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Advancing health equity in wastewater-based epidemiology: A global critical review and conceptual framework

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A B S T R A C T

Population health data from wastewater-based epidemiology (WBE) are being used at unprecedented scales worldwide, yet there is limited focus on how to advance health equity in the field. Addressing this gap, we conducted a critical review of published literature in PubMed, targeting studies at the intersection of WBE and health equity. Of 145 articles assessed in full-text screening, we identified 68 studies with health equity considerations. These studies spanned various spatial scales and biochemical targets, addressing domains such as study design and methodologies, ethical and social considerations, and the feasibility and implementation of WBE monitoring. We summarize and synthesize health equity-oriented considerations across the identified domains. We further propose five key considerations to advance health equity in WBE research and practice, and integrate these considerations into a conceptual framework to illustrate how they apply to major steps in the process of conducting WBE. These considerations include global inequities in WBE access, the need to prevent potential harms and stigma via data misuse (inappropriate reporting of data and potential use of WBE for criminal surveillance), and the importance of regulation and community engagement, particularly amidst the growing privatization of WBE, especially in the United States.

1. Introduction

The COVID-19 pandemic has catalyzed the rapid expansion of wastewater-based epidemiology (WBE) globally. WBE is broadly defined as a process involving the detection and analysis of chemicals or biomarkers extracted from wastewater samples, with the aim of interpreting these results as a measure of community health (Sims & Kasprzyk-Hordern, 2020). Since March 2020, WBE has expanded to become one of the largest monitoring systems of exposure and disease dynamics, with over 4,500 sites reported globally (Aguiar-Oliveira et al., 2020; COVIDPoops19 Dashboard, 2020). While WBE has expanded overall public health monitoring capabilities, WBE's potential to specifically advance the scope of monitoring – and action to reduce – health inequities has received relatively little attention, with health inequity defined as unjust, avoidable, and preventable differences in health outcomes and exposures across sociodemographic groups (Whitehead, Dahlgren & Europe W. H. O. R. O. for, 2006).

Among its potential strengths, WBE is unconstrained by structural barriers to conventional clinical testing and case-based reporting (e.g., systematic exclusion via high costs, lack of supportive services including language services, medical discrimination and mistrust, lack of paid time off, and poor geographic access) that disproportionately affect marginalized and underserved communities (Acosta et al., 2022; Fielding-Miller et al., 2023; McQuade et al., 2023). WBE further enables granular spatial and spatiotemporal tracking of community-level health indicators (including at the level of individual buildings), and thereby can facilitate strategic prioritization of public health resources (e.g., vaccinations and clinical testing), and serve as a sentinel for early outbreak detection, providing advance notice ahead of lagging clinical indicators.

Despite WBE's potential for monitoring inequities, no review articles have critically assessed the WBE literature for how it engages with health equity considerations, including how jurisdictions implement, analyze, report, and act on data generated from WBE to equitably benefit populations. As such, our aim was to identify a body of literature at the intersection of WBE and health equity, and critically assess how each article engages with topics of health equity in its framing, language, motivations and study conclusions. We further synthesize this

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literature across five identified domains, highlighting key gaps and considerations for future work, and propose a conceptual framework. This framework integrates health equity considerations at each major stage of the WBE process – ranging from site selection and sampling, laboratory techniques, epidemiological and statistical methodology, and ultimately, public health reporting and action.

2. Methods

Our critical literature review was guided by a critical public health perspective (Schrecker, 2021), and key exploratory questions: "How has health equity been discussed and how can it be advanced in WBE?" The author team comprised Canadian and U.S. public health researchers, with mixed expertise in infectious disease, drug use, clinical practice, and public health monitoring, in the field of health equity in the United States (US).

In consultation with a research librarian specializing in literature reviews and search string development, we developed a search string (Table S1) to identify WBE studies at the intersection of WBE and health equity, focusing on WBE's relation to disparities, socioeconomic factors, racialized and minoritized groups, neighborhoods, and other social determinants of health. Our search terms were intentionally broad to attempt to capture *a priori* the full spectrum of how health equity may have been considered (or not considered) within existing WBE literature. We identified titles, abstracts, and studies in PubMed from database inception (1966) to March 29th, 2023. Our focus on PubMed stemmed partly from our understanding that WBE is an emerging field with used predominantly for monitoring biological and chemical targets for biomedical and health purposes (e.g., disease and biomarkers). As such, we anticipated that much of the relevant literature might be concentrated within PubMed, the largest collection of medical and health science research in the world. Two reviewers (SM; RB) screened titles and abstracts of identified articles, excluding studies that did not predominantly focus on human health and those without full text available. Any discrepancies between reviewers were resolved through discussion and consensus. Of those articles deemed eligible for full-text review, we first subdivided them into two broad categories: studies with stated health equity considerations and studies lacking any stated health equity considerations (Fig. S1). Among those studies deemed to have health equity considerations, we critically analyzed the framing, language, motivations, and research questions of each study to understand how (or if) health equity considerations were integrated or highlighted as part of the study's discussion of findings. We extracted a range of health equity terms used in each study (see Supplemental Tables 1 and 2), which allowed us to categorize studies as either implicitly (had health equity considerations but were not explicit in their use of the term "health equity") or explicitly (i.e., used the term "health equity") engaging with health equity. We used the explicit use of the term as an indicator of the study's intentional engagement with the concept of health equity, while acknowledging that relevant discussions might also occur in studies not using the term. We additionally extracted health equity-related terms (e.g., environmental justice) in Supplemental Table 2. To ensure a shared understanding of health equity, we were guided by the definition provided by Whitehead, Dahlgren & Europe W. H. O. R. O. for, 2006. We further analyzed and categorized studies based on their primary motivations: (1) examining inequities in health outcomes or exposures, (2) addressing a specific health equity issue, or (3) not explicitly motivated by health equity (examples are shown in Supplemental Table 3 and detailed in Supplemental Table 4). Lastly, we inductively developed a classification system of five cross-cutting domains to describe the variety of ways studies engaged with health equity based on their methodological approaches and content, with each study being assigned a primary and secondary domain (Fig. 2). In Table 1, we provide definitions of each domain along with exemplar studies.

Throughout this review, we took care to use the term "monitoring" as opposed to "surveillance" unless it was explicitly mentioned in the

Table 1
Identified domains in which health equity was discussed in wastewater-based epidemiology literature and exemplar studies.

Domain	Description	Studies included
Descriptive Epidemiology/ Prevalence Estimation Studies	Studies that use WBE to measure and describe health outcomes, including estimating prevalence of health outcomes and/or inequities in health outcomes across groups or communities	Examples of studies examining variations in WBE targets across sociodemographic parameters (e.g., income, education, age, poverty, housing indices, population density, among other area-based measures (Ahmed et al., 2023; Choi et al., 2019; Courjon et al., 2021; Haak et al., 2022; Lai et al., 2013; Lancaster et al., 2022; Price et al., 2021; Rousis et al., 2022; Yang et al., 2022). In addition, Barbosa et al., 2022, specifically examined WBE data reliability in urban slums in Brazil (Barbosa et al., 2022).
Feasibility Studies	Studies assessing the feasibility and/or developing and validating methodology for WBE. This could include assessing feasibility of implementing WBE in an underexplored setting or target, or explores examining or developing WBE methodology, including methods for sampling, laboratory analysis and/or validating WBE data methods against external data sources (e.g., clinical data)	Examples of studies conducting localized WBE monitoring at higher spatial resolution to enable rapid detection of emerging variants, and the ability to identify infection hotspots in marginalized neighborhoods compared to regional WWTP data (Acosta et al., 2022; D'Aoust et al., 2021; Driver et al., 2022; Fielding-Miller et al., 2023; Layton et al., 2022) Examples of studies focused on the challenges of conducting WBE in LMIC settings with limited infrastructure, including the absence of centralized sewer systems and sanitation infrastructure (Barbosa et al., 2022; Chaudhuri et al., 2023; Chigwechokha et al., 2023; Haque et al., 2022; Jakariya et al., 2022; Mota et al., 2021; Murni et al., 2022; Wehrendt et al., 2021).
Representativeness	Studies examining how representative wastewater monitoring is of the target population with regard to sociodemographic characteristics and/or health outcomes	Example studies include Tscharke et al., 2019, who demonstrate the use of national censuses and area-based socioeconomic measures to validate catchment areas of WBE and suggest that WBE studies at the WWTP level should take advantage of when the census occurs to calibrate population biomarkers and methodologies (Tscharke et al., 2019).
WBE Ethics and Social Considerations	Studies discussing ethical and social considerations for WBE for different settings, targets and spatial scales	Hall et al., 2012 discusses the use of WBE to monitor illicit drug use, raising ethical issues when WBE is used at smaller spatial

(*continued on next page*)

Table 1 (*continued*)

Domain	Description	Studies included
		scales such as entertainment areas, prisons, schools, and workplaces (Hall et al., 2012). The study recommends giving lower priority to workplace and school settings until methods are ready for routine use and suggests mitigating risks by not identifying study locations when publishing results. Hrudey et al., 2021 offers ethical guidance for environmental scientists conducting WBE for SARS-CoV-2, highlighting the need for a clear purpose, data quality, consideration of community values, risk minimization, and secure data handling, along with open dialogue with communities to address and weigh individual concerns and public health benefits (Hrudey et al., 2021). Doorn, 2022 argue that traditional individual-focused ethical frameworks are inadequate for assessing contemporary WBE. They state that WBE ethics intersect with data, public health, research, and environmental ethics, necessitating specialized guidelines incorporating these various fields. While WBE benefits public health, Doorn argues it is ethically unsuitable for legal surveillance (Doorn, 20222).
Frameworks	Studies providing frameworks to conceptualize and/or implement wastewater monitoring and pointed towards a global audience	Several studies present frameworks for WBE in low- and middle-income countries (LMICs), emphasizing its role as an early warning system and for public health monitoring (Gonçalves et al., 2022; Kasprzyk-Hordern et al., 2022). Haque et al., 2022 discuss logistical and financial challenges in LMICs, advocating for low-cost sampling methods like passive samplers and validated analysis methods (Haque et al., 2022); Gwenzi, 2022 suggests expanding WBE to environmental reservoirs, proposing calling WBE wastewater, waste, and water-based epidemiology (WW W-BE) to account for WBE in LMIC contexts that lack centralized sewage infrastructure (Gwenzi, 2022). Travis et al., 2021 advocate for using WBE in schools to enhance safety and equity, emphasizing actionable data and collaboration with local health departments (Travis et al., 2021). Adhikari et al., 2022 highlight global inequalities in wastewater treatment infrastructure and suggest improved WBE could aid in monitoring UN Sustainable Development Goals (SDGs). Their study shows that many SDGs are trackable via wastewater biomarkers (Adhikari & Halden, 2022). Other notable frameworks include Keshaviah et al., 2021, which emphasizes national WBE systems for coordinated, standardized public health monitoring (Keshaviah et al., 2021; Thompson et al., 2020 and Sharara et al., 2021) highlight the need for neighborhood-level WBE (Sharara et al., 2021; Thompson et al., 2020).

study, as the term surveillance is under debate among public health scholars due to its association with policing/law enforcement activity (Krieger, 2024a.; Morabia et al., 2024). We used Covidence for data management, and RStudio v.4.2.2 for analyses and data visualization (Covidence—Better systematic review management; Posit, n.d.).

3. Results

Our PubMed search yielded 185 studies which matched search criteria, comprising 10.6% of the total number of PubMed articles indexed by "wastewater based epidemiology" (n = 1,729). Of the 185 articles, 6 lacked abstracts and full-texts and were excluded. Of the remaining 179 (97%), 145 (78%) met criteria for full-text screening (Fig. S1). Across all studies, COVID-19 was the most analyzed outcome (n = 74, 51%). A map of the global distribution of the 145 studies is shown (Fig. 1). Studies were predominantly concentrated in the US (n = 35, 24%), China (n = 10, 6.9%), and Australia (n = 9, 6.2%).

68/145 (47 %) studies included stated health equity considerations, while 77 did not. Among these 68 studies, 9 studies explicitly used health equity terms, and 14 studies had a primary motivation to look at health inequities between groups or countries (Table S3).

The 68 studies that were deemed to have health equity considerations were largely conducted at the Wastewater Treatment Plant (WWTP) level scale (40/68, 59 %), followed by neighborhood/maintenance hole level (30/68, 44%), focused on COVID-19 as the target of interest (56/68, 82%), and were empirical analyses (43/68, 63%). These studies discussed health equity across five primary domains – descriptive epidemiology/prevalence estimation (20/68, 29%), frameworks (20/68, 29 %), feasibility (18/68, 27%), ethics and social considerations (8/68, 12%), and representativeness (2/68, 3%), (Fig. 2). The full citation list for each domain is shown in Fig. 2.

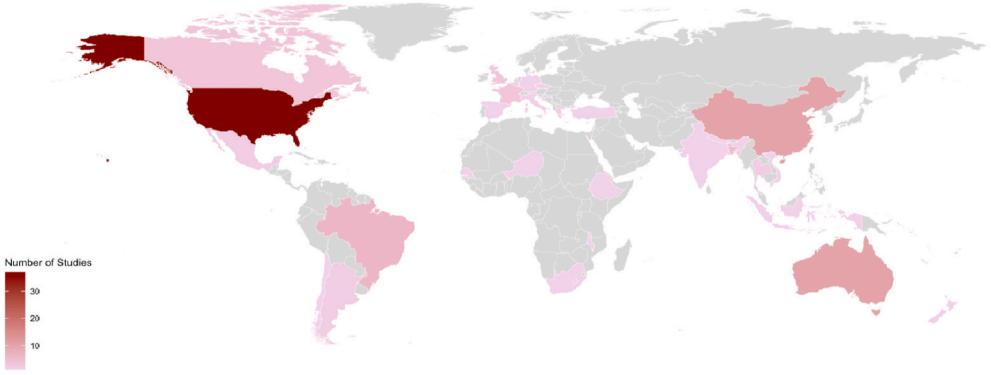


Fig. 1. Global distribution of studies collected in review. All 145 studies included for full text extraction are represented in this map. Legend represents a heatmap of the number of studies included in each country. Map was generated using the ggplot, geom_map function in R version 4.2.2.

3.1. Domain 1: descriptive epidemiology/prevalence estimation (n = 20)

All studies in this domain were empirical analyses and were largely conducted in the post-2020 year period (15/20 75 %), and at the WWTP-level scale (16/20, 80%) (Fig. 2).

Studies in this domain aimed to use WBE to estimate and describe the prevalence or compare epidemiologic burdens between sociodemographic groups or geographic areas. These studies assessed a variety of targets, including COVID-19 (5/20, 25%), illicit drug use (7/20, 35%), prescription drug use (8/20, 40 %) and other targets/biomarkers (9/20, 45%) (Fig. 2). Many of these had a secondary domain of representativeness and feasibility (Fig. 2).

3.2. Domain 2: feasibility (n = 18)

Almost all studies in this domain were empirical analyses (17/18, 94%), mostly focusing on COVID-19 as the target (16/18, 89%), and mostly deemed to have descriptive epidemiology/prevalence estimation as a secondary domain (12/18, 67%) (Fig. 2). Compared to other domains, empirical studies in the feasibility domain were often conducted in low- and middle-income countries (LMIC) and explored multiple spatial scales, including sampling at smaller scales upstream of WWTP-level sampling (Fig. 2).

Feasibility studies often focused on the development, validation, and refinement of methods to implement WBE at small and local scales to prioritize populations impacted by health inequities, including American Indian/Alaska Native (AIAN) reservations, specific neighborhoods, and building-level monitoring in congregate settings (e.g., schools, college/university dormitories, carceral facilities, and in congregate care facilities) (Acosta et al., 2022; Driver et al., 2022; Fielding-Miller et al., 2023; Layton et al., 2022; Pico-Tomàs et al., 2023; van Dyken et al., 2014). These studies also address the feasibility and challenges of conducting WBE in rural and remote areas, emphasizing WBE's role in filling data gaps where sewerage infrastructure and/or clinical monitoring is limited (Table 1) (Driver et al., 2022; Jarvie et al., 2023).

3.3. Domain 3: representativeness (n = 2)

There were only two studies deemed to have a primary domain of representativeness, both of which were empirical analyses that were focused at the WWTP-level and had secondary domains of feasibility (Fig. 2).

Studies in this domain developed methodologies to estimate and characterize the catchment populations of various WBE monitoring programs, to account for biases in WBE systems and reporting that may leave out certain communities and individuals. Studies also investigated the impact of demographic variability on WBE studies, with factors including household income, educational attainment, and military service (Hart & Halden, 2020; Tscharke et al., 2019), and were concerned with understanding whom the WBE data represent (Table 1).

3.4. Domain 4: WBE ethics and social considerations (n = 8)

Most studies in this domain were published in the post-2020 period (6/8, 75%), discussed ethics in WBE illicit drug monitoring (6/20, 30%), and COVID-19 (5/20, 25%) (Fig. 2). Unlike other domains, all these studies were deemed to be health equity motivated.

Studies in this domain highlight the need for comprehensive and continuously revised ethical guidelines that address privacy, consent, and data use, incorporating ethical guidance from the multiple disciplines that form WBE (Doorn, 2022; Hrudey et al., 2021; van Dyken et al., 2014). Recommendations include: mitigating risk at the community level through aggregation techniques and cautious reporting of data; specifically not identifying study locations at small scales when publishing monitoring results; expanding ethical oversight and review of wastewater monitoring; advocating for guardrails to prevent WBE data use/misuse by law enforcement; and the importance of collaboration, transparency and communication with communities prior to introducing monitoring systems, and aligning WBE priorities with community priorities. The only empirical analysis in this domain explored public perceptions of WBE among an online non-representative sample in the US, finding support for community-level monitoring but opposition to sampling individual residences (Table 1) (LaJoie et al., 2022).

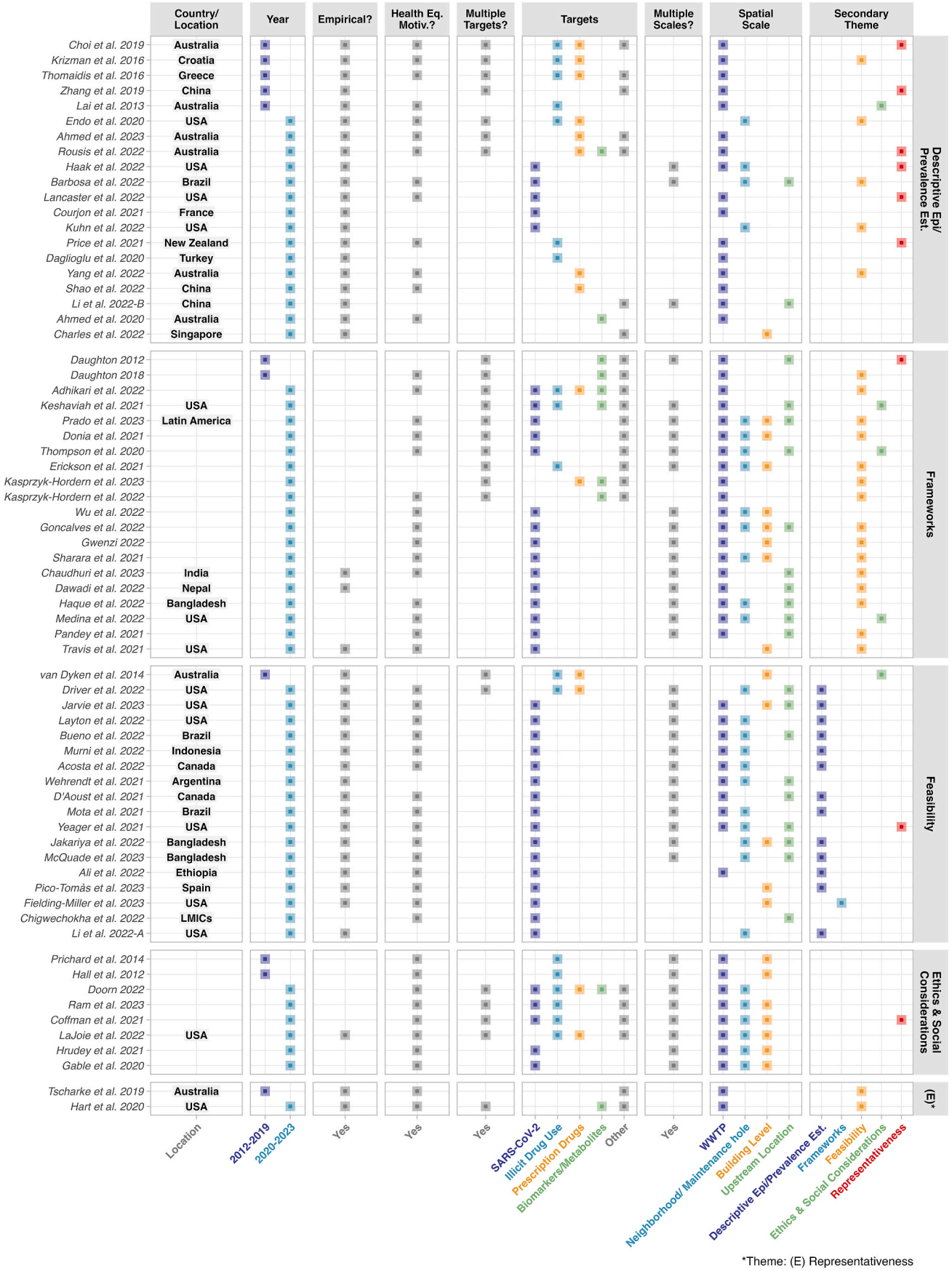
3.5. Domain 5: frameworks (n = 20)

Most frameworks were developed in the post-2020 period (18/20, 90%), with COVID-19 as the primary target (15/20, 75%), and often explored feasibility as a secondary domain (15/20 75%) Fig. 2). There were very few frameworks that also incorporated empirical analyses (3/20, 15%).

Several frameworks were focused primarily on LMIC settings, discussing the critical role of WBE as an early warning system and the use of public health monitoring to enhance public health infrastructure in these settings. Several studies discussed the logistical and financial challenges involved in performing wastewater monitoring in low resource settings, advocating instead for the use of passive samplers or other low-cost methods. Other studies, in turn, proposed frameworks for WBE be integrated into school systems to act as early warning systems and advocated for coordinated efforts on a national scale to establish country level monitoring infrastructure (Table 1).

4. Discussion

We critically reviewed the WBE English-language scientific literature



*Theme: (E) Representativeness

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Fig. 2. Heatmap depicting cross cutting nature of health equity domains identified. All 68 studies classified with health equity considerations are shown on the left axis grouped by primary domain. Country/location, the year of publication (2012–2019 vs 2020–2023), empirical nature of the study (yes vs no), whether the study was health equity motivated (yes vs no), presence of multiple targets of monitoring (yes vs no), type of targets (SARS-CoV-2, illicit drugs, prescription drugs, biomarkers/metabolites, other), multiple scales of monitoring (yes vs no), spatial scale resolution (at the wastewater treatment plant level (WWTP), neighborhood sewer hole, building level, upstream location) is indicated for each study. A secondary theme was classified for each study (if present), by having two authors identify a potential secondary theme (RB, SM) and having a third author adjudicate this decision (TC). In total, 14 studies had a primary motivation to look at health inequities between groups or countries, 39 were motivated by another health equity issue, and 7 were not motivated by health equity but had a health equity consideration elsewhere in the manuscript (see Table S3).

to assess how it engages with issues of health equity. Notably, the 145 articles we identified using PubMed with a focus on human health comprised only 10% of articles indexed by WBE in PubMed. Among these 145 articles, 68 (47%) included health equity considerations (i.e., comprising only 5% of the PubMed articles indexed by WBE), of which only 9 explicitly used health equity terms. Among these 68 articles, five domains in which health equity was discussed emerged: descriptive epidemiology/prevalence estimation, feasibility, representativeness, WBE ethics and social considerations, and frameworks. The net implication is that there is a dearth of WBE literature engaging with issues of health equity, even among studies we identified that met search criteria designed to capture the intersection between WBE and health equity. While it is beyond the scope of our review to ascertain reasons why health equity is so sparse in current literature, we believe that this may be attributable in part to broader patterns of research and funding that have historically prioritized biomedical and technological research over equity-oriented research (Krieger, 2024b).

WBE studies on descriptive epidemiology and prevalence estimation demonstrate that a "one size fits all" approach does not exist in estimating population exposures and trends due to differences in geography, population composition, spatial scale, types of sampling, targets, infrastructure, and environment (Ahmed et al., 2023; Ahmed et al., 2020; Charles et al., 2022; Zhang et al., 2019; Thomaidis et al., 2016; Li et al., 2022b; Shao et al., 2023; Kuhn et al., 2022; Choi et al., 2019; Courjon et al., 2021; Haak et al., 2022; Lai et al., 2013; Lancaster et al., 2022; Price et al., 2021; Rousis et al., 2022; Yang et al., 2022). These studies emphasize the need to integrate detailed socioeconomic and demographic data with WBE data for equitable public health monitoring (Ahmed et al., 2023; Choi et al., 2019; Haak et al., 2022; Lancaster et al., 2022; Price et al., 2021; Rousis et al., 2022). In addition, studies show that approaches at more granular spatial scales are needed to accurately measure and address health inequities, particularly in communities with large health inequities between populations within the same WWTP catchment (Cowger et al., 2024; Holm et al., 2023). Applying national wastewater surveillance methods at the neighborhood level has been shown to obscure inequities and underestimate COVID-19 levels in areas with high morbidity and mortality, prompting the development of equity-centered methods for local monitoring (Cowger et al., 2025). Methodological challenges, such as the need for innovative sampling techniques, especially in rural and LMIC settings, and standardized data analysis methods that allow for broad comparisons across sampling sites, while accounting for local context are also needed (Barbosa et al., 2022; Haak et al., 2022; Lancaster et al., 2022; Murni et al., 2022). Recommendations include using tailored disease prediction models, integrating detailed socioeconomic and demographic data with WBE findings, and employing advanced sampling and GIS-based analysis to improve data accuracy (Haak et al., 2022). These insights are crucial for informing public health programs and policies, guiding equitable resource allocation, and enhancing the effectiveness of intervention programs to advance health equity based on WBE data (Cowger et al., 2024; Holm et al., 2023).

Feasibility studies demonstrate WBE's potential for equitable monitoring. Studies in this domain highlight diverse contexts and approaches for implementing WBE (Ali et al., 2022; Li et al., 2022a; Yeager et al., 2021). Together, these studies underscore the importance of tailored, context-specific approaches to WBE to advance health equity. In high-income countries (HICs), studies often focused on refining methodologies at smaller scales, including building level sampling (e.g., schools, dormitories, carceral facilities), locations upstream of WWTPs in rural and remote communities, and at the neighborhood-level to improve accuracy and spatial granularity of the data (Acosta et al., 2022; D'Aoust et al., 2021; Driver et al., 2022; Fielding-Miller et al., 2023; Layton et al., 2022). In LMIC, studies emphasized developing cost-effective, feasible methods for sample collection and analysis, recognizing informal sewage networks and various environmental media (e.g., surface waters), and addressing technical challenges posed by existing infrastructure (Barbosa et al., 2022; Chaudhuri et al., 2023; Chigwechokha et al., 2023; Haque et al., 2022; Jakariya et al., 2022; Mota et al., 2021; Murni et al., 2022; Wehrendt et al., 2021). Across settings, localized and hotspot community monitoring shows promise to fill data gaps to support equitable public health monitoring in areas lacking adequate monitoring, particularly those not served by a WWTP.

The representativeness domain underscores the importance of accurate population data for advancing health equity in WBE. Tailored approaches, leveraging socioeconomic and demographic data and routine calibration methods (timed with national censuses, if available or other population indicators), are essential for maintaining WBE data reliability over time (Tscharke et al., 2019; Hart et al., 2020). More research is needed to expand these methodologies to low-income settings and at smaller spatial scales to ensure comprehensive and equitable public health monitoring. Studies in this domain often demonstrated that sampling and monitoring at smaller spatial scales provided more detailed, representative data than monitoring at the WWTP-level, and can better capture inequities by addressing biases that arise from monitoring in larger sewersheds (Tscharke et al., 2019). Monitoring temporal and spatial population trends in exposure and disease can be used to guide effective public health responses, especially when WBE findings are corroborated by existing public health data sources (e.g., clinical data) that support WBE's reliability and validity.

WBE ethics and social consideration studies highlight considerations around privacy, consent, communication, risk, the responsible use of data generated, and the need for ethical guidelines that incorporate ethics across multiple disciplines (e.g., environmental health, water ethics, data ethics) (Prichard et al., 2014; Hall et al., 2012; Doorn, 2022; Ram, Shuster, Gable, & Ram, 2023; Coffman et al., 2021; LaJoie et al., 2022; Hrudey et al., 2021; Gable et al., 2020). These studies emphasize the importance of considering ethics when conducting WBE, especially for non-infectious targets and monitoring scales down to smaller populations (Coffman et al., 2021; Doorn, 2022; Hall et al., 2012; Hrudey et al., 2021; Prichard et al., 2014). While guidelines have been proposed, traditional research ethics oversight may have limitations, as their focus may largely be on the assessment of individual-level risk, whereas WBE largely pertains to community-level risk (Doorn, 2022). A prominent and important concern pertains to researchers' ethical obligation to proactively address issues of marginalization, systemic racism, and community trust (Coffman et al., 2021; Doorn, 2022; Ram, Shuster, Gable, & Ram, 2023). Key ethical considerations raised include: avoiding re-identification or stigmatization of communities based on the dissemination of WBE data; engagement of diverse scholars, communities, and stakeholders throughout the research process, to align WBE monitoring with community priorities; the development of clear guidelines for appropriate data use; and balancing privacy rights with potential public health benefits (Coffman et al., 2021; Doorn, 2022; Hall et al., 2012; Prichard et al., 2014; Ram, Shuster, Gable, & Ram, 2023).

WBE framework studies also demonstrate WBE's potential for enhancing both local and global health equity efforts (Daughton, 2012; Daughton, 2018; Medina et al., 2022; Pandey et al., 2021; Donia et al., 2021; Erickson et al., 2021; Dawadi et al., 2022; Wu et al., 2022). Many studies highlight and address the uneven global deployment of WBE, as HICs have been the predominant beneficiaries of WBE. The studies in this domain recommend a multi-faceted approach to address these global inequities and includes the need for frameworks and methods for conducting WBE in decentralized sewerage systems, which should be tailored to the specific needs and infrastructure of the region (Gwenzi, 2022; Adhikari et al., 2022; Prado et al., 2023; Haque et al., 2022; Chauduri et al., 2023). Decentralized approaches, such as targeted-WBE, are suggested as an effective means to monitor specific groups within communities, especially in areas with limited sanitation coverage (Thompson et al., 2020). Furthermore, some frameworks advocated for the integration of WBE into national public health monitoring programs to improve early warning systems and enhance public health preparedness (Kasprzyk-Hordern et al., 2022; Sharara et al., 2021). While other frameworks reviewed WBE's ability to address UN Sustainable Development Goals (SDGs) and socioeconomic and ethical concerns to ensure equitable population benefits from WBE systems (Adhikari et al., 2022; Kasprzyk-Hordern et al., 2023).

Informed by findings from our critical review, we delineate five key considerations to guide future work on WBE and health equity and conclude by offering a conceptual framework to delineate how equity considerations can be addressed across major stages of WBE public health monitoring (Fig. 3).

4.1. Key consideration #1: privatization of WBE data

As discussed in both the WBE ethics and social considerations and framework domains, the first consideration concerns the ongoing privatization of WBE data, particularly in the U.S. Several countries have established fully nationalized public wastewater monitoring programs in response to the COVID-19 pandemic, including the Netherlands, Spain, and New South Wales in Australia (Sharara et al., 2021). In the U.S., however, a large share of federally-funded WBE is contracted through corporate entities, including Verily, a Google subsidiary, and Biobot Analytics, privatizing the means by which public wastewater is collected, analyzed, and reported; this raises concerns over how private interests control the production and use of public health data gathered using public resources and infrastructure. In light of a lack of governmental implementation, oversight and regulation of WBE, private entities may prioritize profits at the expense of public health priorities and protection of public interests (e.g., limited choices of testing targets, privacy concerns associated with selling/sharing data) (Thompson et al., 2020). This concerning movement towards privatization is likely part of a broader phenomenon in the US related to chronic governmental disinvestment in public infrastructure, rendering public entities reliant on technologies and services held by private entities (Feldman & Bassett, 2024). Shifting this trend requires sustained, long-term investments in public health infrastructure. In the short term, however, data regulation and usage agreements are crucial to ensure the responsible collection, sharing, and utilization of wastewater monitoring data, especially by private entities (Ram, Shuster, Gable, & Ram, 2023). These agreements can help protect community privacy, prevent data misuse, and establish clear guidelines for data ownership and access. Importantly, these agreements can provide mechanisms by which scientists and public health practitioners can quickly and efficiently access data during crises. Agreements of this nature can also ensure that data is shared efficiently within existing public health infrastructure, for example by ensuring that there is an obligation for wastewater data to be shared with other public agencies in outbreak settings (Ram, Shuster, Gable, & Ram, 2023).

4.2. Key consideration #2: health equity challenges raised by use of WBE for surveillance and criminalization by law enforcement

Our findings within the WBE ethics and social consideration, and descriptive epidemiology/prevalence estimation domains, highlight a second consideration — the notion of 'function creep', in which the original use of technology (such as WBE for public health monitoring) gradually extends beyond its initial scope to uses outside the original scope (e.g., WBE for criminal surveillance) (Doorn, 2022; Koops, 2021; Scassa et al., 2022). Indeed, the use of the term "surveillance" is under debate among public health scholars, especially when used interchangeably with "monitoring," because of the former's connotations of law enforcement activity (Krieger, 2024a; Morabia et al., 2024). As mentioned, we took care in this review to ensure the term monitoring was used unless the type of monitoring referred to surveillance outside of the scope of clinical/public health use, or when the word surveillance was explicitly used in the discussed paper. Additionally, function creep, and the ability to conduct WBE at smaller scales (e.g., schools, prisons) also raises important questions around the level of aggregation of WBE needed to avoid harms to individuals and communities. The potential expansion from public health wastewater monitoring to punitive surveillance by law enforcement, will only serve to widen inequities through increased policing and criminalization of vulnerable communities (Advancing Public Health Interventions to Address the Harms of the Carceral System, 2021; Scassa et al., 2022). While most studies had the intention of identifying patterns of and reducing harms from illicit drug use across various settings, very rarely did studies discuss the implications of this type of monitoring on the threat or harm of increased policing, including impacts on harm reduction efforts via the potential of communities being stigmatized and labeled as communities who use drugs, or impacts in settings usually subject to increased ethical review and oversight, such as prisons (Krizman et al., 2016; Lai et al., 2013; van Dyken et al., 2014). For example, van Dyken et al., 2014 noted that ethical review can be waived in studies monitoring wastewater for illicit drug use and also highlights potential risks of WBE in prisons, including risk of collective punishment, such as restricting familial visitation and sensationalized media coverage that could be used to justify politically-motivated 'crack downs' on drug use. One study in particular instead suggested criminalization and contributions to the "fight against drugs," as a primary motivator for the use of WBE in illicit drug surveillance (Daglioglu et al., 2021).

Legal scholars in the US have noted that WBE monitoring often falls within the state's broadly recognized police powers (Gable et al., 2020). An example includes the requirement for police forces in many US jurisdictions as traffic controllers to perform sampling from main sewer infrastructure lines that run along high-traffic corridors. This increase in police presence in neighborhoods, however, should not be overlooked, especially in marginalized communities, where negative encounters (e.g., being stopped, searched, or arrested) have been associated with deleterious health outcomes (e.g., poorer mental health, in addition to engendering stigma and fear) (Del Toro et al., 2019; Bowleg et al., 2019; 2020; Geller et al., 2014).

As applications of WBE expand globally, across different sociopolitical contexts, including those where harsh and even deadly consequences are associated with criminalization of drug use, there is a pressing need for global governance and regulation on uses of WBE. The threat of function creep urgently warrants active and global efforts to ensure data protection and proper data dissemination are put into place to solidify wastewater monitoring as a public health strategy intended for the sole use in public health monitoring. A 2023 National Academy for Science, Engineering and Medicine report recommends a strong firewall to be built and maintained to prevent the use of WBE for surveillance and criminalization by law enforcement (Wastewater-Based Disease Surveillance for Public Health Action, 2023).

4.3. Key consideration #3: individual vs community level risk

As discussed in the ethics and social considerations domain, a third consideration for the field is the distinction between individual- and community-level risks. WBE is lauded as a low-risk tool for public health monitoring because the data is already in aggregated form, potentially posing little to no risk of individuals being identified in the data that are collected. Concerns about this notion is amplified when we consider whether wastewater data can truly be anonymized, with salient examples including SARS-CoV-2 detection in wastewater being traced upstream to single toilets (Shafer et al., 2024). Even in cases where individuals cannot be identified in wastewater data, the focus on individual-level risks, especially by Institutional Ethical Review Boards (IRBs) overseeing research at universities and research institutions, ignores the potential for tangible community-level risks (e.g., stigmatization, collective punishment) associated with reporting of WBE data. While routine public health monitoring conducted by public health departments may not fall under the purview of IRBs, it is crucial to recognize that ethical considerations regarding potential community-level harms remain relevant. The potential for harm is especially apparent in studies leveraging WBE to monitor illicit drug use, where one study had suggested increased policing as an intervention (Daglioglu et al., 2021). Ultimately, ethical frameworks and IRBs must consider risks to communities associated with reporting of WBE data, and the possibility of eventual identifiability of individuals through WBE data with growing technologies, to ensure that risks to individuals and risks to communities are adequately considered in WBE monitoring, especially for studies conducted at smaller spatial scales.

4.4. Key consideration #4: public trust and engagement with WBE

Our findings within the WBE social ethics and considerations domain regarding the dearth of knowledge and assessment of public perception of WBE spurs our fourth consideration for the field (LaJoie et al., 2022). WBE involves community-level monitoring that can directly impact public health decision-making, which, as discussed previously, has implications for action within communities (Coffman et al., 2021; Doorn, 2022; Ram, Shuster, Gable, & Ram, 2023). For both research and public health monitoring – transparency, community engagement, and communication about the goals, methods, and potential implications of WBE, are crucial for building and maintaining public trust. Building public trust ensures that individuals and communities feel confident in the confidentiality and ethical handling of their data and allows for implementers of WBE to align public health goals with community priorities. As it stands, consent from community members is not required for monitoring to occur, as noted above, wastewater data have been considered de-identified, aggregate data in many jurisdictions (Gable et al., 2020; Ram, Shuster, Gable, & Ram, 2023). Community-level consent is nonetheless important, especially when monitoring illicit substances, not only to ensure that monitoring is conducted ethically but also to foster trust and buy-in from community members. Establishing credibility and acceptance by communities are important determinants for the success of any public health monitoring system and the corresponding interventions (Doorn, 2022; LaJoie et al., 2022). This area of research was notably underrepresented in our review, with only one study addressing this aspect. In particular, LaJoie et al., used a non-representative online sample in the US to assess public perceptions and acceptance of WBE research. Of concern, the study represented a majority White non-Hispanic population, who may not be representative of the communities who are disproportionately impacted by criminalization and stigma, which is a known consequence of increased police presence in neighborhoods (Doorn, 2022; LaJoie et al., 2022). Nonetheless, the study demonstrated that communities should have input into future policy, application, and regulation measures of WBE practices, emphasizing the importance of community engagement in WBE practices. Further efforts are needed to examine public acceptability of WBE in the context of potential community harms, particularly for illicit drug use monitoring. Investing in trust-building and engagement efforts between public health departments and communities will enhance the credibility and acceptance of WBE initiatives.

4.5. Key consideration #5: profound inequities in the human right to sanitation and water

As discussed predominantly in the frameworks and feasibility domains, our fifth consideration pertains to profound inequities in the human right to sanitation and water, a primary barrier to WBE monitoring in numerous countries. This inequity impacts a considerable number of people, many of whom also face inequities in access to diagnostic testing, vaccinations, and other critical health services. Most WBE monitoring systems are concentrated in HICs, which account for 65 % of systems globally (Naughton et al., 2023). Nations with persistent inequities in access to clean water and sanitation, which could greatly benefit from this low-cost, population-level health monitoring tool, are disproportionately underrepresented in the benefits of WBE. Implementing WBE in impoverished settings can enhance the targeting of health resources and establish ongoing public health monitoring, addressing immediate and long-term health inequities. This underscores the value of WBE in these contexts, given its cost-effectiveness and broad detection capabilities. Our review highlights several studies focused on addressing the global inequities in the use of WBE, through development of laboratory and methodologies to sample a wide range of environmental media, as these forms of methods development remain a major gap in the field. While several studies offer guidance on how to perform wastewater monitoring in LMIC settings (Gwenzi, 2022; Adhikari et al., 2022; Prado et al., 2023; Haque et al., 2022; Chauduri et al., 2023), the field should consider how methods developed in HICs can be reliably adapted to LMIC settings to support addressing the global inequity in the use of this important form of public health monitoring (Hamilton et al., 2024). LMIC settings are either dependent on on-site sanitation systems or lack sufficient solid waste and/or wastewater infrastructure. WBE monitoring in these settings pose numerous unique challenges, notably in detecting pathogens and chemicals across various environmental media, including: raw/untreated wastewater and surface/ground waters, drinking water systems, and solid waste, thus resulting in advocacy to rename WBE to Wastewater, waste and water-based epidemiology (WW W-BE) (Gwenzi, 2022). The predominance of WBE research and monitoring in high-income settings, typically featuring large urban populations served by extensive, centralized sewage networks, make WBE research less applicable and accessible to other contexts, and thus efforts to adapt to LMIC contexts are vital. Finally, it is also crucial to address the broader, marginalizing global forces that contribute to the inability for low-income regions to fulfill their human right to sanitation and safe drinking water. Achieving these fundamental rights would not only facilitate WBE monitoring, but also advance other critical human rights and equity-related health goals (Human Rights to Water and Sanitation, 2022).

The conceptual framework we propose (Fig. 3) engages with these five equity-related considerations and maps them onto the interconnected phases of WBE approaches, explicitly considering spatial scale (e.g., hyperlocal vs. regional), targets (e.g., pathogens vs. illicit substances), and settings (e.g., types of communities) at each stage in the WBE process including laboratory techniques, data analysis and modeling, public health reporting, and public health action. Use of this conceptual framework can help conceptualize how WBE, depending on implementation, the scale and target chosen, can both widen and narrow health inequities through site selection and sampling, laboratory techniques, data analysis and modeling, public health reporting, and public health action. The conceptual framework we propose also emphasizes the importance of explicitly considering all interconnected phases of WBE together, ensuring a cohesive and comprehensive approach to addressing health equity in WBE research and practice.

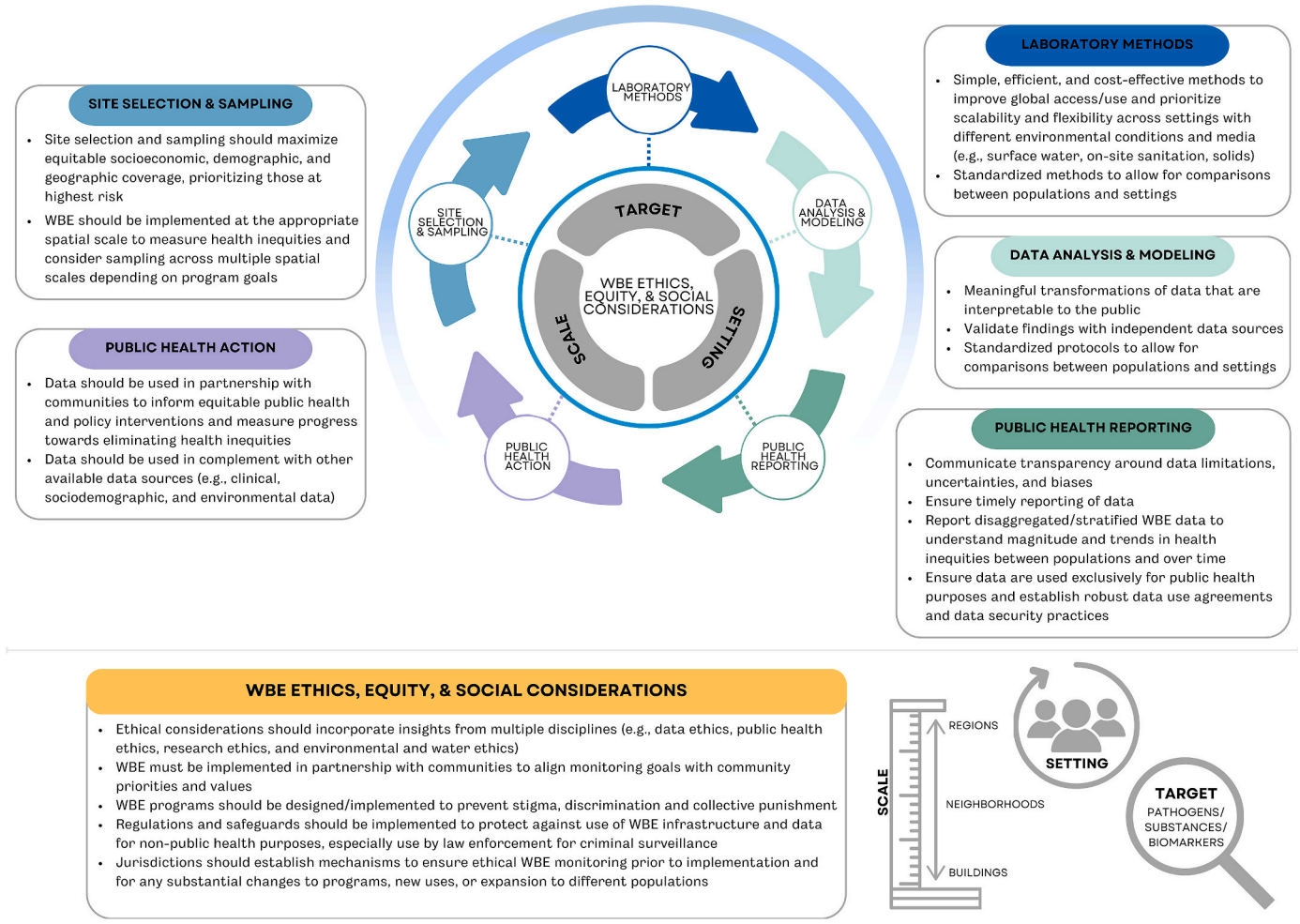

Fig. 3. Overview of the conceptual framework for incorporating health equity into wastewater-based epidemiology research and practice. Key avenues for intervention along the cycle of WBE monitoring, data production and use include during site selection and sampling, establishing of laboratory techniques, data analysis and modeling, public health reporting, and public health action. We also introduce cross-cutting recommendations for ethics equity and social considerations to be considered across all stages, and highlight that these considerations should depend on/interact with the spatial scale, target, and setting in which WBE is implemented.

Our study has several limitations. First, this critical review was limited by the inclusion of only English-language articles and articles indexed in PubMed. We recognize that knowledge claims are influenced by both power dynamics and historical contexts, including our focus on solely English-language scientific literature which may be reflected in the distribution of studies shown in Fig. 1. More specifically, most of the reviewed studies came from English-speaking countries, particularly the US. The corresponding literature overrepresents certain regions, populations, and types of studies related to publishing and index biases in PubMed. In addition, we opted to conduct a critical literature review rather than follow a systematic review protocol to better reflect the broad, exploratory nature of our research question – inductively assessing how studies on wastewater monitoring engage with issues of health equity. Part of our categorization of what is and is not considered health equity may be additionally impacted by our analytic standpoints. We acknowledge the limitations inherent in a critical review approach. While a systematic review focuses on a specific, often narrowly focused research question and aims to minimize author bias through a predefined and structured protocol, broad search strategy, and strict explicit inclusion/exclusion criteria, such a review was not feasible at this stage. The relatively nascent state of health equity considerations within WBE research, and the lack of consistent definitions and frameworks, precluded the development of a robust systematic review protocol. Our critical review, therefore, represents an exploratory first step, designed to identify emerging themes and approaches that may serve as the foundation for future systematic reviews. Additionally, PubMed is extensive, including over 50,000 journals, however future research should consider incorporating additional databases to broaden our understanding of how health equity is being considered within WBE research. Although we used a comprehensive search string to find health equity-related WBE articles, our search only yielded about 10 % of articles indexed by the term WBE in PubMed. This could suggest that researchers do not adequately consider health equity in WBE, including explicit use of keywords and terms related to health equity– where they could be relevant – which thereby reduces our collective ability to find and leverage WBE research to meet key global health equity targets.

5. Conclusion

Amidst the burgeoning field of WBE research and practice, and WBE's potential for advancing health equity, it is concerning that so few studies directly address health equity in their approach. In order for WBE to extend the reach of public health equity efforts, policymakers, researchers, and public health practitioners must ensure that equity is considered at every phase and level of this work. This includes who has access to this technology, the sampling, laboratory and statistical transformation of samples, and estimation of population-level trends and incidence. We also raise five key considerations that require urgent

attention, including the ongoing privatization of WBE data, risks to health equity raised by WBE use for surveillance and criminalization by law enforcement, understanding both individual- and community-level risks, public trust of and engagement with WBE, and the profound inequities in the human right to sanitation and water, which our review highlight as critical omissions in the WBE literature, yet directly relevant to advancing health equity in the field.

CRediT authorship contribution statement

Soroush Moallef: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruchita Balasubramanian:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Nancy Krieger:** Writing – review & editing, Investigation, Conceptualization. **Loni P. Tabb:** Writing – review & editing, Investigation. **Jarvis T. Chen:** Writing – review & editing, Investigation. **William P. Hanage:** Writing – review & editing, Investigation. **Mary T. Bassett:** Writing – review & editing, Investigation, Conceptualization. **Tori L. Cowger:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data sharing

All data and code used to reproduce the figures and results of this paper can be found in the following github repository: https://github.com/ruchitab24/WastewaterHealthEquity. All remaining information is present with this manuscript and supplementary materials.

Ethical statement

The work undertaken involved no human or animal subjects and is in compliance with Elsvier's publishing ethics policy. Specifically, the work described has not been published elsewhere nor is it under consideration for publication. The article's publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. All authors have made substantial contributions to the work in accordance with authorship standards and guidelines. We affirm that if this article is accepted it will not be published elsewhere in the same form. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. William Hanage reports a relationship with Biobot Analytics, Inc. that includes: board membership. Soroush Moallef reports a relationship with Canadian Institutes of Health Research that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2025.101786.

Data availability

All data and code used to replicate the results in the paper can be found at this github repository: github.com/ruchitab24/WastewaterHealthEquity

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