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TECHNICAL NOTES

Systemic Equity in Wastewater Management: Preparedness Roadmaps for Health Justice

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Abstract
This study examines how prioritizing systemic equity can transform wastewater management into a foundation for health justice by ensuring that infrastructure and policies are inclusive and resilient. The pandemic has highlighted that inequities within wastewater systems exacerbate public health threats, leaving marginalized communities vulnerable to poor sanitation and increased exposure to pathogens. While affluent areas were able to utilize tools like wastewater-based epidemiology (WBE) for outbreak tracking, underserved regions faced challenges with overwhelmed treatment facilities. This research identifies key barriers to equitable wastewater management, including fragmented governance, chronic underinvestment, and gaps in technology, and assesses how these issues were worsened during the pandemic. Through qualitative analysis of policy documents and global case studies, the study proposes strategies for building pandemic-resilient infrastructure. It emphasizes decentralized systems, inclusive governance, and climate-adaptive upgrades. The study advocates for actionable strategies such as equity-centered funding, cooperative frameworks that integrate public health and environmental agencies, and community-driven surveillance networks to democratize access to WBE. Ultimately, this research argues that equitable wastewater management is vital for pandemic resilience. It outlines a pathway to transform these systems from sources of inequity into tools for universal health protection through targeted investments and participatory governance. Achieving health justice in wastewater management is both an ethical obligation and a practical necessity to mitigate future public health crises.
Keywords: Wastewater Management, Inclusive Infrastructure, Public Health Surveillance, Systemic Equity, Sewage-Based Epidemiology.

1. Introduction

The COVID-19 pandemic has revealed the vital connection between wastewater infrastructure and public health equity, bringing to light significant differences in how wastewater systems are operated and their effectiveness in safeguarding vulnerable groups(Daza-Torres, Montesinos-López, et al. 2024, Holm, Pocock, et al. 2023). As the pandemic continued, these inequalities became more apparent, particularly in marginalized communities that did not have access to safe sanitation options. In regions with inadequate or fragile infrastructure, increases in wastewater volume and shifts in composition (including heightened pathogen levels and pharmaceuticals) overwhelmed treatment facilities, worsening both environmental pollution and public health threats(Hu, Reckling, and Keshaviah 2023, Arefin et al. 2025). These issues highlight an important truth: wastewater systems are not just technical entities; they are social determinants of health, shaped by systemic inequities arising from historical underfunding, policy oversight, and exclusionary planning that heighten vulnerability during crises.

While wastewater systems are crucial for disease tracking and environmental safety, their availability and resilience greatly differ. Marginalized populations, particularly those in low-income and rural areas, frequently encounter elevated health risks due to insufficient infrastructure. Conversely, wealthier areas benefit from advanced wastewater treatment and monitoring capabilities, thereby widening the health protection gap(Yu et al. 2024, Moradhasseli and Orth 2015). The COVID-19 pandemic underscored the immediate need to reassess wastewater management practices with a focus on systemic equity, highlighting the need for inclusive infrastructure that can address these disparities and improve public health reactions(Corburn 2022, Reckling, Hu, and Keshaviah 2024).

The pandemic illustrated how current wastewater practices can reinforce inequities. Many low-income and rural communities depend on outdated or decentralized systems that are vulnerable to failure, especially during surges in demand, while urban areas with advanced infrastructure employed wastewater-based epidemiology (WBE) to track outbreaks. These discrepancies expose systemic obstacles, including fragmented governance, inequitable funding favoring wealthier regions, and insufficient community engagement in infrastructure planning. Addressing these shortcomings necessitates a move toward inclusive infrastructure, guided by principles such as adaptive capacity, cooperative decision-making, and fair resource distribution(Daza-Torres, Montesinos-Lopez, et al. 2024, Allaire et al. 2024). Such a shift would guarantee that wastewater systems function as instruments for health justice instead of worsening inequality.

To address these issues, this study investigates how systemic equity can reshape wastewater management into a basis for public health resilience. By performing qualitative content analysis on scholarly articles, policy documents, and case studies, the study explores how inclusive infrastructure can reduce public health risks through effective wastewater management. It examines the systemic obstacles to achieving equitable wastewater systems and identifies methods for overcoming these barriers. Additionally, the research looks at how the COVID-19 pandemic highlighted disparities in wastewater infrastructure and its effects on public health protection, particularly in marginalized areas.

Moreover, the study emphasizes the integration of systemic equity frameworks into pandemic preparedness strategies to ensure that wastewater systems are resilient and equitable during future health emergencies. Finally, the research evaluates the design principles and policies necessary for creating inclusive, pandemic-resilient wastewater systems that ensure equitable public health protection. This paper seeks to address the following critical questions:

1. How did the COVID-19 pandemic reveal disparities in wastewater infrastructure and public health protection?
2. What systemic obstacles impede the establishment of inclusive wastewater infrastructure, and how can these be dismantled?
3. What design principles characterize equitable and pandemic-resilient wastewater systems?
4. How does systemic equity strengthen the resilience of wastewater management during crises?

By synthesizing insights from the pandemic, this study outlines preparedness strategies that emphasize health justice. The findings provide actionable methods for incorporating equity into policy frameworks, infrastructure investments, and wastewater monitoring tools like WBE. Ultimately, this paper argues that equitable wastewater management is not only a moral obligation but also a practical necessity for enhancing public health resilience and reducing future outbreaks. Through this research, the paper contributes to the ongoing discussion on health justice, highlighting the imperative for proactive, equity-oriented reforms to ensure that wastewater systems act as means for public health protection rather than sources of systemic inequality.

2. Methodology

This study employed a qualitative content analysis approach to examine the impact of systemic equity in wastewater management, with a specific focus on the challenges and solutions related to public health crises, such as the COVID-19 pandemic. A comprehensive search strategy was developed to identify relevant peer-reviewed articles published over the past decade across multiple academic databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search utilized specific keywords, such as "systemic equity," "wastewater management," "public health equity," "wastewater-based epidemiology," "inclusive infrastructure," and "health justice," to ensure the capture of pertinent literature.

The inclusion criteria were rigorously defined, selecting only English-language, peer-reviewed articles that specifically addressed issues related to wastewater management and public health, emphasizing systemic inequities in infrastructure and crisis response. The studies included in the analysis provided comprehensive insights into the role of wastewater infrastructure in mitigating public health risks and the disparities exacerbated by inadequate systems, particularly in marginalized communities. Full-text availability was a prerequisite for inclusion in the final dataset.

Data extraction followed a structured process using a coding sheet developed after a thorough review of the existing literature. The coding scheme focused on key themes, including the role of wastewater infrastructure in public health, systemic barriers to inclusive infrastructure, the effectiveness of wastewater-based epidemiology (WBE) in monitoring health outcomes, and strategies for improving wastewater resilience in marginalized regions. The study also considered design principles for equitable, pandemic-resilient wastewater systems and examined how systemic equity can strengthen wastewater management during public health emergencies.

To ensure the reliability and validity of the coding process, inter-coder reliability was assessed through independent coding by two researchers, followed by a comparison of results to ensure consistency. Member checking was conducted by consulting field experts to confirm the accuracy and interpretation of the data. The qualitative data analysis software MAXQDA was utilized to assist in coding, categorization, and thematic analysis of the collected data. This software helped to identify patterns and key themes across the literature, facilitating the synthesis of findings related to the central questions of the study.

A total of 863 research articles were identified during the initial search phase. After applying the inclusion criteria and conducting a thorough review, a final set of relevant studies was selected for detailed analysis. Relevant data was extracted from these articles, focusing on the key concepts and themes identified in the literature. The database, along with the complete list of articles included in the analysis, is available upon request.

By analyzing the accumulated data, this study aimed to understand how systemic equity can inform wastewater management strategies that ensure public health protection, particularly for marginalized populations during health crises. The findings contribute to the ongoing discourse on health justice, offering policy and infrastructural roadmaps for more equitable and resilient wastewater management systems.

3. Interconnected Pandemic Impacts on Wastewater: Pollution, Demand, and Public Health

The analysis identified three interconnected main categories shaping the pandemic's impacts on wastewater systems: water pollution, changes in water demand, and public health. We illustrated these interconnected relationships in Figure 1 and have shown the main categories and subcategories/key themes in Table 1. Under water pollution, two key subcategories emerged: (1) changes in wastewater composition—such as alterations in pathogen loads, pharmaceuticals, and disinfectants that affect treatment dynamics—and (2) environmental risks stemming from long-term contamination of ecosystems. In the category of changes in water demand, the primary subcategory identified was the increase in wastewater volume, driven by heightened hygiene practices and home isolation, which significantly strained infrastructure capacity.

Within the realm of public health, three critical themes were identified: (1) wastewater-based epidemiology (WBE) as a surveillance tool for disease tracking, (2) health risks associated with pathogen transmission and waterborne diseases, and (3) challenges faced by sewage utilities, including staffing shortages and supply chain disruptions. Notably, the environmental and health risks connected both water pollution and public health, illustrating their dual consequences for ecosystems and human well-being.

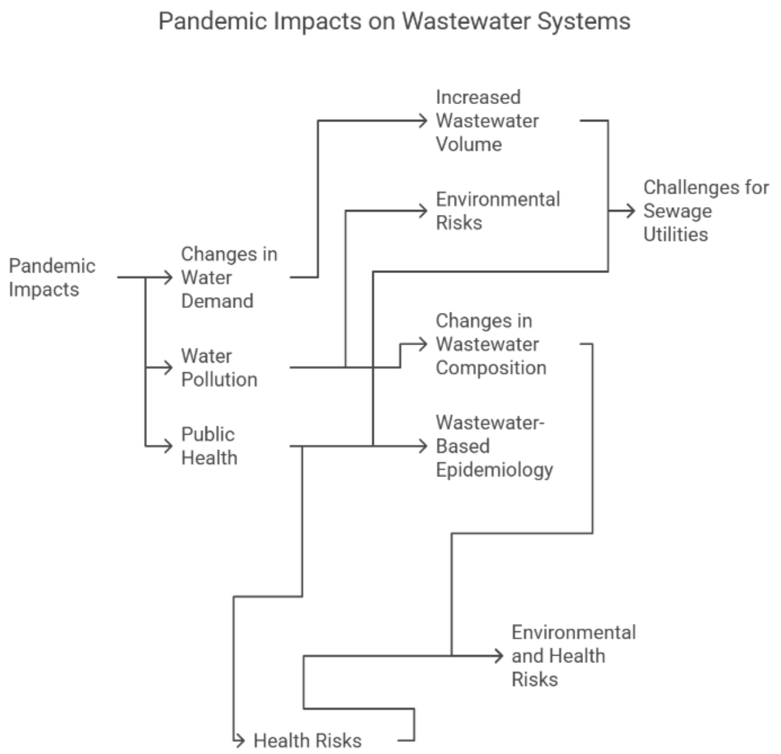

Fig 1: The interconnectedness of pandemic impacts on wastewater systems

Table 1: interconnected main categories shaping pandemic impacts on wastewater systems

Main Category	Subcategories/Key Themes	Key Details
1. Water Pollution	1.1 Changes in Wastewater Composition	Altered chemical, biological, or pathogen content (e.g., SARS-CoV-2 RNA, pharmaceuticals, disinfectants).
	1.2 Environmental Risks (Environmental Dimension)	Long-term contamination of water bodies, soil, and ecosystems due to pollutants in untreated/overloaded wastewater.
2. Changes in Water Demand	2.1 Increased Wastewater Volume	Surges in domestic water use (e.g., hygiene practices, remote work) straining treatment capacity.
3. Public Health	3.1 Wastewater-Based Epidemiology (WBE)	Surveillance for early detection, variant tracking, and community-wide disease monitoring.
	3.2 Health Risks (Health Dimension)	Direct and indirect health hazards (e.g., pathogen transmission, waterborne diseases).
	3.3 Challenges for Sewage Utilities	Operational strains (staffing shortages, supply chain disruptions) affecting treatment reliability and public health safeguards.

3.1. Water pollution

The COVID-19 pandemic has significantly altered the composition of wastewater and intensified pollution risks, primarily due to changes in human behavior, health protocols, and the dynamics of pathogens. Concerns regarding pathogen contamination have arisen, particularly with the detection of SARS-CoV-2 RNA in wastewater, highlighting the potential for indirect transmission in areas with insufficient sanitation(Bandala et al. 2021, Lahrich et al. 2021). Although respiratory transmission remains the primary concern, the virus's persistence in wastewater emphasizes the necessity for strict treatment measures. Additionally, the increased usage of pharmaceuticals, such as antibiotics and antivirals, alongside disinfectants like chlorine, has resulted in higher levels of pharmaceutical and personal care products (PPCPs) and disinfection byproducts (DBPs) in water. For instance, ibuprofen concentrations in UK treatment plants surged by 50%, while U.S. drinking water experienced a 15% rise in trihalomethanes. Moreover, the rise in single-use personal protective equipment (PPE), such as masks and gloves, has contributed to microplastic pollution, complicating treatment efforts(Wojcieszyńska, Guzik, and Guzik 2022, Wilburn, Guha, and Beni 2024). Overwhelmed wastewater treatment systems, strained by staffing shortages, supply chain issues, and increasing volumes of wastewater, have led to instances of untreated or inadequately treated discharges, thereby exacerbating problems like eutrophication and groundwater contamination(Chetia et al. 2021, Paleologos et al. 2020). In the short term, while there was a temporary decrease in certain industrial pollutants, this was overshadowed by a surge in medical waste and pathogen-contaminated wastewater. Looking ahead, challenges such as climate change and economic recovery in the post-pandemic era threaten to reverse any short-term improvements in water quality. Effective mitigation strategies include upgrading treatment facilities to effectively manage pathogen and chemical loads, implementing dedicated waste disposal systems for medical waste, and strengthening regulations on industrial discharges, along with public education to promote responsible waste management and sustainable water practices, such as rainwater harvesting.

3.2. Water Demand Changes

The COVID-19 pandemic has significantly reshaped water demand patterns across various sectors due to changes in behavior, disruptions in supply chains, and policy interventions. Domestic water usage saw notable increases as heightened hygiene practices and remote work led households to consume more water for activities such as handwashing, cooking, and laundry, with reports indicating rises of 15% in the UK and 10% in New York City during lockdowns(Abu-Bakar, Williams, and Hallett 2021, Menneer et al. 2021). In urban settings, a shift towards home gardening contributed to a 20% surge in residential water demand in Chicago(Lüdtke et al. 2021, Warner, Zhang, and Rivas 2020). Conversely, the hospitality industry faced substantial declines, with hotels and restaurants in Spain reporting a 30% drop in water consumption due to closures. Despite this, essential industries like pharmaceuticals in India experienced a 20% increase in water demand to maintain production levels(Filimonau 2021, Garcia et al. 2023). Agricultural water use varied, as California's table grape sector witnessed a 15% reduction in irrigation owing to decreased export demand, while shifts in crop patterns and the rise of home gardening complicated water allocation in both rural and urban areas(Medellín-Azuara et al. 2022, McMillan 2020). Furthermore, the pandemic led to increased wastewater generation, with UK households producing 15% more and healthcare facilities experiencing a 30% rise due to the disposal of medical waste(Alda-Vidal et al. 2020). Industrial activities, particularly in pharmaceutical production in China, contributed to a 20% increase in wastewater discharge(Socal, Sharfstein, and Greene 2021). These changes placed significant strain on wastewater treatment facilities, risking untreated discharges that could lead to environmental contamination and public health issues. Utilities are facing heightened operational costs amidst declining revenues from commercial sectors, highlighting the need for effective mitigation strategies such as upgrading infrastructure, promoting water conservation through efficient appliances, and integrating water management policies with public health initiatives, alongside financial support for utilities to navigate these challenges.

3.3. Public Health

Wastewater management during pandemics serves a dual purpose as both a vital surveillance tool and a potential public health risk. Wastewater-Based Epidemiology (WBE) facilitates early detection of outbreaks by identifying SARS-CoV-2 RNA in wastewater, enabling targeted interventions and monitoring of emerging viral variants through genetic sequencing(Orive, Lertxundi, and Barcelo 2020, Halwatura et al. 2022). This method captures community-level trends and asymptomatic cases, offering a cost-effective alternative to traditional clinical testing. However, improper wastewater management poses significant risks, including pathogen transmission through contaminated surfaces and the potential for waterborne diseases, particularly affecting vulnerable populations in areas with inadequate sanitation. Additionally, the pandemic has led to increased domestic wastewater volumes, overwhelming treatment plants and straining infrastructure, resulting in elevated pollution risks and treatment challenges. To build resilience, it is crucial to invest in infrastructure upgrades, integrate WBE for proactive infectious disease response, prioritize equity in sanitation access, and establish stricter regulatory frameworks for pollutant discharge. Despite its promising potential, WBE faces limitations due to technical barriers and data challenges, underscoring the need for innovative, equitable solutions to address systemic risks and safeguard public health in the face of future crises.

These findings underscore the mutually reinforcing nature of pandemic-driven stressors. Surges in water demand exacerbate operational challenges, while altered wastewater composition heightens pollution and health risks. Together, they highlight the necessity for a holistic framework to address these interconnected risks.

4. Inclusive Infrastructure and Wastewater Surveillance

Inclusive infrastructure is essential for reducing public health risks associated with wastewater management by ensuring that all communities, regardless of socioeconomic status, have access to reliable, safe, and resilient sanitation systems. During public health crises like the COVID-19 pandemic, equitable infrastructure becomes especially important for preventing disease spread and protecting vulnerable populations(Holm, Osborne Jelks, et al. 2023). This type of infrastructure is designed to address the specific needs of marginalized and underserved communities, which are often most at risk due to inadequate or outdated wastewater systems(Keshaviah et al. 2023). By integrating principles such as adaptive capacity, resilience, and accessibility, inclusive wastewater systems can manage surges in wastewater volume effectively, monitor changes in wastewater composition (e.g., pathogen loads), and implement real-time surveillance methods such as wastewater-based epidemiology (WBE) to track infectious diseases. This proactive approach helps mitigate public health risks by identifying outbreaks early and directing resources to areas in greatest need.

Inclusive infrastructure also highlights the importance of community participation in decision-making. This ensures that wastewater management systems are designed and maintained with health equity as a priority. For instance, communities can provide feedback on infrastructure needs, ensuring that investments are made in the areas facing the greatest vulnerabilities—such as low-income or rural areas that often lack access to advanced treatment facilities. Ultimately, inclusive infrastructure not only reduces health risks associated with poor sanitation but also strengthens the resilience of wastewater systems against future public health threats, protecting all populations. In Table 2 and figure 2, we tried to identify systemic barriers to inclusive wastewater infrastructure.

Systemic barriers to inclusive wastewater infrastructure are structural challenges that impede equitable access to safe and reliable wastewater systems, particularly in marginalized or low-resource communities. These barriers often stem from historical underinvestment, fragmented governance, political neglect, and funding biases that favor affluent areas over disadvantaged ones. Additional barriers include outdated or inadequate technology, a lack of community engagement in decision-making, and insufficient policy frameworks that do not address the unique needs of vulnerable populations. In low-resource or marginalized regions, several significant barriers hinder the implementation of inclusive infrastructure. One major issue is insufficient funding; these areas often lack the financial resources necessary for the development and maintenance of infrastructure, with funds frequently getting diverted to wealthier regions or other priorities. A lack of political will can also lead to neglect or insufficient commitment to equity, delaying efforts to meet the needs of marginalized populations.

Fragmented governance and coordination further complicate matters. The lack of collaboration among local governments, private sector stakeholders, and communities slows progress and creates inefficiencies. Additionally, outdated or unsuitable technology poses a challenge. High costs, lack of expertise, and infrastructure incompatibility can prevent the adoption of advanced or sustainable solutions. Limited community involvement in planning and decision-making often results in infrastructure that does not cater to the specific needs of marginalized populations, leading to systems that lack cultural sensitivity. Furthermore, regulatory and policy gaps may fail to address the unique challenges faced by underserved communities, leaving them without the legal frameworks necessary to ensure equitable access to services.

Social and cultural barriers, such as poverty, discrimination, and inequality, further complicate the implementation of inclusive infrastructure. Environmental and geographical challenges, like remote locations or harsh climates, can also hinder development. Together, these barriers exacerbate health risks and limit access to safe, sustainable infrastructure in low-resource regions.

To overcome these barriers, it is crucial to adopt a more inclusive and equity-focused approach to wastewater management. This could involve prioritizing investments in underserved areas, integrating community input into infrastructure planning, and ensuring that policies and funding mechanisms support equitable resource distribution. Promoting innovation in wastewater technologies such as decentralized systems and low-cost treatment methods can also help address infrastructure limitations in resource-constrained regions.

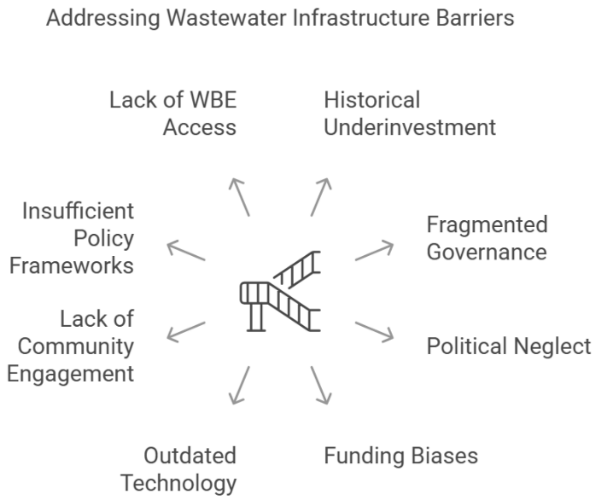

Figure 2: Systemic barriers to inclusive wastewater infrastructure

Table 2: barriers hindering the implementation of inclusive infrastructure

Barrier	Description	Impact on Inclusive Infrastructure	Proposed Solutions
Insufficient funding	Limited financial resources allocated to low-resource areas, often diverted to wealthier regions or other priorities.	Inability to develop or maintain adequate wastewater infrastructure, exacerbating health risks.	Increase public and private investments, establish targeted funding mechanisms, and leverage international aid and grants.
Lack of political will	Political neglect or lack of commitment to equity, with policymakers not prioritizing marginalized regions or addressing systemic disparities.	Delays or failures in addressing infrastructure gaps, leaving vulnerable populations at risk.	Advocate for policy reforms, foster political commitment to equity, and engage stakeholders in the decision-making process.
Fragmented governance	Weak coordination and collaboration between local governments, private sector actors, and communities.	Inefficiencies in infrastructure development, lack of shared resources, and fragmented implementation.	Strengthen governance frameworks, improve inter-agency collaboration, and

Barrier	Description	Impact on Inclusive Infrastructure	Proposed Solutions
			create centralized management structures.
Outdated or unsuitable technology	Use of outdated or inadequate technologies that do not meet the needs of marginalized communities, often due to high costs or incompatibility.	Poor infrastructure performance, inability to address health risks, and limited adoption of sustainable solutions.	Invest in innovative, scalable, and adaptable technologies suited for low-resource settings. Prioritize green technologies.
Limited community involvement	Lack of meaningful participation from local communities in planning, design, and decision-making processes.	Infrastructure may not align with local needs or cultural context, reducing effectiveness and acceptance.	Promote participatory planning processes, engage communities early, and ensure culturally sensitive designs.
Regulatory and policy gaps	Existing policies and regulations that do not support inclusive infrastructure development or fail to address marginalized communities' unique challenges.	Absence of legal frameworks for equitable infrastructure distribution, leading to unequal access to sanitation and services.	Develop and enforce policies that ensure equitable distribution, include marginalized communities in policy development.
Social and cultural barriers	Socioeconomic factors like poverty, discrimination, or cultural stigmas that impede the acceptance or use of new infrastructure systems.	Increased exclusion of vulnerable groups, inability to overcome barriers to sanitation access.	Conduct awareness campaigns, ensure education and training, and foster inclusive and non-discriminatory systems.
Environmental and geographical challenges	Difficult environmental conditions (e.g., remote locations, harsh climates) that hinder infrastructure development.	Inability to deliver wastewater services in challenging environments, leading to gaps in coverage and health risks.	Implement context-specific solutions, such as decentralized systems, and adapt infrastructure to local environmental realities.

5. Wastewater Surveillance: Ensuring Inclusivity During Public Health Crises

Wastewater-based epidemiology (WBE) can be utilized to create equitable outbreak response strategies by offering a cost-effective, community-wide method for detecting and tracking infectious diseases. This is especially important for underserved or marginalized populations that may have limited access to other forms of health surveillance. WBE enables the monitoring of wastewater for pathogens such as viruses, bacteria, and other contaminants, providing early warning signals for public health threats before they can spread widely within communities(Cuadros et al. 2024, Grassly, Shaw, and Owusu 2024). By testing wastewater from different neighborhoods or regions, it is possible to identify infection hotspots in real time, even in areas where individuals may not seek medical care or testing due to social, economic, or cultural barriers(Gahlot et al. 2023, Shrestha et al. 2021).

To promote equity, WBE can help prioritize resources and interventions in the most vulnerable areas, particularly those with limited access to traditional health services. This ensures that funding and public health efforts are directed where they are most needed, preventing marginalized communities from being overlooked. Additionally, WBE can serve as a tool for monitoring disparities in health outcomes, providing data that highlights areas with higher levels of infection or greater health risks. This information can inform targeted interventions, such as tailored public health messaging, improved access to healthcare services, or enhanced sanitation efforts. Incorporating WBE into equitable outbreak response strategies requires ensuring that all communities, especially those with low socioeconomic status or limited access to healthcare, are represented in surveillance efforts. For instance, expanding WBE to rural or remote areas, or ensuring that the data collected addresses gaps in healthcare infrastructure, can foster more inclusive, data-driven responses. Furthermore, community engagement and transparent communication are essential; local populations must be informed about the benefits of wastewater monitoring, and their concerns or needs should be considered when implementing these systems. By using WBE as a tool for equitable outbreak detection, public health responses can become more inclusive, helping to reduce the disproportionate impact of diseases on vulnerable populations.

Wastewater surveillance plays a crucial role in ensuring inclusivity during public health crises by offering a method to monitor public health at the community level, particularly in underserved and marginalized populations that may have limited access to healthcare or traditional testing methods. Unlike individual-level diagnostics, wastewater surveillance aggregates data from entire populations, allowing for the detection of disease presence across various demographic groups, including those who might be reluctant to seek medical help due to social, economic, or cultural reasons. This provides a more comprehensive understanding of public health trends, ensuring that all communities, regardless of their socioeconomic status or geographic location, are included in public health surveillance.

By identifying outbreaks early on, wastewater surveillance ensures that resources—such as medical supplies, testing capacity, and healthcare personnel—can be directed to the areas most in need, especially low-resource regions that are typically at greater risk during health emergencies. For example, during the COVID-19 pandemic, wastewater testing enabled authorities to identify regions with higher concentrations of the virus even before clinical cases became apparent. This head start allowed them to implement preventative measures, allocate resources, and prioritize support for vulnerable communities. Moreover, wastewater surveillance is particularly valuable in areas with marginalized populations, where other forms of health data collection may be incomplete or inaccessible due to barriers like poverty, lack of transportation, or fear of stigma. By offering an anonymous and non-invasive approach to disease monitoring, wastewater surveillance ensures that these populations are not excluded from public health surveillance efforts. This inclusivity can help foster more equitable responses during public health crises, reducing the risk of worsening existing health disparities. Ultimately, wastewater surveillance serves as an equalizer, enabling more proactive and inclusive public health responses by making sure that all communities, regardless of their socioeconomic conditions, are included in monitoring, planning, and response efforts during public health crises. Figure 3, shows summarizes the role of wastewater surveillance in ensuring inclusivity during public health crises.

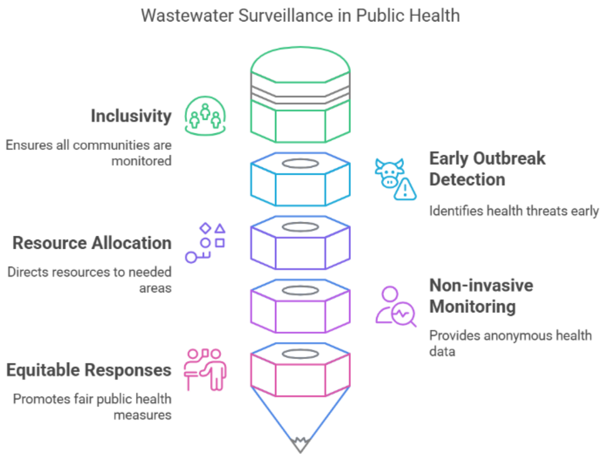

Figure 3: role of wastewater surveillance in ensuring inclusivity during public health crises

6. Conclusion

Achieving health justice in wastewater management requires a transformative approach that integrates systemic equity into policy frameworks, infrastructure development, and crisis response strategies. Historically marginalized communities continue to face disproportionate risks due to inadequate wastewater systems, limited surveillance, and exclusion from decision-making processes. Addressing these disparities necessitates a paradigm shift that prioritizes inclusive policies, equitable resource distribution, and sustainable infrastructure tailored to the unique needs of vulnerable populations.

A robust and equity-centered policy framework is critical to ensuring just wastewater management. Legislative reforms must mandate universal access to sanitation and wastewater services, while targeted funding mechanisms should prioritize historically underserved regions to prevent investment gaps that often leave marginalized communities exposed to environmental and health hazards. Additionally, transparent governance structures and data-sharing policies must empower communities with real-time public health insights, fostering participatory decision-making and accountability.

Infrastructure investments should focus on decentralized, climate-resilient, and cost-effective wastewater solutions to enhance accessibility and sustainability. Adaptive wastewater treatment systems, particularly in resource-limited settings, can reduce dependence on centralized infrastructure that often excludes remote or low-income areas. Moreover, integrating wastewater-based epidemiology (WBE) into public health strategies can strengthen disease surveillance, enabling early outbreak detection and targeted interventions in high-risk communities. Promoting sustainable, low-cost technologies such as biofiltration, constructed wetlands, and water recycling is essential for ensuring long-term affordability and effectiveness.

However, achieving systemic equity in wastewater management goes beyond policy and infrastructure; it requires meaningful community participation and empowerment. Capacity-building initiatives must equip local populations with the knowledge and skills necessary to maintain and manage wastewater systems, fostering long-term resilience and self-sufficiency. Co-designing wastewater strategies with community stakeholders ensures that solutions are not only technically sound but also culturally responsive and aligned with local priorities. By embedding systemic equity into every aspect of wastewater governance, infrastructure, and crisis preparedness, we can transform wastewater management from a source of systemic disparity into a tool for public health protection and environmental justice.

Despite providing a comprehensive analysis of systemic equity in wastewater management, this study has several limitations. The research primarily relies on content analysis of existing literature, policy frameworks, and case studies. While informative, this approach lacks empirical validation through primary data collection. The absence of field research, such as interviews or community assessments, limits the study's ability to capture the real-world challenges faced by marginalized populations. Additionally, wastewater infrastructure and governance vary significantly across regions, and while this study identifies overarching themes, the findings may not fully encapsulate local nuances. Furthermore, while the study focuses on wastewater management in public health crises, broader environmental, economic, and social implications remain underexplored.

To build on this study's findings, future research should incorporate empirical case studies that evaluate the effectiveness of inclusive wastewater interventions in diverse socio-economic and geographical contexts. Comparative analyses between high-resource and low-resource regions could identify scalable best practices. Additionally, research on innovative, low-cost wastewater technologies tailored for marginalized communities could provide practical solutions for bridging existing infrastructure gaps. Investigating governance structures and political accountability in equitable wastewater policies would also offer valuable insights into dismantling systemic inequities. Lastly, interdisciplinary research integrating public health, environmental science, and social justice perspectives can provide a holistic understanding of how wastewater management can advance health equity, climate resilience, and pandemic preparedness.

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* As mentioned earlier, we used MAXQDA 24 for creative data analysis. It uses artificial intelligence protocols to create deeper and more accurate data analysis.

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