requires accounting for variables such as dilution in sewage, biomarker stability, population size served by the sewer system, and per capita excretion rates. Population estimation can be challenging, especially in dynamic urban settings with fluctuating populations. Some studies use human-specific markers, like creatinine or certain viruses common to humans, to estimate contributing population size more accurately. Mathematical models and statistical methods help to normalize biomarker loads and correlate them with epidemiological data. The temporal resolution of data allows for trend analysis, outbreak detection, and the assessment of intervention efficacy [13].

Applications in Public Health

Wastewater-Based Epidemiology (WBE) has rapidly evolved as a vital tool in public health for monitoring diverse community health parameters. By analyzing sewage, WBE offers a real-time, non-invasive method to assess population-wide health trends, playing a crucial role in infectious disease surveillance, drug consumption tracking, antimicrobial resistance monitoring, and early outbreak warning systems [14].

Infectious disease surveillance

One of the most prominent applications of WBE is infectious disease surveillance. The COVID-19 pandemic highlighted its potential when researchers detected SARS-CoV-2 RNA in

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wastewater before clinical cases surged, providing early warnings of community spread. This capability allowed public health officials to respond proactively with targeted testing and containment strategies. Beyond COVID-19, WBE has been instrumental in monitoring other viral pathogens such as poliovirus and norovirus. For instance, polio eradication efforts have incorporated wastewater surveillance to detect silent virus circulation, especially in regions with low vaccination coverage. Similarly, norovirus, a leading cause of gastroenteritis, can be tracked in sewage to monitor seasonal outbreaks, providing insights into viral transmission dynamics [14].

Drug consumption and abuse tracking

WBE also serves as an innovative approach to assess population-level drug consumption patterns, including both illicit substances and pharmaceuticals. By measuring drug metabolites excreted in urine, researchers can estimate community-wide drug usage more accurately and anonymously than traditional surveys, which often suffer from underreporting or bias. This method has been applied globally to monitor trends in opioids, cocaine, amphetamines, and new psychoactive substances. Tracking pharmaceutical residues also informs on prescription drug consumption and potential misuse. These insights help policymakers and healthcare providers tailor addiction treatment programs and law enforcement strategies based on real-time data. WBE allows simultaneous surveillance of various public health markers, including illicit drug use and infectious diseases (Figure 2) [15,16].

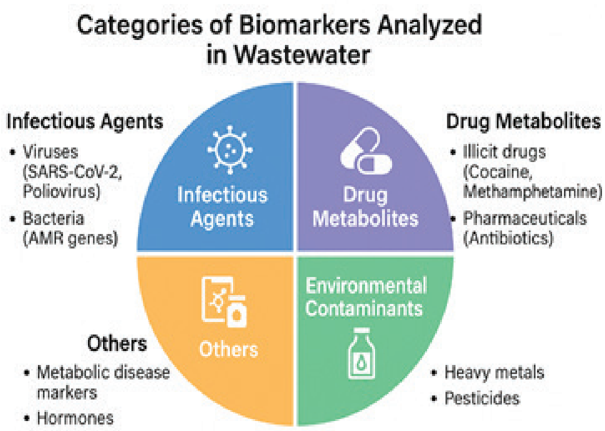

Figure 2. Categories of biomarkers analyzed in wastewater for public health applications.

Antimicrobial resistance (AMR) monitoring

The growing threat of antimicrobial resistance (AMR) poses a major public health challenge worldwide. WBE provides a unique platform to monitor the prevalence and spread of antimicrobial resistance genes (ARGs) within communities. Wastewater contains bacteria from human and environmental sources, making it a reservoir for ARGs. By detecting and quantifying these genes, WBE helps to identify hotspots of resistance, track the emergence of resistant strains, and evaluate the effectiveness of interventions aimed at reducing antibiotic misuse. This surveillance is critical for informing antibiotic stewardship policies and preventing the escalation of resistant infections [17].

Early warning systems for outbreaks

WBE functions as an effective early warning system for various health threats. Because wastewater aggregates biological signals from entire populations, changes in biomarker levels can signal emerging outbreaks before clinical diagnoses increase. This timeliness allows health authorities to implement preventive measures promptly, minimizing disease spread and reducing healthcare burdens. Early detection via WBE has been applied not only to viral outbreaks but also to monitor community exposure to environmental toxins and chemical hazards. Integrating WBE data with traditional epidemiological surveillance enhances situational awareness and improves public health responses [18].

Case Studies

COVID-19 tracking

The COVID-19 pandemic catalyzed widespread adoption of WBE as a critical surveillance tool. In the United States, large-scale wastewater monitoring networks were established across cities like New York and Boston. These programs successfully detected SARS-CoV-2 viral RNA in sewage days to weeks before clinical testing revealed spikes in cases, enabling earlier interventions. Similarly, the Netherlands pioneered nationwide sewage surveillance early in the pandemic. Their comprehensive program consistently tracked viral load trends, correlating closely with reported infection rates and helping guide lockdown and reopening policies. Australia's state-level wastewater programs also contributed valuable data, identifying community transmission and informing targeted public health responses, particularly in low-incidence regions where clinical testing was limited. Several countries have successfully implemented WBE programs for early COVID-19 detection (Table 2) [19].

Table 2. Selected global case studies demonstrating the application and impact of WBE in real-time public health surveillance.

Location	Target Biomarker	Application	Outcome/Impact
USA (New York)	SARS-CoV-2 RNA	COVID-19 surveillance	Early outbreak detection
Netherlands	SARS-CoV-2, Poliovirus	Infectious disease	Nationwide monitoring, policy guidance
Australia	SARS-CoV-2 RNA	COVID-19 tracking	Localized outbreak response
Canada	Opioid metabolites	Drug abuse monitoring	Informed harm reduction strategies
UK	AMR genes	Antimicrobial resistance	Identification of resistance hotspots

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Regional and local monitoring programs

Beyond global efforts, localized WBE initiatives have provided actionable insights. For example, university campuses in the U.S. used wastewater surveillance to detect COVID-19 outbreaks among students, enabling rapid isolation and containment measures. In Canada, municipal programs tracked opioid metabolites in wastewater, helping authorities understand patterns of drug use and design effective harm reduction strategies. These regional applications highlight WBE's versatility and scalability for diverse public health challenges, from infectious diseases to substance abuse [20].

Impact on policymaking and community response

WBE data has increasingly influenced policymaking by offering real-time, population-level health information. Governments have integrated wastewater findings into public health dashboards to complement clinical data, enhancing situational awareness. This integration supports evidence-based decisions on resource allocation, testing priorities, and public advisories. Moreover, community-level WBE results have fostered public engagement and trust by providing transparent health indicators. The ability of WBE to detect emerging threats early has proven invaluable in shaping timely and effective responses, reducing transmission rates, and mitigating healthcare system burdens [21].

Challenges and Limitations

One of the primary hurdles in WBE is the complexity of sample collection and analysis. Wastewater is a heterogeneous matrix containing numerous interfering substances that can affect the stability and detectability of biomarkers. Variability in wastewater flow, temperature, and chemical composition can influence results, requiring rigorous sampling protocols and quality control measures. Analytical techniques such as qPCR and LC-MS/MS, while highly sensitive, demand specialized equipment and expertise. Moreover, low biomarker concentrations and the degradation of target molecules during transit through sewer systems can complicate detection and quantification. Despite its promise, WBE faces several operational, ethical, and analytical challenges. These include variability in sample composition, privacy concerns, and lack of standard protocols across regions (Figure 3). Addressing these limitations is crucial for scaling WBE into mainstream public health monitoring [22].

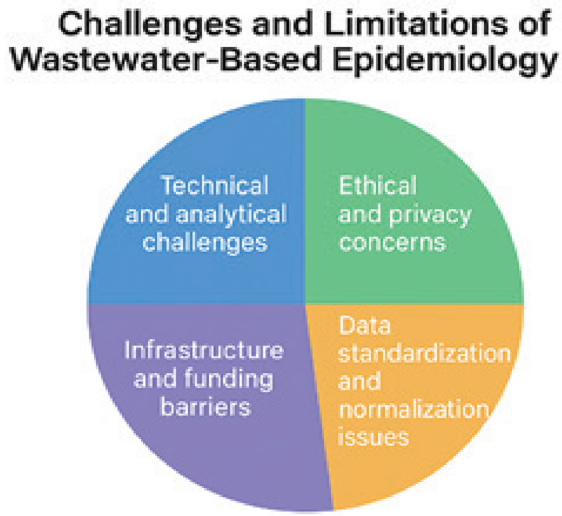

Figure 3. Challenges and limitations of wastewater-based epidemiology.

Ethical and privacy concerns

WBE involves analyzing collective human waste, raising important ethical and privacy considerations. Although WBE does not identify individuals, the potential to monitor small populations or specific buildings can lead to concerns about stigmatization or discrimination. Transparent communication with communities and clear guidelines is necessary to ensure ethical use of data and maintain public trust. Establishing robust data governance frameworks can help balance public health benefits with privacy protections [23].

Data standardization and normalization issues

Comparing WBE data across different locations and time points is challenging due to the lack of standardized protocols. Differences in sampling methods, analytical procedures, and data reporting hinder the establishment of universal benchmarks. Additionally, normalizing biomarker concentrations to account for population size, wastewater dilution, and biomarker excretion rates is complex and can introduce uncertainty. Improved standardization and harmonization efforts are needed to enhance data comparability and reliability. Data standardization and privacy issues remain key challenges in WBE (Table 3) [24].

Table 3. Challenges and mitigation strategies in WBE.

Challenge	Description	Potential Solutions
Sample variability	Fluctuating wastewater composition	Standardized composite sampling
Analytical sensitivity	Low biomarker concentrations	Advanced concentration & detection
Privacy concerns	Potential stigmatization of small groups	Ethical guidelines & anonymization
Data standardization	Lack of harmonized protocols	Development of international standards
Infrastructure & funding	Resource constraints, especially in low-income areas	International collaborations & funding

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Infrastructure and funding barriers

Implementing WBE on a large scale requires significant infrastructure, including laboratory facilities, sampling equipment, and trained personnel. Many regions, particularly in low- and middle-income countries, may lack the necessary resources. Sustained funding is critical to support ongoing monitoring programs, equipment maintenance, and data analysis. Without long-term investment, WBE efforts risk being sporadic or unsustainable, limiting their potential public health impact [25].

Future Directions

The fusion of WBE with digital health technologies and artificial intelligence (AI) promises to enhance data analysis and interpretation. AI algorithms can process large, complex datasets from wastewater samples, identifying patterns and predicting disease trends more accurately and rapidly than traditional methods. Coupling WBE data with real-time health information systems enables dynamic monitoring and decision-making, supporting precision public health. Such integration facilitates early outbreak detection, resource allocation, and targeted interventions, improving responsiveness and efficiency [26,27].

While WBE has primarily focused on infectious diseases and substance use, its potential applications are broadening to include non-communicable diseases (NCDs). Biomarkers related to metabolic conditions, cardiovascular diseases, and even mental health could be detected in wastewater, offering population-level insights into chronic disease prevalence and exposure to environmental risk factors. This expansion could revolutionize how public health monitors and manages NCDs, complementing existing clinical data and informing prevention strategies [28].

To fully harness WBE's potential, establishing coordinated global surveillance networks is essential. Such networks would facilitate data sharing, standardization of sampling and analytical protocols, and cross-regional comparisons. International collaborations could improve early warning capabilities for pandemics and environmental hazards, particularly in resource-limited settings. The development of standardized guidelines and quality assurance frameworks will enhance data reliability, interoperability, and policy relevance. These efforts will promote equitable access to WBE technologies and support a unified global health surveillance infrastructure [29,30].

Conclusion

Wastewater-Based Epidemiology (WBE) has emerged as a powerful and innovative tool for public health surveillance, providing timely, community-level insights into infectious diseases, drug use, antimicrobial resistance, and environmental exposures. Its ability to capture aggregated biological and chemical markers non-invasively makes it a cost-effective complement to traditional epidemiological methods. The COVID-19 pandemic underscored WBE's value in early outbreak detection and real-time monitoring, demonstrating its potential to transform public health responses.

Looking forward, integrating WBE with digital health technologies and artificial intelligence will further enhance its predictive capabilities and precision. Expanding its applications to monitor non-communicable diseases and establishing global surveillance networks with standardized protocols will be critical for maximizing impact. However, addressing technical challenges, ethical considerations, and funding gaps remains essential.

Continued research and investment in infrastructure are necessary to realize the full promise of WBE. By advancing these efforts, WBE can become an integral part of future public health systems, enabling more proactive, data-driven, and equitable health management worldwide.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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