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Advancements in and Integration of Water, Sanitation, and Solid Waste for Low- and Middle-Income Countries

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Abstract

The water, sanitation, and solid waste sectors are closely related and have many interactions between their respective service chains in low- and middle-income countries. Currently, these interactions mostly lead to cross-contamination, and opportunities for co-benefits are seldom realized. This review presents the key advancements within each of these three development sectors in the past two decades. We identify numerous similarities such as decentralization, resource recovery, community involved planning, and digitalization. Despite the potential for synergies and the opportunities to maximize positive interactions, there have been few attempts to break the existing sectoral silos in order to integrate these three service chains. We argue that, with the right enabling environment, an integrated approach

to holistically planning and implementing water supply, sanitation, and solid waste management can create positive interactions resulting in co-benefits among complementary development goals.

Contents

1. INTRODUCTION

Water, sanitation, and solid waste are inextricably linked and form the fundamentals of basic service provision across the world. These services are essential not only for the protection of both public and environmental health but also for economic development, especially in low-income contexts where exposure to environmental pollution and disease is a major cause of morbidity and mortality (1, 2; also see the sidebar titled Importance of WASH and SWM for COVID-19).

There are numerous parallels that can be drawn between the water, sanitation, and solid waste sectors, from service delivery mechanisms to end users' needs and preferences. There are clear physical interactions between the three service chains throughout the source, transport, storage, treatment, and reuse/disposal stages (**Figure 1**). Some examples include the consumption of supplied drinking water leading to wastewater production and inadequate solid waste disposal resulting in trash-blocked sewers, stormwater drains, and surface waters. **Figure 1** indicates the various interactions within and between these service chains. Currently, negative outcomes as a result of these interactions remain the norm in many low- and middle-income countries (LMICs), such as cross-contamination, incomplete (or nonexistent) treatment, and linear end uses. However, there is great potential to foster more positive interactions in support of circular economy–based value chains instead (3, 4).

Service chain: series of stages through which the physical stream, such as water, excreta, or solid waste, passes

Linear end use: pathways that begin at consumption and end at disposal with no reuse, recycling, or recovery of resources

IMPORTANCE OF WASH AND SWM FOR COVID-19

The coronavirus disease 2019 (COVID-19) pandemic has placed Water, Sanitation, and Hygiene (WASH), and especially hand hygiene, as a first line of defense against disease transmission (143). Forty percent of households globally do not have even basic handwashing facilities, and the situation in schools is worse, and there are insufficient data for healthcare facilities (144). COVID-19 has also highlighted the inequities in the WASH sector: Poor people across the world are more vulnerable due to limited access to safe, reliable, and affordable water, sanitation, and solid waste services. Residents of informal settlements are especially vulnerable due to the high population density, uncertain tenure, and unreliability of WASH and social services, making the standard prevention advice of social distancing, handwashing, and testing compliance extremely difficult (145). The impacts of COVID-19 on solid waste management (SWM) through the use of disposable masks, hygiene wrappings, and other single-use materials have implications for WASH, such as blocking of sanitation conveyance and contamination of water supplies (146). Nevertheless, this crisis also presents an opportunity to invest in safe and resilient WASH and SWM for the long term, to not only support recovery efforts during the current pandemic but also prevent future ones.

Due to these cross-sectoral interlinkages, both positive and negative spillover effects are widely observed (5, 6). However, these three sectors' activities remain largely siloed and seldom unify holistic interventions planned and implemented in development contexts. Even though the supporting aid agencies, and recipients of these interventions, are often the same for water, sanitation, and solid waste, planning and implementing these programs in an integrated fashion is highly complex (7). Particularly in international development projects, whether targeting urban development or climate change, breaking silos could help overcome the institutional barriers necessary to realize the co-benefits of integrated approaches (8).

Water and sanitation often go hand-in-hand, as evidenced by United Nations Sustainable Development Goal (SDG) 6 on Water, Sanitation, and Hygiene (WASH), or the Human Rights to Water and Sanitation (9). However, on-the-ground implementation of such combined interventions, in many cases, is fragmented, and there is a need for greater integration (7). Furthermore, solid waste management (SWM) is almost always left out of WASH discussions, even though it is part of environmental sanitation, along with greywater and stormwater management (10; see also the sidebar titled Where Does Hygiene Fit?).

Whereas high-income countries across the world have little or no lack in access to safe management of water, sanitation, and solid waste, the technologies and approaches used in such contexts cannot be directly replicated in the Global South where the challenges are unique and varying (11). Innovative, cost-effective, and locally appropriate technologies and management approaches are required to achieve sustainable access to water, sanitation, and solid waste services in LMICs (7, 12).

In this article, we present a detailed review of the major advancements in water supply, sanitation, and SWM in LMICs over the past two decades and explore the possible synergies between them. For each of the sectors, we present an overview of the current situation, with perspectives on technology, planning, management, and governance highlighted. Furthermore, we discuss the similarities and synergies between the sectors, thereby making a case for more integrated approaches to their planning and implementation. We leverage our unique perspective from applied research projects carried out in urban, rural, and small town contexts globally, as part of the Department of Sanitation, Water and Solid Waste for Development at the Swiss Federal Institute of Aquatic Science and Technology (Eawag), which has been conducting research in these fields for five decades.

Circular economy: an economic system based on reducing waste and the continuing use of waste resources; its waste management strategy includes the principles of the 4Rs: Refuse, Reduce, Reuse, and Recycle

Co-benefits: positive impacts arising from the measures taken in a single sector that benefit other sectors synergistically

Environmental sanitation: management of sanitation, greywater, stormwater, solid waste management, and water supply

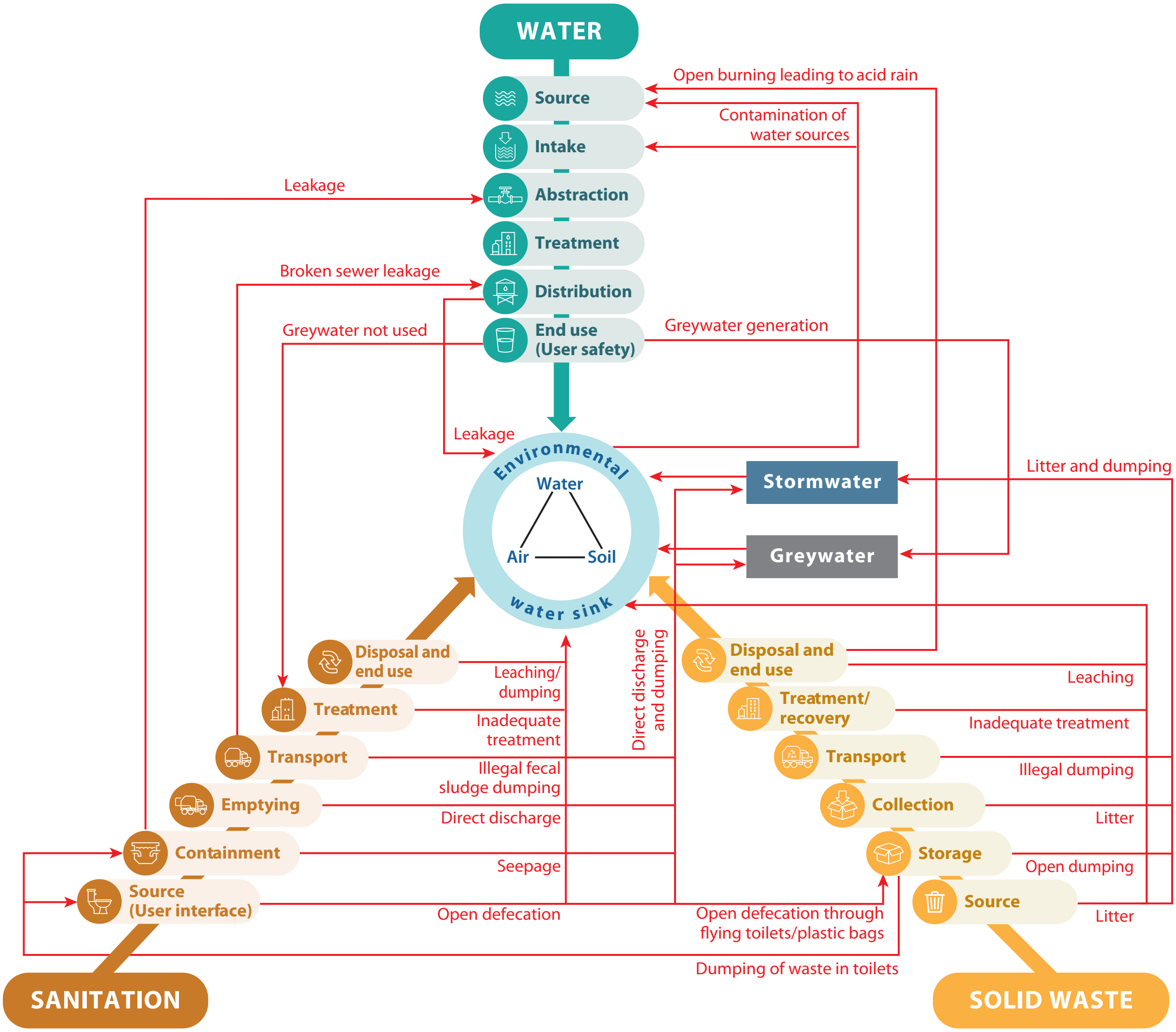

Figure 1

An illustration of the various undesirable interactions that are taking place between the three different service chains of drinking water, sanitation, and solid waste. The central circle is the environmental sink of the three fundamental resources—water, air, and soil—where the chains ultimately culminate. The red arrows and labels indicate the undesirable negative interactions. The Stormwater and Greywater boxes are provided separately to show their interaction with these three service chains. This figure is illustrative, but not comprehensive, of all possible negative interactions. See **Figure 2** for an illustration of the various positive interactions.

2. WATER SUPPLY

2.1. Introduction

In their July 2010 resolution, the General Assembly of the United Nations recognized "the right to safe and clean drinking water... as a human right that is essential for the full enjoyment of life and all human rights" (13). The right to water entitles everyone to have access to sufficient, safe, acceptable, physically accessible, and affordable water for personal and domestic use. Yet, although 71% of the global population used a safely managed drinking water source in 2015,

WHERE DOES HYGIENE FIT?

Although WASH as a term in early works stood for water and sanitation for health, given the importance of hygiene in accruing the benefits of water and sanitation, the acronym was amended to stand for Water, Sanitation, and Hygiene (147, 148). Good hygiene, in particular, has huge health implications, e.g., reducing neonatal mortality and diarrheal diseases, thereby being the most cost-effective of all major disease control interventions at 5 US dollars per disability adjusted life year averted (1). However, hygiene promotion has rarely been a standalone activity and has always been part of water and/or sanitation interventions making it part of a systemic approach (4). Hygiene by itself is not a separate service chain; rather, it manifests differently as an integral part of the existing chains of water, sanitation, and solid waste (**Figure 1**).

2.1 billion people globally still lack safe water services at home (14). Great inequalities in access to safe drinking water are present between sub-Saharan Africa and the rest of the world, within countries (especially at the rural-urban divide), and between the richest and the poorest residents across all geographies. In addition, women and girls experience discrimination in their right to water. The burden of collecting and managing water in the home falls primarily on women and girls, and they are more vulnerable to water-related diseases when they are pregnant (15, 16).

Sustainable Development Goal 6.1 was formulated to achieve by 2030 universal and affordable access to safely managed drinking water, defined as a source that is "located on premises, available when needed and free from faecal and priority contamination" (16, p. 12). Achieving the SDGs requires considerable efforts in scaling up and extending water supply to the household level, as well as implementing strategies that treat contaminated water at the source and prevent secondary contamination during abstraction, transport, and storage. Alongside efforts to extend and improve water service quality, the sector must also invest in the long-term functionality of existing water systems. This is especially crucial in rural areas where poor functionality of water infrastructure is a persistent challenge and external support programs, which are positively associated with household satisfaction and financial stability of the system (17), remain underfunded.

Water supply and treatment systems are generally implemented at three different scales: centralized, community based, and household level (12). Increasing access to well-functioning water supply schemes in rural areas and informal urban settlements has been a challenge for governments (17); therefore, community management for non-networked water points has been the main model for rural water supply in Africa since the 1980s. Greater benefits can be expected, however, for people receiving reliable access to water at the household level compared to those relying on a water point located some distance from the home. Studies have found that a reduced risk of diarrhea, particularly among children under five, was associated with on-plot water supply (18). The positive association between on-plot water supply and health may be explained by a lower risk of recontaminating water during transport and storage (19) and larger volumes of water being available for hygienic practices (20). In addition, providing household-level access to water will lead to social, economic, educational, and health benefits, especially for the water-carrying women and children (21).

External support programs: externally sourced technical, administrative, and financial assistance provided to water systems, especially community-managed rural water supplies

Therefore, there were great hopes at the turn of the millennium that water treatment at the point of consumption would largely increase access to safe drinking water for marginalized communities. However, experiences during the past two decades revealed that consistent use of water treatment devices is essential for reducing health risks (22), but establishing the corresponding behavior change has been difficult (23, 24). Particularly innovative strategies will be required to enhance access for the marginalized poor in urban informal settlements, rural-urban transition zones, and rural communities, taking into account efficient and accountable financing mechanisms that consider the limited capacity of unserved households to finance improved access through private spending (25).

2.2. Technology

In this section, we highlight four promising technological developments for expanding drinking water treatment and access to safe drinking water in LMICs. Water treatment technologies installed in such contexts have to meet specific criteria to increase the likelihood of sustainable operation: They have to be durable and robust to reduce the need for frequent and costly maintenance, easy to operate, independent of external inputs, and affordable for people living in marginalized regions.

2.2.1. Filtration. Gravity-driven membrane (GDM) filtration has emerged as a promising technology for low-income settings. Contrary to conventional membrane technology, GDM uses the weight of water to generate very low transmembrane pressure to operate the system, which leads to the formation of a porous biofilm on the membranes and, in turn, prevents their clogging. The flux is quickly stabilized and can be maintained over several years without backflushing (26). This mechanism enables the technology to be operated with limited maintenance and at low cost, as demonstrated by a successful application in Uganda for the treatment of water from Lake Victoria in water kiosks operated by the surrounding community (27). Another breakthrough in the sector has been the development of inexpensive hybrid membranes made from amyloid fibrils present in milk protein together with activated porous carbon, which can be a low-cost approach for removing heavy metals from water via adsorption (28).

2.2.2. Safe storage. A common challenge is recontamination of treated water during distribution in pipes or during transport and storage in uncleaned containers following collection (29). Safe storage strategies combined with a chlorination treatment step to provide residual disinfection are often required to assure that water is safe at the point of consumption (30). In other settings where uptake of safe storage practice is high, safe storage alone could be equally effective as storage with chlorination for reducing heavy contamination and diarrhea prevalence in children below two years of age. These studies indicate the importance of good storage vessel design and the need to use disinfected containers to mitigate recontamination risks (31).

2.2.3. Chemical disinfection. In terms of the challenge to establish consistent drinking water chlorination by individual users, passive in-line chlorination avoids manual dosing by using the flow of water to operate chlorine dosers connected to water pipes. The installation of passive in-line chlorinators in public water points, water kiosks, and small-scale water supply schemes is a promising approach to achieve reliable levels of free residual chlorine at the point of consumption (32). Stand-alone chlorine dispensers installed at water collection points in rural Kenya were also identified as a cost-effective solution for dramatically increasing households' uptake of chlorinated water, especially when paired with a community promoter (33). Nevertheless, acceptability of chlorinated water varies geographically and is closely tied to dosage levels. A study among Dhaka (Bangladesh) residents indicated that doses below the typical target of 2.0 mg/L may increase consumption in this setting while still providing effective disinfection (34).

2.2.4. UV treatment. Another strategy to reduce recontamination of treated water is the installation of secondary disinfection in the water distribution scheme, at the tap or at the point of use. Ultraviolet C light-emitting diodes (UV-C LEDs) have characteristics that could make their future installation as a secondary disinfection barrier promising. The LEDs do not contain mercury, as in conventional UV lamps, require less power, and have a long life span; they are capable of achieving high log reduction rates for protozoa, bacteria, and viruses (35). In addition, their production costs are rapidly decreasing. Challenges for the broad implementation of these technologies are reduced radiation absorbance by biological fouling, possible regrowth of pathogens after insufficient disinfection, the management of waste heat generated by the LED, the need for UV sensors to monitor system operation, and power requirements for installation in remote areas (35).

Water Safety Planning: a comprehensive risk assessment and risk management framework to ensure drinking water safety from catchment to consumer

2.3. Planning

In recent decades, the water sector has experienced several shifts in the dominant paradigm for planning and implementing water supply projects. The reliance on supply-led, infrastructure-oriented approaches in the 1980s proved ineffective for realizing sustained water supply provision, thereby limiting the public health benefits (36). The lessons learned during this decade paved the way for a new era of demand-responsive, service-oriented modalities of project planning and implementation (37), including a strong emphasis on the need for external support programs (17). Cutting-edge planning approaches recognize that service sustainability is a dynamic process involving complex, interactive systems that take into account social, financial, and environmental factors and the interactions between them (38).

A study of community-managed water supplies in Ghana, Kenya, and Zambia revealed that social capital (i.e., interpersonal structures that foster cooperation toward a common aim) and community members' sense of ownership (i.e., the feeling that the water system is "mine" or "ours"), although interlinked, facilitate distinctly different processes crucial to achieving sustained functionality of water systems (39). Some forms of early community engagement, such as meaningful involvement in decision-making about the project, were associated with users' enhanced sense of ownership for the water system, which in turn bolstered its regular use (40). In the context of small towns in Uganda, planning models and infrastructure designs that had been transplanted from urban contexts were ill-suited to such transitional environments (41), indicating a need for more flexible and integrated service modalities at the rural-urban divide (42). For example, outside of urban centers it is common for households to use multiple water sources for different purposes, to switch sources seasonally, and/or to rely on intermittent piped water supplies (43). Accommodating these realities requires matching appropriate levels of treatment to various uses of water as well as devising innovative solutions for improving service continuity.

Finally, the water sector is increasingly facing water scarcity, water safety, and management issues due to climate change and population growth. In response, risk adaptation frameworks have been widely adopted for LMICs, notably the Water Safety Planning approach that emphasizes the need for flexibility to match local contexts and ongoing training and capacity building (44, 45). Initiatives in support of the transition to sustainable urban water management conditions that are more resilient to climate change, i.e., future so-called water sensitive cities, recognize the need for investments in capacity development, cultural reform, and standardized benchmarking tools (46). Others have highlighted the need for including climate vulnerability and resilience considerations when planning and implementing water supply infrastructure, particularly in island nations (47).

2.4. Management and Governance

The drivers of WASH policies in urban informal settlements include donor and government prioritization along with local collective action; however, social exclusion, sector fragmentation, residents' uncertain tenure status, and insufficient data for decision-making all impede effective policies (48). In rural settings, community management of a single water point puts the burden of risk on those often least equipped to manage it. Collectively managing a network of water points as a future model would allow pooling of resources and responsibilities and facilitate more professional maintenance and management with economies of scale (49).

Safely managed sanitation: use of improved facilities that are not shared with other households and where excreta are safely disposed in situ or transported and treated off-site

Fecal sludge management (FSM): the storage, collection, transport, treatment, and safe end use or disposal of fecal sludge—what accumulates in onsite sanitation technologies and is not transported through a sewer

Container-based sanitation (CBS): an end-to-end service in which toilets collect excreta in sealable, removable containers or cartridges

Public, private, and community-managed water utilities have faced the common challenge of generating sufficient income to finance reliable operation and sustain maintenance. The performance of community management was assessed in relation to hand-pump failure, decision-making rules, leadership, the finance system, affordable maintenance and repair, and external support programs across 600 sites in Ethiopia, Malawi, and Uganda; this assessment found that affordable maintenance and repair were the best predictor of borehole functionality (50). This finding indicates that affordability, with an estimated benchmark at 3 to 5% of the total household budget for water, is an important element of a sustainable water supply (51). Technical innovations such as smart meters and real-time operational monitoring are new digital tools that have the potential to enhance revenue generation and facilitate improved response in the case of system failures (52). As a result, customers' willingness to pay tariffs could be increased and the health risks due to poorly functioning water supply schemes reduced (23, 53). Digital innovations have contributed to effective decision-making for immediate actions and long-term planning (e.g., as part of Water Safety Planning), in terms of maintenance and monitoring of remote systems (54, 55).

3. SANITATION

3.1. Introduction

Sanitation, as a field of development, underwent significant changes in the past two decades. After receiving prominence in the Millennium Development Goals [MDGs (7C)], which set to halve the population without access to basic sanitation, the subsequent SDGs (6.2 and 6.3) set far more ambitious targets, which aim to provide safely managed sanitation for all. Achieving the new targets by 2030 will require providing universal access to improved sanitation for more than double the number achieved during the MDGs, and four times for safe management of fecal waste, all at an estimated cost of at least 71 billion US dollars per year (56). The benefits of improved sanitation, particularly on health but also on social and environmental development, have been well documented (57). Likewise, the economic benefits of sanitation are now also internationally acknowledged (58). The attention that sanitation received in the past decade has galvanized countries to take actions toward providing improved sanitation leading to institutional behavior change, for example, through the Clean India Mission, which aimed to end open defecation in India over a five-year period (59).

Such a step-change has been driven by an evolution of thinking of sanitation beyond access to toilets, to the safe management of the entire sanitation service chain, and a service delivery approach rather than mere infrastructure provision (60, 61). Perhaps the most significant shift is the increased acceptance of non-sewered and decentralized sanitation systems as adequate and long-term options, on par with sewer-based centralized treatment systems (62, 63). Evidence of this acceptance is increased incorporation in development agendas and the rapid rise of non-sewered solutions, including fecal sludge management (FSM) (64), container-based sanitation (CBS) (65), and decentralized/small-scale sanitation systems (66).

Although rural areas in most countries have yet to catch up with sanitation progress in urban settings, the complexity of challenges in the latter due to rapid urbanization, poverty, and population density has resulted in urban sanitation gaining more attention than the rural counterpart. In urban sanitation, there has been a recent trend to break sectoral silos and look for interlinkages with other basic urban services toward a citywide approach (5). An important realization of the past decade is that end-of-pipe sewered systems will not be able to cover the huge spatial footprint of rapidly urbanizing areas of Africa and Asia. In the future, non-sewered solutions, from onsite to small-scale (or decentralized) solutions, will be implemented in parallel as networked solutions or as an alternative to expensive sewer-based systems (62). These changes have resulted in the paradigm shift toward Citywide Inclusive Sanitation (CWIS). The goal of CWIS is for everyone to have access to equitable, safely managed sanitation through implementation of a range of solutions tailored to the realities of rapidly growing cities, including sewered and non-sewered, decentralized, and centralized technologies (62, 67, 68).

3.2. Technology

A broad range of technology solutions are required for CWIS. Centralized, sewer-based technologies are well established, with a long record of research, knowledge, and implementation, and guidelines for onsite containment of excreta for rural areas are well accepted (69, 70). The concept of integrated FSM in urban areas is, in comparison, relatively new, but recent acceptance has led to research funding from foundations, increasing scientific journal publications, and rapidly evolving technology development along the sanitation service chain (64, 71, 72).

An important driver in developing treatment technologies for non-sewered sanitation has been the acknowledgment that it is different than municipal wastewater or types of wastewater sludge and cannot simply be co-treated with wastewater, requiring separate technological solutions (73, 74). A major barrier for all innovations is that the characteristics of fecal sludge as well as other factors influencing treatment performance are not well understood. More scientific knowledge on the effects of the flow behavior, redox conditions, nutrients, salts/ions, stabilization, particle size, extra polymeric substances, undigested plant fibers, and microbial community composition are still required (75–77). Increased scientific knowledge also requires standard methods of analysis for comparable results, along with open sharing of raw data (72). Furthermore, many treatment plants currently operate without adequate operator or laboratory capacity, which is needed to ensure adequate treatment performance. Guidelines are urgently needed for monitoring and operation with simple, easy-to-measure parameters and for the dynamic operation of treatment plants to account for fluctuating loadings (73, 75).

There is no one-size-fits-all solution, and new technologies are greatly needed to meet the demand and reduce the required footprint for treatment in urban areas. As technologies are advancing, they can be considered, from a risk management perspective, as (*a*) established (e.g., existing guidelines for operation), (*b*) transferring (e.g., borrowing from established treatment of other waste streams), and (*c*) innovative (e.g., still in development) (71). For rapid uptake of the last two kinds of technologies, methods are needed to ensure adequate protection of public and environmental health during implementation.

Innovations at the level of onsite containment include technology developments for the collection and containment of excreta with a CBS approach for collection (65) and improved emptying technologies for pit latrines (78). The closed-loop solutions being investigated within the "Reinvent The Toilet Challenge" are designed to simultaneously contain and treat excreta onsite with technologies including hydrothermal carbonization, microwave technology, supercritical oxidation, pyrolysis, and electrochemical processes (79). Successful scaling up of these innovations could result in a profound change to the entire service chain. Technologies being transferred from the wastewater and the paper and pulp industry include the use of conditioners, presses, and geotextiles for dewatering (72).

In the past decade, there was a shift toward resource recovery in the hopes that it would "close the loop" and offset the financial costs of sanitation provision. This reimagined thinking drove advances in resource recovery that have greatly expanded the list of possibilities, including energy (e.g., fuel, heat) (80, 81), food [e.g., animal fodder from plants, protein production from black soldier flies (BSF)] (82), nutrients (e.g., soil conditioner, fertilizer) (83), and water (reclamation from effluent) (64). Market demand for treatment products can also help drive operation of the service chain to meet customer demand. However, the potential revenue will, realistically, only offset disposal costs and a fraction of operating costs depending on demand, end products, and chosen technologies (84).

Black soldier fly (BSF) treatment: waste treatment technologies use the natural life cycle of the black soldier fly to upcycle organic waste into quality protein for pet and animal nutrition, along with other valuable by-products

Enabling environment: a set of interrelated conditions that are conducive to the facilitation of a desired outcome

3.3. Planning

Sanitation planning is also a rapidly evolving field, and the past decade has seen the evolution of integrated planning guidelines and frameworks that address aspects of inclusiveness and stakeholder engagement (85). Planning-related challenges range from a lack of human resources, to narrow aspirations toward conventional sewered solutions (which result in socially segregated service levels), to the lack of a planning culture apparent in many LMIC settings (86).

The concept of the sanitation service (or value) chain provides a systems approach to the flow of waste from capture to disposal (87). This concept has been standardized through the *Compendium of Sanitation Systems and Technologies* (88) and *Faecal Sludge Management: Systems Approach for Implementation and Operation* (64). Consequently, numerous new planning approaches and tools have been developed based on the service chain concept, including the Shit Flow Diagram (SFD), the World Health Organization's Sanitation Safety Planning, Citywide Service Delivery Assessment (CSDA), and the Methodology to estimate Quantities & Qualities of fecal sludge (Q&Q) that advocate and plan for improved citywide service delivery (89–92).

More recently, the communicative planning processes that could increase community ownership and empowerment by improving the long-term sustainability of basic urban services have been popularized (10, 93). Community involvement and demand creation are now recognized as critical steps in sanitation planning and implementation in unserved and underserved areas (94), including the widely known Community-Led Total Sanitation approach, which targeted rural communities (95). The value of coproduction and the incorporation of local knowledge have been documented as key factors for long-term sustenance (96). With the advent of CWIS, planning is required to be even more inclusive and comprehensive, given that sanitation solutions need to be equitable, sustainable, and contextualized with multiple modes of service delivery (62).

3.4. Management and Governance

An enabling environment is seen as an important driving factor for achieving and maintaining universal coverage of sanitation (10, 97). Yet, the enabling environment, which includes the investments, policies, regulations, socio-cultural acceptance, and institutional capacities, remains elusive for most LMICs given the political economy of sanitation (98). Globally, the sanitation sector has matured in the past two decades with new organizations and networks promoting sector innovations (e.g., Sanitation and Water for All, Sustainable Sanitation Alliance, FSM Alliance) and industrial standardization (e.g., ISO 30500- Non-sewered sanitation systems).

The recent shift toward non-sewered, onsite, and decentralized solutions has expanded the room for private sector engagement in the sector. This diversified sanitation landscape allows for the creation of new business models with high returns on investment (65, 99). Delvic Sanitation Initiatives in Senegal is one such example where an entrepreneur seeks to build profitable and sustainable businesses by providing urban sanitation solutions adapted to the West African market needs (100). Digital innovations would allow for better planning, maintenance, and monitoring of decentralized and/or remote systems, where lack of monitoring often leads to failure (66, 75) and such use of digitalization has proven to be cost-effective and successful in sanitation service provision (101).

4. SOLID WASTE MANAGEMENT

4.1. Introduction

Inadequate SWM affects public health, the environment, and the economy at all scales—from local to global. At the neighborhood and city scale, deficient service negatively impacts the health of residents through multiple pathways: Uncontrolled waste burning can cause acute respiratory diseases, uncollected waste allows disease-carrying vectors to breed, and trash-blocked drains contribute to flooding. Municipal and industrial wastes that are discarded without control or treatment have adverse impacts on soil, water bodies, groundwater, and the coastal and marine environment, thereby indirectly impacting public health (102). At the global scale, the adverse impacts of solid waste are prioritized based on their contribution to greenhouse gas (GHG) emissions and climate change as well as plastic ocean pollution (103), which affects marine life.

SDG 11.6 (waste collection and safe management), SDG 12.5 (waste prevention, reduction, recycling, and reuse), and SDG 14.1 (marine litter) recognize the human and environmental threats posed by solid waste. However, many of these waste-related targets and indicators lack definitions, well-defined methodologies for data collection, and reliable baseline data, especially for LMICs (104), so it is difficult to assess progress or ensure governmental accountability (105).

It has been shown that increasing welfare and consumption results in a direct increase in per capita waste generation and changes in waste composition (102). Rapid urbanization and high population density intensify the negative effects of deficient waste management services and infrastructure (106) and increase the likelihood of exposure. Although per capita waste generation is lower in LMICs, the impacts of poorly managed waste remain critical.

Basic waste management service is widely considered a public good. Individuals cannot and should not be excluded from the availability and use of this service (107). Although inadequate SWM impacts everybody—the rich and the poor—the direct negative consequences fall predominantly on the poor: those who remain unserved or suffer from waste being dumped in close proximity to their homes, which increases the risks of pollutant and pathogen exposure (108).

International initiatives and conventions are calling on governments to reduce adverse global impacts (e.g., GHG emissions and marine litter), and civil society is pushing for more local action to improve service and the overall cleanliness in cities. A paradigm shift from a linear end use approach toward an understanding of waste and resource management has gained popularity. This model involves looking at waste prevention, resource recovery, and recycling as components of a circular or green economy. A second paradigm shift relates to taking a holistic approach to SWM, which considers inclusivity, financial sustainability, a base of sound institutions, and proactive policies (105).

4.2. Technology

With a shift toward a circular economy and a commitment to incorporate 4Rs (Refuse, Reduce, Reuse, and Recycle) strategies, technology innovation is mainly driven by a vision to create more value from waste: to satisfy market demand. A global review on biowaste treatment revealed a shift in research away from composting—a simple and robust technology which, nevertheless, is not widely practiced in low- and middle-income settings—to investigations of anaerobic digestion of organic waste for biogas production (109). This transition is driven by global efforts to increase energy recovery from renewable sources to replace fossil fuel. However, the low energy density of biogas poses a storage challenge, and finding solutions for transformation into a more easily transportable fuel remains an important line of research needed to foster implementation.

Informal waste sector: individuals or microenterprises that intervene in waste management without being registered or being formally charged with providing waste management services; they play an important role in managing municipal solid waste in most low- and middle-income countries

Another innovation that has emerged for biowaste processing is that of BSF insects for the production of alternative protein sources for animal feed (110). After having grown on a biowaste substrate, the harvested BSF larvae can be used as a high-quality, effective (although partial) fish meal replacement in animal feed for fish, chicken, or pigs (111). Additionally, there is value in using BSF to reduce GHG emissions, given that the direct CO_2 equivalent emissions from BSF biowaste treatment are 47 times lower than the emissions from composting (112) and fresh insect biomass is almost twice as sustainable in terms of a life cycle analysis as fresh chicken meat (113).

The traditional approach to plastics recycling has been and still largely remains mechanical, which includes the sorting of different plastic fractions, washing, and then grinding the material before reprocessing. The use of paints and coatings complicates the process of mechanical recycling and lowers the product quality. In high-income countries, this complication has led to increased chemical recycling based on converting the polymers into smaller molecules (114). For low-income settings, however, such technologies remain unattainable, and the focus for improving the process is predominately on improving collection logistics and sorting for mechanical recycling as well as exploring opportunities for new products made from recycled materials such as plastic-bonded sand blocks and paving stones (115). The simplicity and replicability of such technologies are considered the basis for broad-scale uptake to generate local employment and to reduce the amount of plastic waste leakage into the environment.

Digitization has helped to optimize waste collection processes and recycling activities. Most of this auxiliary technological development revolves around the use of GIS and GPS, sometimes combined with sensors to measure the mass of containers and trucks for optimization and monitoring (116). Digital applications for mobile phones help connect informal waste collectors and recyclers to waste generators, and to those that then process and recycle the waste. Such information and communication technology, besides improving the waste collection process, has resulted in greater respect and appreciation for the recycling work, made people more aware of the importance of recycling materials, and improved the quality of informal waste pickers' lives through improved working conditions (117).

4.3. Planning

In the past decade, the solid waste sector has experienced a shift from an engineer-led planning approach with a focus on technological fixes to a more holistic and comprehensive approach that embraces the concept of sustainability. For LMICs, this practically means involving a wide range of stakeholders and considering the enabling environment (political, institutional, social, financial, economic, and technical) (118). A more holistic approach also includes greater attention to environmental and resource recovery implications besides the traditional focus on waste collection and transport driven by public health concerns (119). Involving stakeholders in planning and operation implies not only waste generators but also the informal waste sector that already plays a critical role in waste collection and recycling services. It has been shown that recycling rates by the informal waste sector can amount to 20–30% of the total collected but at no direct cost to the local authorities (118). The process of integration and formalization of this sector must not underestimate the importance of the enabling environment (120) and the need for the policy and legislative support that goes hand-in-hand with approaches such as organizing informal sector workers into associations or cooperatives, or supporting community-based organizations and/or micro- and small enterprises.

Given the variation of waste typology and generation rates based on different social-economic situations, SWM solutions must be considered on a case-to-case basis and tailored to each community's situation and needs. Local governments' support of community-based solutions is important, where decentralization is not a devolution of responsibility but rather an operational alternative to enhance performance and create ownership of the system by local communities (121).

Informed decision-making for sound planning depends on reliable data. Regrettably, such data are lacking in most low-income countries. There is a lack of standard methodologies and measurements; ones that exist are neither comprehensive nor consistent (102, 108). Authorities rely on waste estimates based on the volume of the vehicles used for collection, despite the fact that collection coverage is limited and thus no actual data on waste generation can be inferred (106). Assessments and data collection also tend to be limited to the formal system excluding the informal waste management or unmanaged waste.

4.4. Management and Governance

Guiding principles of solid waste governance are defined at the national level. Strategic directions at the national level may be influenced by global trends and priorities of global-level actors, for instance, striving for a waste hierarchy—from prevention as first priority to disposal as last resort—or setting high priority on the mitigation of GHGs. Such strategies, however, might be misguided when considering the specific context and their economic implications. For instance, the average per capita waste amount produced in low-income countries is significantly lower than in more affluent countries (108), and implementing avoidance or minimization initiatives may contribute little to reduction objectives (119), whereas strengthening the informal recycling sector and its stakeholders—driven by potential profits made from the resale of recovered materials—through policies and incentives can achieve more impact (106). Policies and strategies must therefore try to balance priorities at both local and global levels, i.e., eliminating the open burning of waste, which is a priority from a health and climate standpoint, given its emission of black carbon: a potent, short-lived climate pollutant (122).

Governance, in terms of ensuring operation and management of services, often remains the responsibility of the local city or even village authorities including the management of infrastructure, human resources, and stakeholder interactions. With the wide range of stakeholders and possible technology options, this becomes a highly complex task for municipal decision-makers and staff already facing scarce resources and inefficient institutional structures or procedures. In recent years, local governments have increasingly mandated certain functions in SWM for citizens (123), the private formal or informal sector (120), or a mixture thereof. In such new management models, the role of the local authorities switches from operator to regulator and facilitator of the service, i.e., a new skill set required in staffing. The difficulties in management may be even greater in rural areas as the complexity and costs of service provision increase with lower population density while capacities and skills remain clustered in urban areas. Here, intermunicipal cooperation (124) or the devolution of tasks to household clusters for household-scale waste management seems most promising. A study in the Philippines showed how the success of community-level SWM depends on clear relationships, institutional and noninstitutional support, as well as the involvement of community members with a well-established network management system that can be extended to include SWM (125).

A challenge in improving recycling rates revolve around obtaining a well-sorted, clean waste material; otherwise, recycling costs remain prohibitive (126). Increasing focus is now being set on investigating effective measures to achieve and sustain behavioral change for segregation at the household level (127, 128) and integrating these changes into an overall waste management operation that includes the informal sector (129).

5. DISCUSSION

5.1. Comparing Developments Across Sectors

In addition to the inherent similarities in the advancements and the interactions within the service chains of water, sanitation, and solid waste discussed above, there are numerous trends that are worth highlighting. In the following sections we synthesize the ways in which these focus sectors have converged and diverged in their developments and highlight other allied sectors that should also, going forward, be addressed.

5.1.1. Introduction All three sectors are strongly driven by their impacts on public health and their interconnectedness with social, economic, and environmental aspects. The SDGs have formulated clear targets for directing the advancements in these sectors. Water and sanitation are bundled under SDG 6, whereas solid waste is dispersed between SDGs 11, 12, and 14. The human rights narrative for water and sanitation has been a key driver of the development agenda ever since the UN adopted the resolution a decade ago (9). Likewise, solid waste has been prominently included in the proposal of the "right to healthy environment" (130). Equity, through a special focus toward marginalized communities as part of the "leave no one behind" agenda is a common principle in all three sectors (12, 68, 107). Whereas most advancements in the past two decades in sanitation and solid waste have been primarily urban due to the nature of the problem (62), the challenges in the water sector and the innovations required respectively are focused more on rural contexts, and in some cases, small towns and informal urban settlements (17, 106).

5.1.2. Technology. Technological innovations fostering solutions at the household level have been important. For example, decentralized solutions for drinking water treatment and safe storage (30), onsite containment of excreta (64), and source-segregation of solid waste (128) have all become mainstream interventions. Such decentralization of technologies in concert with community-level management have found their place in both high-density urban contexts (66, 106) as well as rural communities (27). User preferences and applicability in low-income contexts are major drivers for their uptake and long-term viability. Low-cost and low-energy technologies that are easy to maintain have become the new design standards across the sectors (27, 78, 109). The recent shift toward technologies to enhance resource recovery and foster a circular economy is more relevant for sanitation and solid waste (84, 119); however, water reuse technologies (e.g., greywater reuse) are receiving increased attention particularly in water-stressed areas.

5.1.3. Planning. We have stressed the need for holistic planning throughout this review, not only for different stages of the service chain but also in accounting for cross-cutting social, economic, and environmental factors (10, 38, 118). All three sectors are steadily moving away from supply-driven infrastructure provision to a more demand-responsive, service-oriented approach. Community involvement has been widely deemed as necessary in development interventions for two reasons: (*a*) incorporating local knowledge and preferences and (*b*) building a sense of local ownership. Both reasons have been repeatedly accepted as critical factors for long-term sustainability (37, 39, 94, 123, 125). Inclusive planning frameworks and tools are more widely available and implemented in the water and sanitation sectors, and there are new frameworks emerging for solid waste (102).

5.1.4. Management and governance. The management of water, sanitation, and solid waste projects requires taking into consideration different elements of an enabling environment including political, institutional, social, financial, and technical aspects (10, 105, 131). Having access to reliable data regarding the context is an important prerequisite for decision-making and management in all three sectors. Monitoring as well as operation and maintenance are identified to be critical factors for long-term success of water, sanitation, and solid waste services (54, 66, 106). Although all of the above factors have been identified as crucial, the complexity of management and governance, especially in terms of who is responsible for monitoring or operation and maintenance, often remains a challenge. Digitalization and remote monitoring have proven to be innovative digital solutions that enable better monitoring and maintenance of all three basic services (54, 101, 116). Outsourcing management tasks through privatization and formalization of informal service providers is a rising trend in sanitation and SWM. Resource recovery from waste can lead to an additional revenue stream (84, 109). However, in the case of water, where privatization has long been a debate, there is an emerging call for remunicipalization (132).

5.2. Integrated Approach

Integration refers to the explicit linking of sectors to achieve more holistic and sustainable outcomes. Although integration has been discussed and emphasized for years, the reality of funding schemes and academic compartmentalization have limited the actual implementation of this oft-praised concept. In the following paragraphs we discuss the reasons for this historical segregation and present ways to change this status quo.

5.2.1. Rationale for greater sector integration. Although there are several similarities in the ways the water, sanitation, and solid waste sectors have advanced in the past two decades, there have been few efforts to embrace integrated planning, management, and governance in the WASH and solid waste sectors. Greater integration of basic urban services and overcoming siloed approaches are considered necessary to achieve wider development outcomes (4, 5, 7). The main reasons advanced are that (*a*) the physical interdependencies of sanitation, water, and SWM necessitate integrated planning and programming—neglect of one service compromises the quality of other basic services; (*b*) integration offers the scope to maximize synergies with factors influencing the enabling environment (e.g., land use control and tenure arrangements); and (*c*) support for stronger accountability of local governments in basic service delivery is enhanced and counteracts institutional and departmental fragmentation.

5.2.2. Integrating the three sectors in planning and implementation. Integrated approaches to WASH and SWM are not a new concept for rural and urban domains; however, they have rarely been operationalized or mainstreamed. This is due to the complexity on the ground and the lack of institutional leadership from local governments (4, 7). Since the Rio Earth Summit in 1992, the Integrated Water Resources Management approach has been operationalized for the improved management of water resources. In the urban domain, settlement upgrading programs of the 1980s and 1990s supported by various donor agencies promoted integrated and incremental approaches that usually encompassed drinking water, sanitation, electricity, roads, stormwater, and SWM.

Successful examples are rare, but there were numerous (donor-led) implemented projects in the past. Cirebon, a city of 2.5 million on the Indonesian island of Java, successfully implemented an integrated approach to basic urban services between 1976 and 1996, providing water supply, sanitation services, and SWM to the growing urban population (133). This project also included capacity development for local authority and utility staff. The World Bank–funded Indonesian Sanitation Sector Development Program (2006–2010) supported effective policy-making, institutional reform, and strategic planning for integrated service delivery in Indonesian secondary towns (134). The outcomes of this national program show that programs at scale that take a systems approach can provide replicable solutions that improve citywide sanitation encompassing solid waste, wastewater services, clean water supply, and micro-drainage systems. More recently, the CWIS principles call for equitable services for all urban dwellers and the greater integration of urban sanitation services with other basic urban services (67).

Systems thinking: the understanding that it takes a whole system to achieve a given objective, and no individual component can succeed alone

Work by the Agenda for Change initiative (**http://www.washagendaforchange.org**) defines the prerequisites for sustainable district-wide (i.e., an entire rural district including villages and small towns) service delivery for WASH systems and how to achieve sustainable services at scale. These prerequisites include institutional arrangements, planning, monitoring, regulation, and accountability, among others. A WASH and SWM system comprises all the social, technical, institutional, environmental and financial factors, actors, motivations and interactions that influence WASH and solid waste service delivery in a given context (131). Systems thinking is an alternative to reductionist approaches that focus on only individual components of a system. Strong WASH and SWM service delivery will require all of the factors to be in place at all institutional levels—from infrastructure, finance, policy, coordination to capacities and environmental conditions—and include different actors—from households and communities to local government, national ministries to private companies and aid agencies—being able to work together effectively and at scale.

However, the integration of WASH and solid waste services faces several challenges to overcome the predominantly single-sector approach. Firstly, the inherent complexities of moving from siloed thinking to wider service delivery systems or bundling of services require more sophisticated planning and heightened interagency coordination and management between different services. Secondly, there is a lack of strong local or district government leadership and commitment. Thirdly, there are weak linkages to formal regional/district or urban planning to anticipate and plan for cost-effective bundling (e.g., integrating sanitation and water supply with drainage infrastructure). Therefore, for an integrated approach to work, there must be a radical shift in perspective in planning for implementation, and it must have institutional support from all the stakeholders involved.

Fortunately, the WASH and SWM sectors are placing new emphasis on service delivery outcomes along the entire service chain, and the debate on service-level standards provides greater impetus to align and integrate water supply, sanitation services, and SWM to be provided by service authorities. This is in line with SDG 1, aiming for enhanced access to basic services (9).

But how can an integrated approach become a reality? The political will and strong leadership are most important. This requires strategic thinking and a lead agency capable of defining issues and setting priorities. The cornerstones of achieving integration are information sharing, regular coordination, a clear delineation of joint service packages at rural district or urban levels, and the introduction of new organizational practices that can evolve incrementally over time. Service integration is a process that will take time and can begin with agreement on overarching goals and shared objectives. This includes the definition of cross-cutting outcomes that allow siloed water, sanitation, or waste management services to be brought together. Experience from other sectors (e.g., health or integrated water resource management at the basin level) suggests starting with low-hanging fruit like data sharing or information pooling (135).

Initially, interagency coordination and the formation of multidisciplinary teams can push forward the integration agenda; in a more mature stage, an umbrella organization with pooled budgets should be formed. The goal is to overcome siloed commissioning, funding and regulatory processes that can increase the effectiveness with which WASH and SWM are delivered and thus become more responsive to citizens. Local contexts will define joined-up service standards, e.g., introducing the co-management of sanitation and stormwater/greywater management, or the collection and conveyance of organic waste and fecal sludge for biogas production at scale. It should be noted that for the private sector, bundling of services might make implementation more efficient. For example, a fecal sludge collection or treatment company might also offer solid waste collection or treatment, interlinking treatment of both materials flows. Ultimately, an enabling environment for an integrated approach that includes (*a*) political leadership, (*b*) shared objectives, (*c*) effective policies, (*d*) institutional coordination, (*e*) integrated planning (*f*), monitoring and accountability, (*g*) strengthened capacity, and (*h*) stakeholder support will allow for synergistic positive interactions between the three service chains of water, sanitation, and solid waste (**Figure 2**).

5.3. Further Inclusion

This review, although comprehensive for the sectors identified (drinking water, solid waste, and excreta management), omits two key areas of environmental sanitation: stormwater and greywater management. (For another key aspect of inclusion, see the sidebar titled Inequality in WASH and SWM.)

5.3.1. Stormwater. Stormwater systems are an important aspect where all the three sectors of water, sanitation, and solid waste interact—by design or unintentionally. Operational stormwater and/or surface run-off management, although complex, requires less infrastructure than other interventions—i.e., ditches, retention ponds, and gutters can be built without concrete—yet is still lacking across much of the Global South. Surface water that accumulates from heavy precipitation or from flooded water bodies can destroy property, promote the growth of vectors, contaminate drinking water systems, cause sanitation containments to overflow, and ultimately create disproportionate impact among the marginalized communities if appropriate drainage is not in place (136). The absence of solid waste collection is often responsible for inhibiting the limited stormwater facilities that exist; narrow channels are quickly and easily blocked by wayward trash and the rubble that remains after burning (given that open gutters are often used for consolidating and burning trash). Despite the obvious interactions with other facets of urban services, stormwater management remains low on the list of municipal priorities (137). Its management falls between the clearly defined agencies that handle solid waste (e.g., city), drinking water (e.g., parastatal), or transport (e.g., roads authority), each assuming it is beyond its purview (136).

Although efficient and modern ways to design and install stormwater management in LMICs have been developed (137, 138), their mismanagement and poor maintenance cause damage to life and property, and at times even cause overflows in wastewater treatment plants. Integrating stormwater interventions with WASH and SWM could extend the life of the infrastructure, improve the infrastructure's functionality, and provide scope for positive interactions (**Figure 2**).

5.3.2. Greywater. Greywater management is similar to that of stormwater in that it directly affects all other aspects of environmental sanitation, including stormwater itself, yet is often left out from WASH and SWM designs. Greywater is the water emanating from showers, sinks, and other nontoilet uses. However, compared to blackwater, greywater constitutes a large proportion of the water discharged from households (65–100%) and is relatively low in nutrients and pathogens (although not entirely pathogen-free) (139). Small quantities of greywater can usually be managed safely onsite with simple technologies, although as access to water increases, so too does the volume of greywater that must be managed (140). The majority of greywater in non-sewered areas is discharged without any treatment into any available space, as it is not perceived to be a harmful substance (141). Multi-stage technologies that are meant to treat greywater at the household level require cleaning and maintenance and therefore are not popular or well used. Because untreated greywater may contain high concentrations of surfactants, oils, and salts, its discharge on

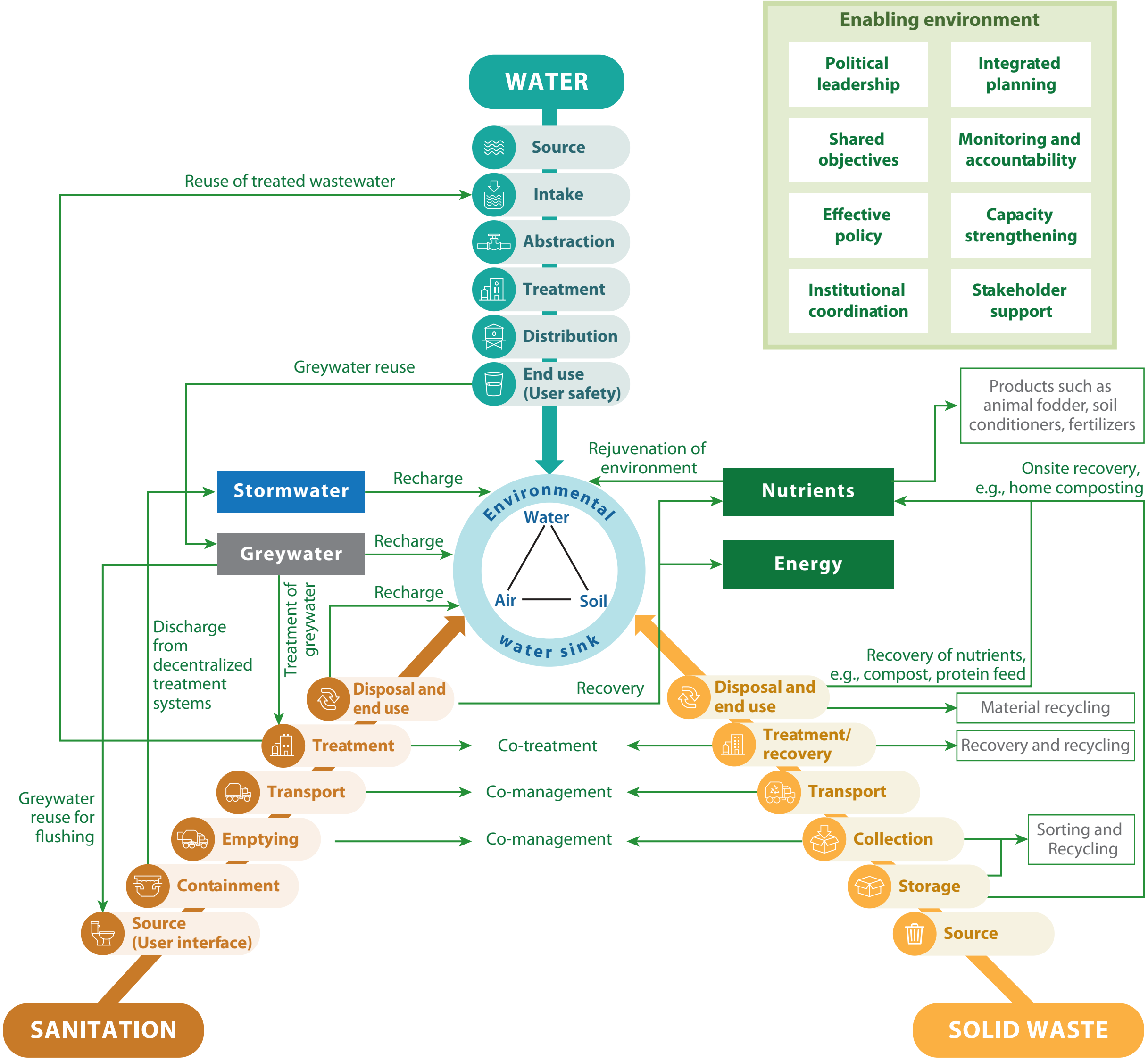

Figure 2

An illustration of the various positive interactions that could take place between the value chains for drinking water, sanitation, and solid waste indicated by the green arrows. The two green boxes labeled Nutrients and Energy are desirable products that could be recovered from these chains and their interactions. Recovering, sorting, and recycling can lead to further end products such as fertilizers, fodder, and raw material for other uses outside of the service chains. This figure shows that with the right enabling environment (here the eight most important factors are listed in *white boxes*), an integrated approach could lead to many of the synergistic outcomes to take place.

soil poses the risk of increased salinity, implications on soil fertility and health, and groundwater contamination (142).

Greywater and stormwater, especially for communities that have installed appropriate technologies, are not the most pressing threats to human health. However, the SDGs and their

INEQUALITY IN WASH AND SWM

Structural inequality, based on race, class, gender, geography, wealth, sexual orientation, etc., continues to present barriers to access for both Water, Sanitation, and Hygiene (WASH) and solid waste management (SWM) services. The UNICEF-WHO's Joint Monitoring Program (JMP) disaggregates global data to highlight the inequalities in the WASH sector and encourages governments to identify and develop mechanisms to prioritize addressing service delivery gaps for disadvantaged and marginalized groups (51). Inequalities, however, also manifest within academia. Although there has been more transformation and inclusivity in recent decades, significant progress remains to be made across all collaborative aspects, including publishing: A substantial share of academic outputs, including most of the work referenced here, is written by white academics, largely without adequate recognition or full involvement of their "partners" from the Global South (149, 150). This privilege must be acknowledged, and necessary commitments must be made to decolonialize the WASH and SWM sectors to truly address the structural inequalities that continue to inhibit just and transformative change in the academic and development sectors.

associated Goals and Targets cannot be achieved without integrating these two often overlooked aspects of environmental sanitation, as they can limit the effectiveness of the other more prominent WASH and SWM interventions. Moving forward, it is critical to examine the contexts in which grey- and stormwater interventions have been successful, and parse out, more concretely, the technologies, enabling environments, and user perceptions that have held back significant developments in this sector, and finally identify the ways in which these issues can be addressed in order to make substantial and lasting progress.

6. CONCLUSIONS

Operationalizing the SDGs requires major adjustments in the rationale, planning, operation, and capacity of service delivery for all. Although there have been key advancements in the individual sectors of water, sanitation, and solid waste for development as discussed in this review, coordination and integration remain distant goals. Uncoordinated approaches in the different sectors have created cross-contamination as well as inefficiencies in service delivery and have led to an underutilization of the potential for resource recovery. Similarities in the enabling environment, decentralization, community inclusive planning, governance and the close coordination requirements call for an integrated approach.

This article began by outlining the synergistic nature inherent to the water, sanitation, and solid waste sectors and concludes by emphasizing the positive interactions between them (**Figure 2**) compared to the current dominance of negative interactions (**Figure 1**). Reshaping future interlinked services will allow for more effective co-management of water, sanitation, solid waste, grey- and stormwater streams, while making better use of energy and nutrient resources.

To effectively tap such synergies between the sectors, comprehensive planning, implementation, and management through an integrated approach are required. Such integrated approaches are complex and face many structural and institutional challenges in practice. However, with strategic planning, strong leadership, clear coordination, and effective regulation, the existing silos can be broken to reap many co-benefits and explore the synergies in implementation and management of these services. Ultimately, for operationalizing many of the shared development goals of water and waste, integrated approaches are useful and necessary.

SUMMARY POINTS

1. There is an inherent set of interactions between the water, sanitation, and solid waste management sectors. Although the spillover effects from one sector to the other are observed, there have been few attempts to holistically plan and integrate these services.
2. The water sector has seen a shift from supply-led, infrastructure-oriented models to demand-responsive, service-oriented approaches that take into account that sustainability arises from complex and interconnected processes.
3. The sanitation sector mainly had a significant shift in the acceptance and development of non-sewered and decentralized technologies and service models. CWIS is the paradigm shift in urban sanitation that places equity and contextualization within its holistic approach.
4. Solid waste generation per capita increases with wealth, and efforts have focused on breaking the linear pathway toward circular economy and better resource management.
5. Many interesting similarities in the recent advancements between the three sectors are observed: relevance for public and environmental health, socioeconomic drivers, principles of equity, demand for low-cost and low-energy technologies, decentralization of infrastructure and management, community-driven planning, digitalization, resource recovery, and ensuring a suitable enabling environment.
6. There is a need to break existing silos and for more integrated approaches to reduce cross-contamination and inefficiencies in service delivery by bundling services and to better reap the potential co-benefits.
7. Such an integrated approach needs an enabling environment of political leadership, shared objectives, institutional coordination, effective policies, integrated planning, shared monitoring-enhanced capacities, and stakeholder support, all from a systems thinking perspective.
8. Storm- and greywater streams are often excluded from the design of water and waste interventions. Yet, these are important for fully realizing the benefits of interventions that focus on WASH and SWM, as well as for meeting international development targets.

FUTURE ISSUES

1. Although equity should be a core principle in the way forward in WASH and SWM, there is a lack of genuine strategic commitment and little evidence-based policy to direct operations.
2. There is a critical gap in documented experiences for integrating storm- and greywater with the WASH sector in LMICs.
3. Although integrated approaches that take into account water, sanitation, solid waste, storm- and greywater are deemed necessary for realizing their co-benefits, there is a need to develop planning frameworks, tools, and guidance material to make the synergy a reality.

4. In the future, we will require more data-driven case studies on integrated approaches to understand the complexity in planning and implementation, the drivers, barriers, and enablers for practice.
5. There is scope for more empirical research on the spillover effects between these sectors in terms of value addition, economic co-benefits, ease of implementation of other interventions and institutional structuring. Such research would help strengthen the case for integration.
6. Existing governance and institutional structures promote the siloed thinking that inhibits the integration of these basic services. Innovations in this space are required to be able to incrementally plan, implement, monitor, and maintain environmental sanitation.
7. Climate change, urbanization, migration, air pollution, and energy are other issues that have direct and indirect links with water and waste. Each of these major links should be explored in greater detail.

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Eawag Dep. Sanit. Water Solid Waste Dev. 2021. Massive Open Online Courses (MOOCs): MOOC series "Sanitation, Water and Solid Waste for Development." *Swiss Federal Institute of Aquatic Science and Technology (Eawag).* **https://www.eawag.ch/en/department/sandec/e-learning/moocs/**

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