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Annual Review of Environment and Resources

Sanitation for Low-Income Regions: A Cross-Disciplinary Review

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Keywords

Sustainable Development Goals, sanitation service chain, human right to sanitation, waste treatment and reuse, health and sanitation, gender and sanitation

Abstract

Sanitation research focuses primarily on containing human waste and preventing disease; thus, it has traditionally been dominated by the fields of environmental engineering and public health. Over the past 20 years, however, the field has grown broader in scope and deeper in complexity, spanning diverse disciplinary perspectives. In this article, we review the current literature in the range of disciplines engaged with sanitation research in low- and middle-income countries (LMICs). We find that perspectives on what sanitation is, and what sanitation policy should prioritize, vary widely. We show how these diverse perspectives augment the conventional sanitation service chain, a framework describing the flow of waste from capture to disposal.

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We review how these perspectives can inform progress toward equitable sanitation for all [i.e., Sustainable Development Goal (SDG) 6]. Our key message is that both material and nonmaterial flows—and both technological and social functions—make up a sanitation "system." The components of the sanitation service chain are embedded within the flows of finance, decision making, and labor that make material flows of waste possible. The functions of capture, storage, transport, treatment, reuse, and disposal are interlinked with those of ensuring equity and affordability. We find that a multilayered understanding of sanitation, with contributions from multiple disciplines, is necessary to facilitate inclusive and robust research toward the goal of sanitation for all.

Contents

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1. INTRODUCTION

Low- and middle-income countries (LMICs): countries with gross national incomes of less than 12,055 USD per capita (as defined by the World Bank)

Open defecation (OD): the practice of defecating in open spaces (e.g., fields, bushes, forests, water bodies) instead of using a toilet

Unsafely managed excreta harm human health overall and child health in particular. They damage the quality of air, soil, surface water, and groundwater. Yet most of the world's excreta today are unsafely managed or not managed at all. Nearly two decades after the United Nations (UN) identified sanitation as a global development priority, more than four billion people, mostly in low- and middle-income countries (LMICs), lack access to safely managed sanitation (1). Two-thirds of all human waste generated remains unsafely disposed of (2). Despite sanitation's economic promise of multifold investment returns and numerous cross-sectoral benefits—from improving health to educational attainment for girls (3, 4)—realizing universal and sustainable sanitation access has proven to be an elusive task. The call for "adequate and equitable" sanitation for all in Sustainable Development Goal (SDG) 6, with "particular attention" to be paid to women, girls, and vulnerable populations, has lent new urgency to the design and dissemination of affordable, accessible, and safe sanitation systems.

Sanitation policy for low-income regions has been, and still is, driven by the need to reduce open defecation (OD). Recent work has emphasized the human and environmental importance of

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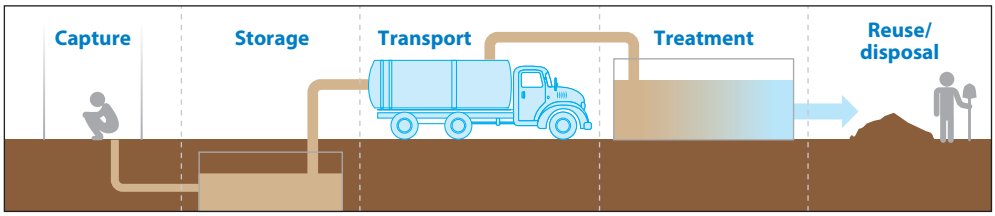

Figure 1

The conventional sanitation service chain, showing the functions of capture (e.g., toilets, pits), storage (e.g., pits, septic tanks), transport (e.g., trucks, pipes), treatment (e.g., centralized or on-site), reuse (e.g., fertilizer amendment), and final disposal (e.g., discharge to environment). Figure adapted from References 18 and 29.

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goals other than public health. These goals include sustainable resource recovery from waste (5), financial and time savings (6), and sanitation as a vehicle for human rights (7) and gender equality (8). Reducing the burden of disease, protecting the environment, increasing economic viability, and safeguarding human rights are all valid goals. In policy and practice, however, differences in how diverse goals are prioritized can lead to contestations about how safe sanitation is to be defined. It is possible to eliminate OD at the expense of dignity and rights, for instance; it is possible to set up waste-to-energy initiatives without sufficient attention to public health. We posit that dissonance between goals may impede progress toward achieving universal access, and a clear articulation of diverse goals and the linkages and gaps among them will benefit both researchers and practitioners.

Diverse goals and diverse priorities are also a feature of disciplinary perspectives within sanitation research. Research on sanitation in low-income regions remains dominated by a focus on containing and removing fecal waste to prevent the spread of disease. These concerns are squarely within the domains of environmental engineering and public health. They are the basis for the sanitation service chain—an established framework describing the multiple functions of waste management from capture to disposal (see **Figure 1**). With notable exceptions, it is only over the past 20 years that the literature has expanded to environmental science, economics, planning and institutional analysis, cultural studies, and gender studies. This diversity has expanded the boundaries of traditional sanitation research, adding richness to our understanding of this complex topic. It has also led to multiple, sometimes disparate, definitions of what sanitation is, what it does, and whom it is for. Most significantly, it has implicitly embedded the conventional sanitation service chain within the many financial, social, and political contexts in which waste flows take place.

The past decade has seen several excellent reviews of sanitation, either alone or combined within water, sanitation, and hygiene (WASH), written from the perspective of a specific discipline (e.g., engineering) or with a focus on a specific impact (e.g., socioeconomic status). Examples include reviews of low-cost sanitation technologies (5), the health impacts of sanitation (9, 10), shared toilets and toilets in informal settlements (11, 12), social marketing (13), behavior change models and experiments (14, 15), the health and education impacts of school sanitation (16), and gender and sanitation (17). Each perspective emphasizes different functions of, and thus priorities for, safe sanitation; therefore, discipline-specific recommendations for progress toward SDG 6 may not always be adequate "for all." Our review takes a broad view and covers sanitation research in engineering, public health, environmental science, economics, planning, and the social sciences. Our goals are to understand the overlaps and differences among these perspectives in how sanitation is seen and why it is important, and thus to facilitate constructive discussion toward greater convergence on safe sanitation for all.

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2. BASELINE UNDERSTANDINGS OF SANITATION

There are two widely used frameworks within which sanitation is often defined in research and practice. The first is SDG 6, which includes specific indicators to define and measure progress toward the UN sanitation goals (1). The Joint Monitoring Program (JMP) is the designated custodian for tracking progress toward SDG 6. The second is the sanitation service chain, which is a descriptive framework rather than a measurement tool, and which has been popularized by the Water and Sanitation Program of the World Bank and the Bill and Melinda Gates Foundation (18, 19). Both the SDG framework and the sanitation service chain are regularly referenced by the disciplines reviewed in this article.

2.1. Sanitation and Sustainable Development Goal 6

In 2000, the international community adopted eight Millennium Development Goals (MDGs) to make and track progress on key dimensions of well-being. Each goal had a set of targets; each target had indicators to measure and report progress. Improved sanitation was included as a target under MDG 7 ("Ensure environmental sustainability"). The target was to halve, by 2015, the number of people without access to improved sanitation. The indicator "improved" sanitation was coined by the JMP to describe a sanitation facility that hygienically separates excreta from human contact, primarily during toilet use. Pour-flush toilets connected to sewers or septic tanks, ventilated improved pit latrines, pit latrines with a slab, and composting toilets were considered "improved." Public, shared, or open pit latrines were "unimproved."

Between 1990 and 2015, 2.1 billion people gained access to improved sanitation and the number practicing OD fell to ~892 million (1), but the MDG sanitation target was not met. The MDGs were critiqued for aiming only to halve the proportion of the population without improved sanitation, thus encouraging countries to target easily accessible rather than difficult-to-reach groups (6, 20). Furthermore, critics argued that the improved-unimproved binary did not reflect the rise of shared toilets, which, while categorized as "unimproved," still provided access to many communities (21, 22). Others advocated for safe waste handling and disposal to be recognized as essential for safe sanitation (5), while gender and health scholars argued for menstrual hygiene management (MHM) as a key component (23, 24).

With the replacement of the MDGs by the SDGs in 2016, sanitation became part of a standalone goal. SDG 6 has eight targets, three of which are particularly relevant for this review. Target 6.2 states the following: "By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations." This now-universal target reflects the explicitly human rights orientation of the SDGs overall; the MDGs called for significant improvements in access to water and sanitation without regard to specific groups such as women or people with disabilities (see the sidebar titled Human Right to Sanitation). Target 6.3 aims to reduce the proportion of untreated wastewater by 50% and increase recycling and safe reuse; Target 6.6 aims to protect and restore "water-related ecosystems" such as rivers and aquifers. SDG 6 represents a significant expansion of the definition of what safe sanitation is, specifically calling attention to marginalized sections of society and to wastewater treatment as part of a safe sanitation system. Furthermore, in the SDGs, several targets and indicators within one goal (e.g., health or education) reference other goals (e.g., water and sanitation). This feature is an explicit recognition that no human right stands alone, and it encourages policy makers and practitioners to go beyond their traditional jurisdictions and seek intersectional solutions to development goals.

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HUMAN RIGHT TO SANITATION

In 2010, the United Nations (UN) explicitly recognized the human right to water and sanitation (160). The UN Committee on Economic, Social and Cultural Rights clarifies the right to sanitation, where sanitation is "a system for the collection, transport, treatment and disposal or reuse of human excreta and associated hygiene [for which] States [i.e., governments] must ensure that everyone, without discrimination, has physical and affordable access to sanitation in all spheres of life, which is safe, hygienic, secure, socially and culturally acceptable, provides privacy and ensures dignity" (161). Through identifying "rights-holders" and "duty-bearers" (usually states), the human rights approach adds a legal dimension to sanitation (157). As with all rights, states can aim for "progressive realization," or continual and steady progress toward ensuring the right for all. The language of this right clearly includes provision of sanitation hardware, but also legal and institutional arrangements, financing, and systems of accountability for sanitation (157). The rights to water and sanitation are often called "gateway" rights, meaning that these rights are precursors to meeting other rights, such as health and education.

What was once the "improved" sanitation indicator is now called "basic" sanitation in the JMP's new sanitation service ladder. The SDG indicator of progress for Target 6.2 is the population proportion using "safely managed" sanitation (1), in which basic—but not shared—toilets are used with the waste being adequately treated either on- or off-site. The conceptual and practical jump from basic to safely managed sanitation is enormous, given that, in 2015, 68% of the global population had basic sanitation but only 39% had safely managed sanitation. Estimates for safely managed sanitation were not available from the least developed countries, where the proportions are likely to be even lower than the global average of the available data (25).

Together, SDG Targets 6.2, 6.3, and 6.6 provide an ambitious framework to guide sanitation policy. Key indicators remain missing, however, for the realization of significant aspects of SDG 6. Indicators do not yet exist for measuring gender-equal access, access for marginalized groups or people with disabilities, or safe wastewater recycling and reuse. For example, the indicator for tracking progress on Target 6.2—the proportion of the population using safely managed sanitation services—cannot, by itself, measure gender-equal access or access for vulnerable populations. Furthermore, while JMP tracks national-level data on primary sanitation access in homes, schools, and healthcare facilities, it has yet to expand to workplaces, refugee settlements, or public places (26). These are especially important for the homeless, migrants, low-income women, and other vulnerable groups (8); even people with household access to toilets may revert to open defecation if they are away from home. The inevitable gaps in the survey- and census-based data that the JMP relies on to track progress—and the mutually reinforcing nature of the sanitation indicators and the data used to measure them—call for a more detailed understanding of where key gaps in sanitation coverage exist and how they can be better quantified.

2.2. Sanitation Service Chain

While SDG 6 sets out global sanitation goals and the targets through which progress toward these goals should be tracked, the sanitation service chain is a descriptive framework with distinct technological steps. The chain as a whole describes the flow of waste from capture to disposal. While precursors of the chain concept (5, 27, 28) can be found in the literature, the Water and Sanitation Program began to diagram and use the terms "sanitation value chain" and "sanitation service chain" in their reports (19, 29), while international development and engineering institutions generated reference literature, standardizing the concept (30, 31). In one of its most widespread forms,

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the sanitation service chain includes the functions of capture (e.g., toilets, pits), storage (e.g., pits, septic tanks), transport (e.g., trucks, pipes), treatment (e.g., treatment plants, on-site treatment), and reuse (e.g., fertilizer) or disposal (e.g., discharge to environment) (see **Figure 1**).

The framework is general and can represent most types of sanitation systems, both safe and unsafe—from open pits or flush toilets to truck-based fecal sludge management (FSM) or sewer-borne disposal—as shown in Shit Flow Diagrams (SFDs) (32) and other sanitation planning tools (31). Not all existing sanitation systems employ all the functions; for example, many LMIC systems convey waste straight to reuse without safe treatment. However, it is assumed that safe sanitation systems should cover all the functions. As with the SDG indicators, labor conditions, social factors, and financing are not explicitly included in the sanitation service chain; it primarily describes managed waste flows from the engineering and public health perspectives. The material flows of the chain, however, cannot exist without nonmaterial flows of political power and finance. We anchor this cross-disciplinary review to the sanitation service chain; we propose an augmentation of the conventional chain to better reflect the understandings of sanitation across multiple disciplines and among multiple actors.

Fecal sludge management (FSM): Collection, treatment, and disposal/reuse of fecal waste captured on-site in containers, latrines, or septic tanks

Shit Flow Diagram (SFD): a visual representation of the proportion of a population that unsafely disposes excreta across the sanitation service chain, used to advocate for strategies to end open defecation and to implement excreta treatment and reuse

High-income countries (HICs): countries with gross national incomes of more than 12,055 USD per capita (as defined by the World Bank)

3. DISCIPLINARY UNDERSTANDINGS OF SANITATION

There is an ancient tale of six blind men who were curious about what an elephant looked like. Each touched a part of the animal, and each concluded that the entire elephant resembled the part that he had encountered. Each understood a partial truth and yet none could imagine the enormous creature in its entirety. Sanitation research is likewise a world of partial perspectives.

To understand how diverse disciplines "see" sanitation, we collected more than 4,000 references in disciplinary and multidisciplinary peer-reviewed journals, as well as from publications of influential implementing organizations. We were not guided by a single focus or question; therefore, this is not a systematic review. Our primary search terms were "sanitation," "toilet," and "latrine," anywhere in the document other than the bibliography. We further collected relevant literature through researcher judgment and expert input. We focused on research outputs; we did not include, for example, policy- or advocacy-based reports prepared by donors or implementers. We also did not include papers published before 1990, the year from which the MDGs started tracking global progress on sanitation. Based primarily on journal type, we organize the literature in the sanitation space into six distinct, albeit partially overlapping, disciplinary perspectives (**Figure 2**). For each perspective discussed below, we (*a*) define its history and scope, (*b*) summarize its key current and emerging themes, and (*c*) discuss how it is represented—or not—in the sanitation service chain. A multiperspective view of sanitation, going beyond the conventional service chain, can lead to a fuller understanding of the flows, functions, and actors that comprise sanitation systems—in other words, of what sanitation is, what it does, and whom it is for.

3.1. Engineering

3.1.1. History and scope. Engineering research has contributed over many decades to designing, developing, and evaluating the physical infrastructures and technologies necessary for sanitation. Engineers have primarily designed toward two major goals: (*a*) separating humans from excreta and (*b*) minimizing impacts of excreta and sanitation systems on human health and environmental quality. The engineering perspective has been a significant pillar of sanitation research, with most research concerning the large, centralized, waterborne systems that became widespread across the cities of high-income countries (HICs) throughout the twentieth century (33). Among the perspectives considered in this review, engineering is most closely tied to the conventional sanitation service chain because it deals explicitly with the physical flow of excreta.

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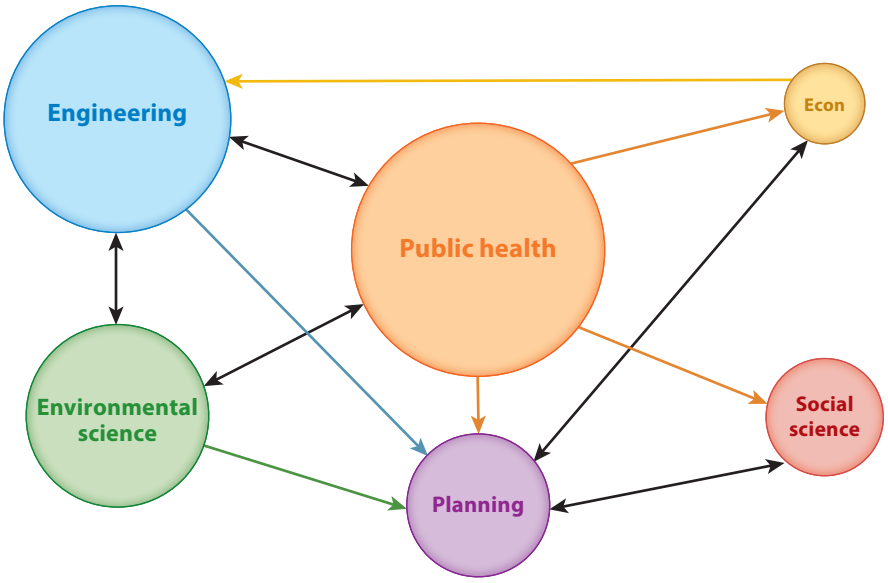

Figure 2

Disciplinary perspectives on sanitation. The size of a circle (not to scale) illustrates the amount of literature that we encountered within that perspective compared to others. The arrows represent a relatively high level of one perspective contributing to—or being referenced by—another (e.g., public health literature is heavily cited in social science, economics, and planning literature). Double arrows represent approximately equal referencing between perspectives. We have omitted connections consisting of few references.

3.1.2. Current and emerging themes. Many research themes in engineering derive from sharp contrasts in sanitation coverage and infrastructure types between LMICs and HICs. In HICs, recent contributions aim to increase the sustainability of centralized wastewater management by reducing energy, chemical inputs, and environmental emissions (34, 35). Ongoing systems-level research aims to assess the sustainability of new treatment and reuse technologies, increasing data quality for more precise modeling and customizing analyses to local conditions (36).

In contrast, much of the engineering research on sanitation in LMICs recognizes the centrality of solutions that emphasize either (*a*) centralized collection and treatment approaches that are less costly and require less electricity, operation, and maintenance than those common in HICs or (*b*) on-site sanitation without waterborne sewerage (37). An estimated 1.8 billion people use on-site sanitation systems (OSS) that require FSM rather than waterborne removal in sewers (38). FSM has emerged as a priority research area for developing options for the safe collection, transport, treatment, and reuse of fecal waste from pit latrines and septic tanks. It is being recognized as a long-term solution for low-income regions and not simply a stopgap until transitioning to waterborne sewerage (30). Both centralized and on-site FSM techniques are being evaluated for their system-level environmental and economic effects, as well as contributions to achieving the SDGs (39–41).

On-site sanitation system (OSS): infrastructure in which excreta are stored or treated where generated, e.g., pit latrines and septic tanks

In HICs, the wastewater treatment sector has become slow to change because of large capital investments in existing centralized infrastructure. In contrast, excreta management in LMICs can be extremely innovative because of differing design constraints as well as lower sunk costs (42, 43). In the past, sanitation has been tailored to HIC constraints; however, designs deemed state-of-the-art in HICs have been unsuccessfully exported to LMICs (43). Future failures can be avoided or minimized only with thorough analysis, rigorous definitions of success, and careful

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risk mitigation (44). More recently, engineers have recognized that decentralized treatment approaches originally developed for unsewered settings in LMICs may have potential in HICs as well, to improve existing on-site systems, to augment centralized systems, or for temporary uses such as emergencies.

Centralized sanitation system: infrastructure in which excreta is collected and transported to a community treatment plant, most often via flush toilets and waterborne sewerage

Container-based sanitation: toilets with replaceable receptacles that can be regularly emptied

Some new technologies and approaches, such as container-based toilets and shared facilities, do not currently meet the SDG definition of safely managed sanitation (2, 38). Given the potential usefulness of these solutions for informal settlements, the definition of "safely managed" sanitation may need to be reexamined (45). New standards are also needed to bring legitimacy to innovative solutions so that they can be scaled-up, including certification of technologies (e.g., safe wastewater reuse) (44). At current expansion rates of centralized excreta management, the majority of people in Asia and Africa will still not experience safely managed sanitation by 2050 (34). To address these disparities, new definitions and designs of safely managed sanitation must be reimagined for extreme scarcity and cost-effective scalability (43).

3.1.3. Engineering and the sanitation service chain. Engineering research addresses several functions of the sanitation service chain. With respect to capture, research has contributed to developing and comparing toilet designs for various low-income settings (5, 31). For LMICs, however, such studies have not sufficiently considered the user experience (e.g., odors, lighting, privacy); insufficient attention has been paid to cultural practices (e.g., washing versus wiping, freedom associated with open defecation, dislike of storing feces in a pit close to home) (46) and to gender- and ability-based design for toilet access. New toilets are being designed with human-centered principles and iterative testing between the laboratory and users in the field (47).

The storage and transport functions are tightly linked for centralized sanitation systems, and the main alternative to conventional sewerage is simplified or condominial sewerage (37). For on-site systems, storage and transport are often delinked; where on-site storage occurs in septic tanks and pit latrines, safe emptying and transport have been a major challenge. New work aims to (*a*) redesign pits for easier emptying (40) or (*b*) employ container-based sanitation, particularly in urban informal settlements, making sanitation storage mobile and thus advancing innovative toilet design and collection strategies (48). Recent research also focuses on improving the efficiency and safety of emptying pits with portable mechanical equipment and safer transport to minimize contaminant emissions and protect workers (40).

Engineering research on the treatment function aims to develop new technologies—or improve existing technologies—by understanding the biological, physicochemical, and mechanical mechanisms through which excreta constituents can be transformed. Historical research areas include low-cost wastewater treatment technologies such as stabilization ponds (49) and on-site treatment through composting or ecological sanitation (31). Recent advances include anaerobic biological treatment to reduce energy use (35); on-site toilets that reduce emissions and combine capture, storage, transport, and treatment (47, 50); and treatment processes specifically designed for fecal sludge (30, 40).

Further along the sanitation service chain, while the practice of reusing treated wastewater and excreta for beneficial purposes has long been recognized (51), recent work emphasizes innovative technologies to facilitate resource recovery. For example, a global spatial analysis identified a large potential to meet fertilizer demands through nutrient recovery and modest potential for energy recovery, while simultaneously meeting multiple SDGs (41). To facilitate resource recovery, new capture, storage, and transport options are being explored, including decentralization to create products closer to the site of reuse (39, 40, 52), as well as source separation of feces, urine (see the sidebar titled Urine and Resource Recovery), and greywater (34). Reuse can also reduce harmful environmental impacts of excreta disposal, such as nutrient-induced eutrophication (34).

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URINE AND RESOURCE RECOVERY

Urine separation is part of a larger body of research on source separation, or separately collecting and treating household waste streams, such as greywater, food waste, urine, and feces (162). One motivation for urine separation is to facilitate the drying of feces; however, as urine treatment processes have developed (163), urine-derived products have become increasingly plausible and attractive. While feces have long been recognized as a source of useful products, over the past two decades, urine has been identified as a low-volume, low-pathogen concentrated source of nutrients. Comprising only 1% of the wastewater volume, urine contains 80% of the nitrogen, 50% of the phosphorus, and 70% of the potassium that humans excrete (164). Urine's high nutrient concentration makes it particularly suitable for production of excreta-derived fertilizers in both sewered and unsewered settings (165). In waterborne sanitation, recovering concentrated nutrients from urine at the toilet can improve treatment efficiency and reduce required inputs while preserving aquatic ecosystems (166). In regions without waterborne sewerage, urine-derived fertilizers can be produced at lower cost than synthetic fertilizers and sold to offset costs of toilet construction and excreta collection (167).

3.2. Public Health

3.2.1. History and scope. The public health perspective focuses on human health outcomes related to sanitation, where health is defined by WHO as "a state of complete physical, mental, and social well-being" (53). The public health–defined goal of sanitation is to protect human health through the complete separation of excreta from human contact. There is a long and illustrious literature on the health consequences of inadequate sanitation, so much so that in 2007, a *British Medical Journal* readers' poll named the "Sanitary Revolution" the greatest medical advance since 1840 (54). Inadequate sanitation has been linked to diarrheal illness, soil-transmitted helminth infection, trachoma, adverse birth and maternal health outcomes, malnutrition, schistosomiasis, and growth faltering (9–11, 55–57). Public health literature on sanitation also includes the study of healthy behaviors (e.g., toilet use) and, more recently, of exposure to animal excreta (58). Major themes in this perspective include (*a*) interrupting the transmission of pathogens, (*b*) toilet use and access for vulnerable groups, and (*c*) intervention strategies and challenges, including behavior change (i.e., adoption and consistent use of toilets).

3.2.2. Current and emerging themes. Diarrheal illness, a leading cause of death among all age groups, is the most commonly measured health outcome in WASH literature, and estimates of the disease burden attributable to inadequate sanitation rely heavily on this outcome (59, 60). Severe diarrhea can have lasting consequences, especially for young children (61). Systematic reviews of sanitation-related outcomes typically cover a range of combined WASH interventions (9, 10), making it difficult to isolate the health outcomes of sanitation alone, especially in observational (as opposed to experimental) studies (62). Details on type, coverage, usage, and quality of sanitation interventions are often poorly reported; these omissions are unfortunate given that these factors may determine the reduction in exposure to feces.

Sanitation interventions are typically conceptualized as interrupting transmission of fecal pathogens from feces to a susceptible host. Tools borrowed from engineering and microbiology are used to identify specific fecal pathogens responsible for specific health outcomes, model associated health risk (e.g., through quantitative microbial risk assessments), and prioritize transmission pathways for intervention (e.g., the SaniPath tool) (63, 64). Recent research has explored environmental enteropathy, linking enteric infections from fecal pathogens to nutrient malabsorption

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MENSTRUAL HYGIENE MANAGEMENT IN SCHOOLS

Menstrual hygiene management (MHM) in schools has received recent attention because of the potential connections between school attendance for girls and the presence of safe facilities. School toilets in low-income settings are often poorly maintained and lack menstruation-sensitive water and sanitation facilities (4). They may not be gender-segregated or even have doors, making it difficult to change sanitary products. The inability to safely and privately dispose of a product leads girls to throw it into the toilet, which makes the school toilet (even more) unusable (147). Although there are few rigorous studies on menstruation and girls' attendance, there is evidence that, without water and convenient facilities for MHM, girls avoid school at least some of the time (16). Recent work suggests that absenteeism overall decreases with clean toilets in schools (14), and that sex-specific school toilets increase girls' enrollment (168). The research on academic performance and safe MHM is inconclusive; however, shame, discomfort, fear of staining one's clothing, and other deeply stressful conditions have been extensively documented. Several authors have found that shame and fear interfere with girls' abilities to concentrate in class when they are menstruating (169). This is also a kind of school absence, albeit not one that is captured in enrollment or attendance data.

(61). Understanding that nutrition and sanitation may interact has led to changing intervention strategies. For example, the recently completed WASH Benefits (rural Kenya and Bangladesh) and SHINE (rural Zimbabwe) studies were large, randomized-controlled trials that included combined WASH and nutrition interventions (65–67); the implications of this work for future sanitation research are still being explored.

A growing body of public health sanitation research focuses on women and girls, who are at higher risk of assault and psychosocial stress related to the lack of privacy and safety when urinating and defecating (68). The field's dominant focus on pathogens fails to account for these nontraditional—and often socially taboo—outcomes (69). However, a focus on menstruators is beginning to expand the public health definition of sanitation (see the sidebar titled Menstrual Hygiene Management in Schools). Qualitative research on psychosocial stress among women and girls suggests that sanitation-related activities should be broadly defined to include fetching water for sanitation use and personal hygiene, bathing, menstrual management, and changing clothes (70).

The public health perspective includes active debates on how to implement effective sanitation in low-income settings. Toilet infrastructure is necessary but known to be insufficient for ending open defecation and achieving health gains (71, 72). Contextual factors at the household, community, or societal level that encourage toilet uptake have largely been ignored in the literature (14); however, these are important determinants of toilet use. The subfield of social epidemiology explores the sociocultural determinants of health: toilet-first (supply-side) narratives list financial constraints as the primary driver of differential sanitation access, while demand-first (demand-side) narratives argue that sanitation interventions need to address social norms and socioeconomic barriers simultaneously (73). Another debate concerns shared versus private toilets: Increased health risks and poorer maintenance are associated with shared toilets (11), but an exclusive focus on disease outcomes undermines benefits such as dignity and privacy that shared solutions could provide (12).

Community-led total sanitation (CLTS): a participatory approach to eliminating open defecation with a focus on changing community-level sanitation behaviors rather than funding toilet infrastructure

Community-led total sanitation (CLTS) is a strategy that focuses on social motivation and peer pressure, rather than financial support, to construct toilets and change sanitation behaviors (74). In a randomized trial in Mali, CLTS was found to increase private toilet access and reduce under-five mortality, even though the simple facilities constructed with local materials would not

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be considered "improved" by JMP's definition (75). However, the overall evidence of CLTS's effectiveness in sustaining behavior change has been questioned (76). Reports of fines, coercion, and shaming as punishment for open defecation within CLTS programs have also prompted reminders that public health goals should not be prioritized over human rights; marginalized individuals are particularly vulnerable to tactics that may reinforce social hierarchies (77).

Overall, public health research is beginning to acknowledge that a narrow focus on reducing diarrhea or increasing child growth falls short of capturing sanitation's full benefits for health, as defined holistically by the World Health Organization (WHO). Additionally, while household sanitation has been the primary focus thus far, there is a growing emphasis on sanitation in schools and healthcare facilities; the SDG goal of universal access covers these non-household settings (16, 78).

3.2.3. Public health and the sanitation service chain. In terms of the sanitation service chain, public health acknowledges multiple steps at which fecal pathogens can be released into the environment. However, public health strategies are primarily concerned with waste capture or lack thereof (i.e., open defecation). The literature's main focus has been on toilets, with systematic reviews often defining sanitation as the use of facilities to reduce contact with human feces (9). However, contact with fecal pathogens can occur at any point along the sanitation chain; for example, if waste captured at the household level is applied untreated to agricultural fields, workers will be exposed. Mainstream health research thus underestimates the benefits of full, community-wide sanitation coverage (10). The later steps in the sanitation chain illustrate clear gaps in public health research. For example, worker exposure to sewage is a major health problem in countries like India, where an estimated two million sanitation workers are tasked with the removal and transport of waste in high-risk conditions (79). Occupational health and safety regulation represents a critical intersection between public health and the establishment of safe sanitation systems; this is gradually emerging as a research (and policy) theme.

3.3. Environmental Science

3.3.1. History and scope. The environmental science perspective highlights interactions between sanitation and the Earth's systems. It includes environmental quality, which assesses the impact of sanitation systems (or lack thereof) on chemical and biological contaminants released to the environment, and environmental microbiology, which extends from public health to infectious disease ecology. Overall, environmental science frames sanitation as a source of pollution emissions as well as a means of mitigating emissions through engineered systems. Such research informs environmental engineering and management, including monitoring, decision making, risk assessment, and regulations for sanitation and environmental quality. Three major themes specific to sanitation in LMICs have emerged from the recent literature: (*a*) reuse over disposal, (*b*) pollution and emissions, and (*c*) climate change.

3.3.2. Current and emerging themes. While the idea of excreta as a resource is not new, it has recently resurfaced through the de facto reuse of wastewater-impacted surface water (80). Globally, 65% of irrigated croplands are in catchments highly impacted by urban wastewater, affecting 1.37 billion residents, the majority of whom live in countries with low levels of excreta treatment (80). Wastewater irrigation productively reuses the nutrients but, if the wastewater is inadequately treated, irrigation increases exposure to biological and chemical contaminants for farmers and consumers. Similarly, fecal sludge can be anaerobically digested to produce biogas, but digester effluent can release contaminants to the environment (5). Producing excreta-derived

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fertilizers, energy, or irrigation water can simultaneously incentivize sanitation management and provide valuable agricultural inputs (81, 82), exemplifying sanitation's role in the food-energy-water nexus (83) and its contribution to a resource-efficient circular economy (81, 84). Regardless of discharge method (wastewater, fecal sludge, or open defecation), the majority of excreta enter the environment unsafely treated (2). When properly treated, safe sanitation reuse can reduce anthropogenic impacts on global biogeochemical cycles of nitrogen, phosphorus, and carbon (84).

Environmental microbiology has focused specifically on microbial pollution resulting from the lack of adequate sanitation, as well as its effects on the quality of water bodies and aquatic species (85–87). Recent work has tracked microbial sources, examined effectiveness of fecal indicator bacteria, and measured specific human pathogens to more precisely assess the contributions of inadequate excreta collection and treatment on environmental emissions (88, 89). Researchers in this field maintain that increasing toilet coverage will attenuate risk, but they recognize that increased coverage alone may not reduce pathogen exposure, suggesting the need for a more holistic, site-specific approach (71, 90).

Chemical emissions from sanitation systems are also important to environmental science. Nutrient-induced eutrophication (87, 91) and trace organic contaminants (e.g., pharmaceuticals) can harm ecosystems and, potentially, human health (92). Recent advances in high-resolution instruments now enable contaminant monitoring at lower concentrations. Sanitation systems also emit airborne pollutants, both directly (e.g., nitrous oxide and methane) and indirectly (e.g., emissions associated with energy use) (36). On-site sanitation systems often employ anaerobic digesters, which can reduce greenhouse gas emissions and recover energy, but which require reliable water access (93) and careful containment to prevent methane emissions (94).

A reversal of the usual focus on sanitation's impact on the environment is research on the environment's impact on sanitation. Hydrologic cycles have mixed influences on diarrheal disease risk: short-term extreme rainfall events can increase risks due to unimproved sanitation, but long-term rainy seasons have a net positive flushing effect on diarrheal disease (95). Recently, animals—specifically ruminants such as cows and goats—have been identified as contributors to fecal contamination in urban and rural households (58); there are no global goals, however, for the management of farm animal waste, although its mass is four times higher than that of human fecal waste (38). Plants can also reduce excreta loads: Wetlands, for instance, can be leveraged to reduce nutrient and carbon loads from sanitation systems (81, 96).

Expanding on the above, the environmental science perspective has begun to consider the effects of climate change on sanitation, describing both positive and negative impacts. In areas likely to become more arid, on-site sanitation infrastructure may more effectively contain pathogens as groundwater tables drop and floods decline in frequency (97). In coastal areas, declining freshwater availability, increased flooding, and higher rates of extreme weather events threaten the effectiveness of sewerage and septic systems using water to convey excreta (97). Environmental science perspectives on how climate change influences sanitation systems inform engineering approaches toward resilient, adaptive sanitation systems with multifaceted controls to safely manage excreta (98).

Several contested ideas have emerged within this perspective. While increasingly sensitive instruments can detect lower contaminant levels, these measurements require context, as detection may not correlate with effects on human health or aquatic ecosystems (89, 91, 92). There is also a debate between centralized, decentralized, and hybrid sanitation systems on account of their differential effects on the environment (e.g., consolidated emissions with centralized treatment versus distributed emissions with decentralized treatment) (34, 52). Lastly, there is tension between safeguarding public health at the expense of environmental quality, because the environmental impacts of on-site sanitation systems and open defecation are often given lower priority than their public health impacts in LMICs (92).

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3.3.3. Environment science and the sanitation service chain. Within the sanitation service chain, the environmental science perspective emphasizes capture, reuse, and disposal. Inadequate capture and disposal are seen as major sources of environmental emissions, while storage, transport, and treatment are secondary. Storage attenuates microbial (but not other) risks, and emissions may occur during transport of excreta. Reuse systems and technologies are not as mature in this literature as their disposal-oriented counterparts. The environmental science perspective emphasizes the non-built (or "natural") environment; it identifies new contaminants that should be measured and attenuated through engineered treatments, such as trace contaminants of emerging concern (92), antibiotic-resistant genes (99), and microplastics (100). These studies often motivate engineering investigations into attenuation mechanisms and broader-scale treatment, such as remediation of surface water bodies. Therefore, environmental science overlaps substantially with environmental engineering because the latter controls emissions from sanitation systems.

Willingness to pay (WTP): the maximum price at or below which a person or group of people will purchase a product or service

3.4. Economics

3.4.1. History and scope. The economics perspective highlights the quantifiable benefits of sanitation (or the costs related to the lack thereof), the preferences and purchasing power of the users of sanitation, and the allocation of resources for the provision of sanitation. Relevant subfields include environmental economics, development economics, public policy, and parts of political economy in LMIC contexts. Overall, sanitation is sparsely covered in top-rated economics journals and not at all in top public policy journals; most of the relevant literature is located in interdisciplinary journals that focus on water and sanitation. Prominent themes include (*a*) sanitation as a proxy or outcome variable, (*b*) benefit-cost ratios for sanitation services, (*c*) cost calculations for services, (*d*) the political economy of sanitation, and (*e*) production efficiency modeling.

3.4.2. Current and emerging themes. Sanitation "access" is treated in economics journals as an explanatory or proxy variable for income, which is itself a proxy for welfare (101). "Access" is also used as an outcome variable when estimating the impact of income on willingness to pay (WTP) for environmental improvements (102, 103). Definitions of access are inconsistent, ranging from access to any type of "improved" sanitation to access to the local utility's sewer system. Economists also assess the impacts of various interventions on sanitation-related outcomes such as toilet access and use. A cluster-randomized trial in Bangladesh, for example, found that subsidies were effective at increasing toilet construction and use, but information campaigns were not (104). Social welfare investments in Nicaragua and Bolivia and foreign aid targeted at water and sanitation also increased access to a toilet (105).

Sanitation-related investments can be evaluated through benefit-cost ratios (BCR), where a BCR of greater than one means that benefits exceed costs. In a review of interventions that included improved access to water and sanitation (including treatment and disposal), the BCR was greater than one in all regions of the globe (106). Similarly, in Southeast Asia, the BCR of on-site sanitation technologies was found to be large and positive across all studied countries, while the BCR for sewerage was lower, but still greater than one, in all but one country (107). BCR can be used as a tool to determine subsidies for sanitation, but generalization is a challenge because the ratio can vary considerably across locations and over time within the same location (108).

In interdisciplinary journals, sanitation is analyzed as a service with associated supply costs and demand preferences, which vary widely by site and by technology. CLTS programmatic costs (e.g., community engagement activities) were roughly three times the cost of private investments in toilets in Ghana and Ethiopia (109). The costs of emptying pits and septic tanks depends on many factors including fuel, mass of waste material, proximity to a disposal site, season, and labor

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(110). Condominial or simplified sewer designs have been found to cost slightly over one-quarter that of conventional sewerage (111). On the demand side, there is ample evidence of user WTP being lower than the cost of toilet construction: In rural Benin, a 75% subsidy would be needed to reach 50% coverage (112). In urban Senegal, tenants were less likely to invest in sanitation, but as likely to pay for emptying, compared to owner-occupied households (113). However, a study of formalized pit-emptying services in Bangladesh found that the average WTP covered only half of the costs (114). Low demand and adoption—even where toilets exist—and the challenges of stimulating demand or behavior change have been widely reported across LMICs (9, 115).

Going beyond households and small communities, political economy research has contributed to important sanitation themes such as autonomy, accountability, decentralization, privatization, participation, and pro-poor policies. There is no consensus, however, on the effectiveness of any of these policies across studies. For example, in Mexico the interaction of decentralization with the commercialization of the water and sanitation sector led to local political conflicts without service improvements (116). In Brazil, participatory, decentralized budgeting improved access to toilets and in turn reduced infant mortality (117). A meta-analysis examining the effectiveness of service provision by "bottom-up approaches," led by NGOs or community-based organizations, often in collaboration with utilities, found that interventions with greater participation of community members were more successful at increasing access, as were services focused on individual as opposed to shared toilets (118). Increased autonomy and accountability in publicly managed water and sanitation utilities have also improved production efficiency (i.e., cost per unit of treatment) and service quality, but not cost recovery (119). In a review of production efficiency studies, benchmarking (i.e., a means to increase accountability through cross-utility comparisons) and increased production scope or scale had a positive impact on production efficiency (120). Overall, political economy of sanitation studies are mostly policy-driven rather than theoretical, and they have overlaps with the domain of urban/sanitation planning.

3.4.3. Economics and the sanitation service chain. Sanitation is depicted in the service chain as a material flow of waste through the environment and through society. But the flows of capital and labor—as determined by financial choices made at the individual, municipal, or national level—determine this material flow. That being said, the economics perspective does not address the full scope of the sanitation service chain; in many cases, sanitation is equated with toilet access (i.e., capture). Even where transport, treatment, reuse, and disposal are included, many papers focus on centralized systems, overlooking on-site or decentralized options. For example, an otherwise comprehensive report on water and sanitation in Karnataka, India, ignored all on-site systems, despite these being common throughout the state (121). Studies that focus on just a part of the sanitation service chain inadvertently conceal the complexities that determine capital and labor allocations within sanitation systems. Furthermore, any mention of MHM or women's and girls' needs in general is largely absent from economic analyses.

3.5. Planning

3.5.1. History and scope. Planners broadly view sanitation as a service that is essential for creating more livable and sustainable communities. With this in mind, much of the current literature critiques overly technological (and elitist) approaches to past planning (122, 123). To avoid this, planners often approach problems by considering the "planner's triangle"—a triangle made up of social equity, economic growth, and environmental protection, within which convergences and conflicts can be negotiated (124).

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The planning perspective encompasses multiple strands that range from highly instrumental to highly theoretical. Some of the more theoretical and critical literatures are covered in the social science perspective below. This section reviews recent research on the practice of planning and governance. Sanitation-related studies focused on LMICs tend to come from development practice with a few prominent studies coming from the more conventional city and regional planning field. There are also studies that originate from engineering-oriented institutions, in particular the growing literature on "sanitation planning." Below, we categorize sanitation research into the subliteratures of (*a*) city and regional planning, (*b*) development planning, and (*c*) sanitation planning.

3.5.2. Current and emerging themes. One of the main contentions in sanitation-related planning research is the disharmony between "modern" centralized infrastructure and the contextual realities across LMICs, often related to the need to consider informal settlements. Conventional city and regional planning research has focused little on the problem of sanitation. In fact, instead of a "wicked problem," in which one set of solutions throws up a new set of challenges, Rittel & Webber (125) called sanitary sewers an "easy problem" that had been dealt with—at least from an HIC perspective. While centralized sewer networks were a significant part of constructing the "modern city" ideal in HICs, sanitation systems in LMICs are often on-site or hybrid (e.g., septic tanks and underground sewers utilized in the same community) (126). Furthermore, in LMICs, networked infrastructure that should unify a city instead splinters it—thus creating a "colonial core" and a periphery consisting of those "not acknowledged as citizens of the network city, even if they are the majority of the population" (122, p. 83). These differences, then, drive planners to consider not only what is planned, but also who is doing the planning. Furthermore, instead of relying on examples from HICs, there is a growing call for planning from the Global South or South–South planning (123, 126). At a more local level, there is also a concern about who participates in various phases of sanitation projects (127) and which stakeholders are left out in sanitation planning (82, 128). Roy highlights the need for deeper, on-the-ground forms of planning participation, building on the Appadurai phrase, "the politics of shit," to emphasize the need for planners to consult the defecators themselves (123, 129).

Development planning and practice literature, as opposed to conventional planning literature, deals more directly with sanitation's political and governance complexities. Sanitation in LMICs is considered comprehensively in terms of both scale and breadth—from the appropriateness of multilateral sanitation agreements (e.g., the SDGs) to contestations over land tenure at the neighborhood scale. *Environment and Urbanization* has offered a year's worth of special issues on sanitation, touching on multiple planning-related challenges (130, 131). What these and other development planning studies have shown are the diverse conditions under which international sanitation norms (e.g., SDG 6) eventually have to be, but are not yet, realized.

Dense urban settlements, where sanitation has been neglected or even ignored (132), have been of particular concern in development planning. Scholars argue that "low-cost" market-based sanitation options that are promoted by domestic and international NGOs may not serve the poorest slum dwellers (133); shared toilets are often unsafe, unclean, and unusable (11), yet private household toilets may be impossible in such spaces (131). Given this reality, improvements in the number, maintenance, and hygiene standards of shared sanitation—which is more scalable and attainable than single-household toilets—may need more attention (21, 22).

McGranahan (134) identifies four "institutional challenges" of sanitation in LMICs, especially in the context of development planning: challenges of collective action, coproduction, affordability, and tenure. Planning problems related to sanitation technology can be understood within these institutional concepts (135). The planner's triangle provides another way of considering

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these challenges, where "property conflicts" are tensions between social equity and economic growth, "resource conflicts" are tensions between growth and environmental protection, and "development conflicts" are tensions between environmental protection and equity. Planners often use several framings that are not in themselves solutions but are helpful heuristics, or ways in which planners explain complex problems (124).

The term sanitation planning has been used broadly in city and regional planning, but it increasingly refers to planning approaches used by development practitioners and engineers. CLTS is a popular intervention to eradicate open defecation in South Asia (74). Beyond this, development practitioners have created planning strategies and tools such as Sanitation 21, community-led urban environmental sanitation, city sanitation plans, and the JMP service ladder (136). A widely adopted advocacy tool used to assist planning is the Shit Flow Diagram (32). Many of these approaches, however, have been only partially implemented, if at all, creating opportunities for future research in sanitation planning. Furthermore, enabling environments, regulations, and enforcement for planning approaches—although called for in policy documents—have not been adequately researched in sanitation planning.

3.5.3. Planning and the sanitation service chain. Considering the comprehensive nature of sanitation planning, this perspective addresses many components of the sanitation service chain, but unevenly so. Historically, planners have focused on sewerage as developed in HICs. With urban challenges in LMICs, researchers have turned their attention to open defecation and toilet building, or the "front end" of sanitation. There are also calls for planning at the "back end" of sanitation—the sanitation service chain beyond the toilet—in terms of technology, affordability, stakeholder participation, and reuse. The integration of governance and infrastructure with economics is where the planning literature extends the current, and technology focused, sanitation service chain. Relatedly, planners are also concerned with the challenges of tenure and equity—neither of which the conventional sanitation service chain can readily address.

3.6. Social Sciences

3.6.1. History and scope. Our final perspective comprises anthropology, geography, political ecology, critical urbanism, and gender studies. Sanitation is treated within the social sciences as a service essential for dignity and citizenship. Historically, sanitation was not a main focus of the social sciences; the "indecent" nature of human waste once made it a taboo subject for explicit discussions within social and policy studies (137). By now, however, toilets and their place in society, culture, and politics have become established research themes. Sanitation-related themes have even been the focus of art, film, and photography.

A sizeable body of work drawing on science and technology studies has analyzed why so many seemingly well-designed sanitation interventions fail in LMICs (138). For instance, a large number of studies we reviewed focus on India. With its enormous slum population and its estimated half-billion people still practicing open defecation (1), India has become a key ethnographic site for understanding sanitation as a social and cultural service (see the sidebar titled Sanitation Challenges in India). We categorize and review three notable approaches within the social sciences that seek contextual understandings of both successful and unsuccessful interventions: (*a*) values and attitudes (i.e., what drives households to adopt toilets), (*b*) social disparities (i.e., the unequal impacts on different groups of how sanitation is defined and promoted), and (*c*) cultural politics (i.e., space and bodies as political objects in sanitation practice).

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SANITATION CHALLENGES IN INDIA

Sanitation literature has historically had a disproportionately large number of studies on India. With more than 500 million people still practicing open defecation (OD) (1), the consequences for child diarrhea and long-term stunting have been severe (141). India's neglect of sanitation in urban planning has led to inadequate and unusable facilities in its sprawling slums (131, 170); the lack of accessible toilets is especially stressful for girls and women, who have high needs for privacy and safety (145, 171). In 2014, the Government of India launched a massive campaign, *Swachh Bharat Mission*, to build toilets and eliminate OD, with a 2018 budgetary allocation of ~$2.5 billion (172). Social marketing campaigns (e.g., "No toilet, no bride!") are also actively promoted. Sanitation uptake and maintenance have been especially hard in India (72, 141) where taboos have traditionally designated (only) the most marginalized castes as toilet cleaners. While the manual removal of feces from unsewered toilets is illegal, it still provides employment for these groups. New technologies for safe fecal sludge management and new business models for sanitation services, both strongly backed by the Bill and Melinda Gates Foundation, have become active sites of research and pilot-level projects in several Indian states.

3.6.2. Current and emerging themes. The values approach seeks to explain the adoption and use—or nonuse—of household toilets, and argues that few households seem to want or use toilets for health reasons. Freedom from shame is essential if women are to use toilets regularly (23), although shaming may be an "effective" tool against open defecation (139). Status, urban proximity, wealth, and education (140), coupled with attitudes toward open defecation (46), are also likely to drive toilet use. In rural India, however, even wealth and education are weakly associated with adoption (141); the authors surmise that culture, in this case the Hindu concept of caste purity, is responsible for the de facto devaluation of household sanitation. This literature overall calls for a contextual understanding of the value of sanitation beyond its role in health and beyond household-level characteristics.

The core disparities in the sanitation literature are well-known: Only 39% of the world has access to safely managed sanitation, and rural–urban and interquintile divides remain sharp in almost all LMICs (1). Recent work has argued that standard measures of access or availability underestimate disparities; the processes and practices through which sanitation is accessed are themselves highly unequal (2, 142). Factors that allow one person's "safe" toilet to harm another through unregulated disposal, for example, must be recognized as sanitation injustice (143). The labor of sanitation, meaning the unprotected conditions in which pit latrines are cleaned and the waste moved out of the community, is also a form of sanitation injustice; the majority of India's manual cleaners are low-caste women who contend with daily assaults on their health and dignity (8, 144). These disparities and human rights violations are mostly invisible in national or international sanitation policy documents (79).

Research on gender disparities has shown that women without safe sanitation face unique stresses—from walking long distances to being assaulted—as they find ways to defecate, urinate, and manage their menstruation (145). For social as well as biological reasons, women and girls need more privacy, time, and space in the toilet than men do, but sanitation facilities are seldom designed around these needs (146). The shame and taboo associated with menstruation have become a global mental health issue (23), which has led to calls for girl-friendly school sanitation (147, 148) (see the sidebar titled Menstrual Hygiene Management in Schools). Toilet promotion programs such as CLTS are starting to include MHM in their training and outreach (149). However, gender-equal access to public toilets as part of equitable urban design (150), transgender-inclusive toilets (151), and the role of accessible public toilets in liberating women and girls when they are away from home (8) remain understudied themes.

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Finally, the cultural politics approach takes infrastructure, place, and the human body itself as terrains over which meanings are made and power is exercised. Unequal and fragmented infrastructure produces unequal and fragmented cities (122). When sanitation is provided by a mixture of sewers, users' associations, small-scale providers, and political patronage, then power over infrastructure services becomes a form of everyday power over citizens (152). Furthermore, inadequate sanitation in informal settlements leads to coping mechanisms and daily inconveniences that reproduce urban inequalities through lived, bodily experiences (153), but also to forms of collective action and political performance such as theater and art (154). Open defecation itself can be considered a threat to public health (which is the prevalent policy discourse) or a threat to the expected social order (which may be only implicitly acknowledged) (155). Through these studies, researchers "see" sanitation infrastructure, governance, and the body as mutually shaping one another.

3.6.3. Social sciences and the sanitation service chain. In terms of the sanitation service chain, the social sciences clearly address access to and the value of toilets (capture), indirectly discuss storage, uniquely address the conditions of the labor that conveys the waste from toilet to disposal site (transport), do not discuss treatment, and just touch on the inequities created by unregulated disposal or reuse. This perspective is most strongly associated with the understanding of sanitation as a human right (see the sidebar titled Human Right to Sanitation). The gendered nature of almost every link in the sanitation chain is front and center in this perspective, especially with respect to front-end access, back-end labor, and MHM. The social sciences highlight perceptions, processes, priorities, and politics—all of which are invisible in the fundamentally "physical" flows of waste that the traditional sanitation service chain comprises. They define sanitation as a service that shapes the daily human experience, and they connect that seemingly small experience to larger networks of pipes as well as of power.

4. DISCUSSION

The sanitation service chain provides a useful framework for understanding the physical flows and functions comprising sanitation systems. Across all disciplinary perspectives that deal with low-income regions, the sanitation literature's primary focus is on capture (e.g., eliminating open defecation, increasing toilet access) with the next level of scrutiny on disposal. The overarching emphasis on capture reflects the earliest and still-dominant focus of sanitation: to separate the human body from its own pathogenic waste.

In its traditional format, the sanitation service chain challenges us to think of the flows of excreta beyond toilets as they are processed through physical infrastructure. At the same time, the current chain bounds the sanitation sector's understanding of what it takes to maintain this flow from capture to eventual reuse and disposal; it de-emphasizes the social, financial, and political "flows" that shape, and indeed make possible, the material flows of waste. An augmented version of the sanitation service chain, showing nonmaterial flows and the stakeholders who shape—and are linked by—these flows, would make clear the simultaneously physical and social nature of the sanitation system. Our cross-disciplinary review suggests that an expansive view of the sanitation system is important for interpreting, and thus achieving, the SDG 6 target of adequate and equitable sanitation "for all."

4.1. Flows and Functions of a Sanitation System

As this review shows, engineering and public health remain the largest bodies of literature represented in the sanitation space. The review also shows that the intellectual domain of sanitation has

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Table 1 Sanitation system flows, functions, and goals as addressed in the literature

Disciplinary research perspectives	Flows[a]	Conventional functions addressed[b]	Additional functions addressed[c]	Goals supported[d]
Engineering	Feces, urine, water, pathogens, nutrients, chemicals	Capture, storage, transport, treatment, reuse, disposal	None	Technologies separating humans and waste
Public health	Pathogens, psychosocial stressors	Capture	Behavior change, monitoring health impacts	Protection of human health
Environmental science	Pollution, hydrologic, biogeochemical	Transport, treatment, reuse, disposal	Monitoring environmental impacts, risk assessment	Environmental protection
Economics	Finance, labor	Capture	Benefit-cost analysis, impact assessment	Economic viability of services
Planning	Decision making	Capture, transport	Planning, participation	Sustainable and livable communities
Social sciences	Political power, labor	Capture, transport	Addressing social norms, analyzing disparities	Dignity, human rights, and equity

[a]Flows include both material and social sanitation system flows.
[b]Conventional functions addressed lists the conventional sanitation service chain functions that are emphasized in each literature.
[c]Additional functions addressed lists the social functions beyond the conventional sanitation chain reported in each literature.
[d]Goals supported identify the sanitation goals supported by each area of research.

gone beyond these two perspectives to encompass environmental science, economics, planning, and social science. These additional perspectives explicate the nonphysical flows within which the physical flows of waste are embedded. Environmental science emphasizes the flows of contaminants into the environment that result from inadequate sanitation. Economics analyzes the flows of investments and financing that households and utilities must procure to install sanitation infrastructure, as well as the types of infrastructure that the resource base can support. Planning is concerned with the flows of policies and decisions, with varying levels of community participation, that determine where and for whom sanitation infrastructures are built or not built, and who maintains what is built. Finally, the social sciences bring in flows of power and labor, along with the economic and gender inequalities that shape the—often invisible—constraints within which planning, economic, public health, and engineering decisions are made and executed. These social flows run between and across stakeholders, but unlike waste flows, they often are multidirectional.

This interdisciplinary perspective highlights the additional sanitation-related functions that are absent in the original, engineering-oriented sanitation service chain (see **Table 1**). By functions, we mean processes or actions that are part of a sanitation system. In the research literature, public health has extended sanitation's "pure" function of interrupting transmission pathways (e.g., through toilet use) by emphasizing social behavior as a component of a sanitation system. Environmental science emphasizes monitoring and risk assessments as a function of safely managed sanitation, an explicit acknowledgment of sanitation's potential third-party effects. Economics contributes benefit-cost and impact assessments of sanitation for households, communities, and utilities. Planning considers participatory decision making and the process of planning itself as part of safe sanitation. Finally, the social sciences foreground the need to analyze and address social disparities and norms in order to achieve adequate sanitation for all. This list of the social functions of sanitation is not comprehensive; for instance, the research literature does not address

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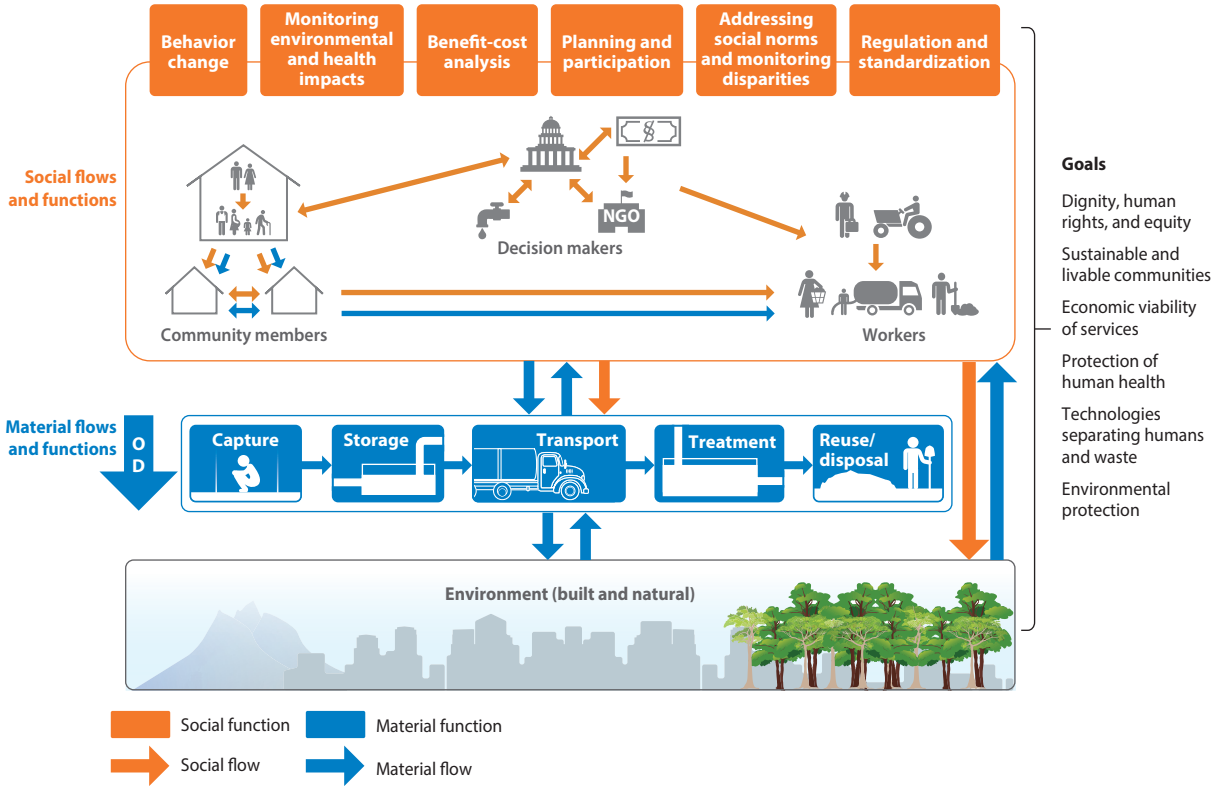

Figure 3

An augmented sanitation service chain. This augmented chain expands the material functions (*blue boxes*) and flows (*blue arrows*) of the conventional service chain by including the environment (*bottom*), social functions (*orange boxes*) and flows (*orange arrows*), and main stakeholders. Social flows include decision making and financial power, and/or ability to affect others. Stakeholders are grouped as community members (households, etc.), decision makers (donors, governments, utilities/service providers, NGOs), and workers (construction workers, truck and plant operators, sewer workers, farm laborers, domestic workers, etc.). OD refers to open defecation. The various material and social functions, flows, and actors of the chain determine the goals (*gray box*), although not part of the chain.

the critical processes of regulating technology and safety standards for sanitation services. Furthermore, as with the physical functions in the conventional service chain, the list is normative; there is no assumption that all sanitation systems will employ all these functions, or that these functions will be carried out in a sustainable and inclusive manner. The flows and functions emphasized within each disciplinary perspective support the goals that each perspective prioritizes for a safe and sustainable sanitation system (see **Table 1**).

4.2. An Augmented Sanitation Service Chain

We thus propose an augmented sanitation service chain that encompasses the social flows and functions through which the material flows and functions take place (see **Figure 3**). In particular, the currently people-free sanitation chain should expand to include the main stakeholders in the sanitation space, to make explicit that social functions shape material functions and that various actors are affected by the way in which these functions are carried out. It is not clear from the conventional chain, for instance, that a household with a pit latrine poses exposure risks for

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sanitation workers and other households, or that regulations and their enforcement shape the physical flows of waste. The main stakeholder categories are community members, decision makers, and workers, with social flows of power, influence, decision making, and finance linking them. Actors within each category are not homogeneous; some are more vulnerable than others at different geographic and political scales. An augmented chain that makes visible the key stakeholder categories and their positions, both vis-à-vis the conventional sanitation functions and one another, provides a heuristic for researchers to communicate across disciplines, and can assist those in siloed research programs to be more aware of sanitation's on-the-ground realities and nonconventional "functions."

4.3. Sustainable Development Goals: Rights, Interlinkages, and Sanitation Research

Unlike their predecessors (the MDGs), the SDGs are grounded in the Universal Declaration of Human Rights (156) and in the intersectionality of these rights. In essence, a claim to a right is a claim to power: "Realizing any right, including the rights to water and sanitation, will almost invariably require that existing power structures be challenged…" (157, p. 29). The progressive realization of the right to sanitation, therefore, calls for progress at the intersection of technology, planning, health and economic policy, and political action. Recent policy-oriented papers have supported these ideas. The SDGs as a group, also unlike the MDGs, are explicitly interlinked. UN documents routinely discuss the linkages between SDG 6 and the other SDGs, such as for poverty alleviation, ending hunger, sustainable cities, gender equality, education, and health. (They rarely link SDG 6 with SDG 8 on "decent work," however, showing the widespread tendency to neglect labor conditions for sanitation workers.)

The augmented sanitation service chain of **Figure 3** attempts to capture the main linkages among flows, functions, and actors within sanitation systems, incorporating technological and health assessment "functions" but also those of collective action and confronting social norms. In this sense, the augmented chain more closely adheres to the inherently cross-disciplinary spirit of the SDGs than the traditional chain does. At the same time, the prominence of actors such as sanitation workers serves as a reminder that, although some of SDG 6's targets address key linkages, the indicators do not fully reflect these interconnections. Sanitation research therefore has the potential to both reflect on and improve the interlinkages of the SDGs, by working across perspectives and across functions.

To take but one example, sustainable sanitation in the face of climate change would require environmental scientists and public health scientists to model the emissions and subsequent health outcomes of sanitation systems; engineers to design resilient treatment systems; economists to analyze the extent and distribution of the costs and benefits of resilient systems; planners to think through how to design and site urban sanitation systems; and urban geographers and gender specialists to assess the terms of access under which sanitation systems would promote adequacy and equity for all (97, 158). This may make sanitation seem like the prototypical "wicked problem" (125), but we contend that not recognizing this characteristic amounts to not recognizing the range of legitimate stakeholders and values that inhabit the sanitation world. In other words, if the reality and challenges of sanitation in LMICs cross disciplinary perspectives, then sanitation research, too, has to cross disciplinary perspectives. Many urban and rural areas of LMICs are implementing or expanding their sanitation systems; the time has come for sanitation researchers to collaborate toward designing systems that contribute to health and cleanliness, and also to climate change adaptation, to sustainable food systems, and to human rights for the poorest communities.

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5. CONCLUSION

"[It's] not rocket science," declares a recent UN video on water and sanitation (see 159), implying that meeting the SDG goal of universal access to sanitation should surely be simpler than rocket science. We argue that this may not be the case. This review was motivated by the hypothesis that achieving adequate and equitable sanitation for all (i.e., SDG 6) would be both slow and challenging because different researchers and practitioners subscribe to different visions of what sanitation is and what it is for (see **Table 1**). The research we reviewed across all six disciplinary perspectives (see **Figure 2**) shows that the common core of sanitation research remains the protection of humans and the environment from exposure to potentially harmful waste. Across the perspectives, however, there is variation in how this purpose is to be approached, and of the extent to which the purpose of sanitation goes beyond limiting harmful exposures (see **Figure 3**).

In broad strokes, the engineering perspective approaches the separation of humans from waste through the design and implementation of physical technology. Public health research investigates human health risks and seeks ways in which to promote safe sanitation practices. Environmental science approaches this purpose through monitoring and management, but of the larger environment. Economics optimizes costs and benefits to see this purpose realized, while planning seeks to realize it through efficient, and hopefully equitable, service provision and governance. The social sciences consider this purpose fully realized only when human rights, gendered needs, and dignity are protected and affirmed. Additionally, many scholars and practitioners, not only from gender studies but also from health, microbiology, and engineering, are calling for the social taboos that still haunt sanitation to be publicly confronted. These approaches and their specific contributions are central within each disciplinary perspective, but they are not as apparent, and thus not as central to scholars and practitioners across the sanitation sector. Seeing, understanding, and valuing these differences can facilitate constructive conversations across epistemic communities and collaborations toward sanitation interventions that simultaneously serve multiple, and mutually compatible, purposes for all.

SUMMARY POINTS

1. Sanitation has conventionally been understood as the separation of humans from flows of waste, with a primary focus on technological functions. This understanding is presented in the conventional sanitation service chain and its functions of capture, storage, transport, treatment, and reuse/disposal.
2. Through the perspectives of multiple disciplines and the Sustainable Development Goals (SDGs), sanitation research now recognizes the multidimensional, multi-actor nature of the service. Key differences in how sanitation is seen, however, characterize the discipline-based nature of sanitation research and may impede progress toward equitable sanitation for all.
3. In general, engineering scholarship focuses on optimizing technologies for the sequestration and treatment of waste.
4. Public health and environmental science focus primarily on interrupting the release and transmission of contaminants for the protection of human health and the environment.
5. Economics and planning analyze financial, policy, and managerial decisions at multiple scales toward the provision of sanitation services.

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6. The social sciences see sanitation provision as necessary for dignity, but also as reflecting gender, power, and culture, which can hinder equitable access for all.
7. We propose an augmented sanitation service chain, acknowledging the material, social, and financial flows and functions, as well as the multiple actors involved, that comprise a sanitation system from excretion to disposal.
8. Such an expanded framework can bring sanitation research—and policy—closer to the intersectional and rights-oriented spirit of the SDGs and possibly improve them.

FUTURE ISSUES

1. In terms of the sanitation service chain, studies on storage, transport, and reuse remain understudied functions across disciplinary perspectives; this is especially true for unsewered and hybrid systems. Cross-disciplinary work from system design to standards and regulation to final governance is needed to ensure both sustainability and equity.
2. The cities of low- and middle-income countries (LMICs) are searching for integrated waste management solutions that incorporate water resources, wastewater, fecal sludge, stormwater, and municipal solid waste; sanitation research can usefully support these efforts.
3. Sanitation research on specific vulnerable and/or underserved communities in LMICs is small but growing; these include homeless and migrant populations, refugees, and social groups considered to be at the margins in terms of ethnicity, caste, religion, gender identity, etc.
4. Sanitation research for public settings beyond schools and health facilities is (very) small but growing; these settings include workplaces, markets and community spaces, transit centers, and other locations outside the home. New models of financing, planning, and management for these settings, from traditional to more participatory methods, should be evaluated for sustainability and inclusivity.
5. Almost all the disciplines engaged in sanitation research neglect the safety and living conditions of sanitation workers around the world. Sanitation research "for all" must necessarily include occupational health and quality of life for those who work at each step of the sanitation service chain.
6. Sanitation, and in particular menstrual hygiene, remains immersed in cultural norms of shame in many parts of the world. For sanitation research to serve all its necessary functions, changing norms around sanitation and gender, ability, age, and the body in general, must become a practical and research priority across disciplines.
7. Finally, sanitation-related "grand challenges" across disciplines and across sectors include climate change, housing, transportation, and the food-energy-water nexus. Future and emerging research on these cross-sector themes should explicitly incorporate the results of sanitation research.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Citywide Inclusive Sanitation: **https://www.globalwaters.org/resources/assets/water-currents-citywide-inclusive-sanitation** (with USAID and the World Bank)

Eawag. MOOC sanitation courses by EAWAG: **https://www.eawag.ch/en/department/sandec/e-learning/moocs/**

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