

Sanitation game changing: paradigm shift from end-of-pipe to off-grid solutions

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Abstract

The toilet-wastewater-pollution nexus – the provision of safe, hygienic and appropriate sanitation solutions – is an emerging, priority issue world-wide. Developed nations have followed a linear design approach to achieve their sanitation needs, with conventional waterborne systems continuously improved to meet more stringent control and pollution regulations while minimising the load on the natural environment. Developing countries, on the other hand, continue to struggle to implement such systems, due to a myriad of factors associated with financing, affordability and revenue, and thus rely heavily on on-site systems. On-site systems pose a different set of technical challenges related to their management, which is often overlooked in the developing world. Whereas, while technology strides increase in conventional sanitation processes towards zero-effluent, these come at a significant cost and energy requirement. Further, climate variability and water security put added pressure on the resources available for flushing and transporting human waste. A new paradigm for sanitation, proposed in this paper, introduces and is based on technology disrupters that can safely treat human excreta, and matches user preferences without the need for sewers, or reliance on large quantities of water and/or energy supplies. Through innovation and smart-chain supply, universal access can be achieved sustainably, and linked to water security and business opportunities. The opportunity arises for leapfrogging these solutions in growing cities in the developing world, reducing water consumption and eliminating pollutant pathways.

Key words: faecal sludge management (FSM), off-grid sanitation, resource recovery

INTRODUCTION

With the conclusion of the drive towards the Millennium Development Goals (MDGs), the United Nations (UN) reported that goal 7, target 10 – halving the number of people who did not have basic sanitation by 2015 – had been achieved. Some 2.1 billion had gained access to improved sanitation (UN undated). While this is a significant achievement, there is a growing concern in the sanitation sector about the acceleration and sustainability of the solutions provided. Conventional waterborne systems connected to centralised treatment are usually preferred. They are associated with flushing toilets and usually viewed as the gold standard among users. On the other side of the technological scale are on-site sanitation systems. These are less popular among users but remain the most prevalent technology choice in the developing world. Water is a critical design consideration, either way, and can influence the approach used.

In the developing world, on-site sanitation approaches are often viewed as stop-gap solutions until conventional waterborne systems can be implemented. The challenge for developing countries is that they need to match the pace of increasing urbanisation and population growth, under increasing

water scarcity, and constrained financial and technical resources. Urbanisation is occurring rapidly in developing countries and their dilemma is whether they will ever reach universal sanitation coverage via conventional systems, while also managing increasing water, energy and pollution demands. In this paper, a new paradigm is presented to current sanitation approaches, which moves away from the linear concept of capturing, transporting, collecting, treating and disposing human excreta – to a holistic model that shortens the management chain through innovative hardware that treats human wastes *off-grid* at the point of generation. Resource recovery is also considered in the process.

THE CENTRALISED APPROACH

Since the 19th century, the centralised approach has been the wastewater management strategy applied. It is typified by a network of sewers linked to communities to transport large volumes of wastewater to one or more collection, treatment and disposal points. Its roots can be traced back to waterborne disease outbreaks, especially cholera, in Europe. Once scientific evidence linking waterborne diseases to poor sanitation became available, there was increased motivation to transport human excreta away from ever-expanding urban populations. Water is an essential transport component in this approach. While this strategy led to significant reductions in the outbreak of waterborne diseases (Lofrano & Brown 2010), it is wasteful as considerable volumes of potentially potable water are contaminated with human excreta and other pollutants to transport the human wastes.

In the developed world, the centralised approach underwent continuous improvement, from basic treatment and dilution strategies to protect public health towards more efficient systems to meet ever-increasing environmental protection and control standards (Lofrano & Brown 2010). Today, the centralised approach can be considered the *de facto* sanitation approach, especially for urban areas, worldwide.

While developed countries have continuously improved conventional wastewater-based strategies to make them more reliable and efficient over time, developing countries have struggled to implement the technologies successfully, for many reasons. They have a significant unserved population and the infrastructure provision has to address these backlogs in urban areas, as well as keeping pace with rapid population growth and urbanisation. Developing countries also need significant investment to provide sewer infrastructure (Lettinga *et al.* 2001). Several technical requirements need to be met: e.g., excavations for pipe-laying, reliable water infrastructure and supply to complement the conveyance system, and pumps and treatment systems to move and treat wastewater. Hauff & Lens (2001) indicated that the financial investment for such systems may be beyond the reach of most developing countries. Even in developed countries, these systems are cross-subsidised to make them financially sustainable (Hauff & Lens 2001).

Connection to a sewer system can be costly. A generalised estimate by WHO/UNICEF (2002) indicated that the cost per person of connecting to a sewer network is 5 to 50% higher than on-site alternatives. Further, the capital cost of treatment can be nearly double that of septic tanks (based on a population of 10,000 and compared with an activated sludge process) (World Bank Group 2016). Cost can be major driver for the technical approach used. Von Sperling (1996) hypothesised that the four main aspects considered by developing countries in selecting wastewater treatment were infrastructure costs, sustainability, operating costs and simplicity. Conversely, developed countries perceive efficiency, reliability, sludge disposal and land requirement as the major drivers for technology selection.

Besides the infrastructure investment, a suite of other resources, such as water and energy, and high-level designers, technicians and operators, are required to manage wastewater plants and their auxiliary equipment properly. Lack of these can result in infrastructure deterioration and/or unreliable services (e.g. Eales 2008; Hawkins *et al.* 2013; UN-Water 2015). Eales (2008) noted that, in South Africa, only a small percentage of plants were operated and maintained adequately, and there was a critical shortage

of skilled staff to operate and maintain treatment works. *Josiane et al. (2013)* reported similarly, with anticipated treatment performance rarely achieved in the African countries analysed. In that study, a common challenge reported was the inability of treatment works to deal with increasing pollution loads. Other issues included unstable energy supplies, poor operation and maintenance, and lack of investment in current infrastructure. The technical requirements needed for conventional waterborne sewer systems are challenging, not only in the developing world (*Hawkins et al. 2013*) but also the developed one (*Tsagarakis et al. 2001*; *European Commission 2004*).

Conventional systems continue to put pressure on water resources, require high energy inputs and pose a continuous threat to the environment. It is clear that application of the centralised waterborne approach in the developing world has not had the desired impact, although it has done in the developed one. As a consequence, the developing world still relies heavily on on-site sanitation approaches.

THE ON-SITE SANITATION APPROACH

On-site sanitation includes ‘drop and store’ technologies such as pit latrines and septic tanks, and their assorted variants. Many are included in the WHO’s definition of improved sanitation (*WHO 2015*) – i.e., (1) access to flush or pour-flush toilets/latrines connected to a piped sewer, septic tank or a pit latrine; (2) ventilated improved pit (VIP) latrines; (3) pit latrine with slab; and (4) a composting toilet – and recognised as adequate sanitation technology. It is estimated that around 2.7 billion people globally use on-site sanitation systems (*Boston Consulting Group 2013*; *Strande et al. 2014*), which are the predominant technology in developing cities of varying population size (*Chowdhry & Koné 2012*). In sub-Saharan Africa, pit latrines and variants are far more common than conventional waterborne systems (*Kjellén & Nordqvist 2012*). In terms of development targets, it appears that the technology can be scaled at a level to match the pace of urbanisation in this region. A general increase in non-sewered flush sanitation facilities was also noted in South East Asia (*Kjellén & Nordqvist 2012*). There is increasing evidence that fully-sewered applications cannot keep pace with the rapid urbanisation of developing countries (*Strande et al. 2014*). For this reason, on-site sanitation will continue to be used until better and more suitable alternatives become available.

The linear design found in centralised approaches also limits on-site sanitation approaches but the set of challenges differs. On-site technologies are associated with poor user experience compared to full-flush toilets – e.g., foul odours – and concerns with environmental and public health safety. There is also a disjunction between infrastructure provision and management of the investment. Full on-site sanitation systems are neither appropriate nor hygienic. In rural areas, the pit can be relocated but in urbanised environments this becomes challenging and leads to the question of what to do when the pit is full. Faecal sludge – a mixture of human urine and faeces of varying stability and pollutant concentration – accumulates in on-site systems and requires regular collection (emptying and disposal). The term ‘faecal sludge’ was developed to differentiate this human waste from domestic wastewater, and is defined as the human faecal waste that is contained or accumulates in on-site sanitation systems that do not rely on sewers for conveyance. The composition of faecal sludge is also highly variable, unlike domestic wastewater, which can be broadly classified into four strength categories (*Mara 2003*) (*Table 1*). This variability can be traced to the collection system, which could be designed on the basis of liquid/solids separation, and/or leaching or non-leaching, and preferential user habits, such as anal washing, which introduces additional water into the system (*Figure 1*).

LESSONS FROM FAECAL SLUDGE MANAGEMENT

With centralised approaches proving prohibitive, many developing countries and international organisations have recognised certain on-site sanitation technologies as adequate sanitation solutions in

Table 1 | Comparison of domestic wastewater and faecal sludge. The data sets used relating to faecal sludge are predominantly from countries where most users are washers and the relevant units are 'mg/L'

Domestic wastewater ^a		
Strength	BOD ₅	COD
Weak	<200	<400
Medium	350	700
Strong	500	1000
Very Strong	>750	>1500
Faecal Sludges		
	BOD ₅	COD
Cesspool/Septic tank ^b	600–5500	1200–76000
Pit latrine ^c	1902	10725

^aMara (2003).^bHeinss *et al.* (1999).^cBassan *et al.* (2013).**Figure 1** | Variation in physical characteristics and detritus content of faecal sludge, Durban – South Africa.

reducing backlogs. Their rapid proliferation due to the lack of suitable alternatives has brought a series of technical challenges related to faecal sludge management (FSM) accumulation, and subsequent emptying and disposal.

Since about 2000, FSM has gained prominence; having been largely neglected previously as on-site sanitation systems were thought of as temporary solutions (until conventional full-sewered systems could be implemented). The rapid proliferation of on-site sanitation to meet national development targets coupled with the lack of technical knowledge on the management of faecal sludges in full systems has led to a drive to develop solutions around the FSM supply chain.

Case study: South Africa

When South Africa's first democratically elected government came to power in 1994, provision of basic water and sanitation for unserved citizens became a priority. Since then, a framework of legislation, policies and guidelines has been developed to support achievement of this goal. The National Sanitation Policy White Paper (DWAF 1996), developed in 1996, defined the basic level of household sanitation as a VIP latrine, which falls under the UN technical category of improved sanitation. Later,

the White Paper on Basic Sanitation (DWAF 2001) highlighted the challenge of cost recovery from rural households with respect to water and sanitation. It was followed by the Strategic Framework for Water Services (DWAF 2003). The latter provided guidance to Water Services Authorities (WSAs) in providing free basic sanitation infrastructure by the then target of 2014, promoting health and hygiene, and subsidising the operating and maintenance costs. VIP latrines were considered adequate infrastructure for sanitary purposes and, according to the Strategic Framework for Water Services, this free basic service should be maintained at government expense (Still & Foxon 2012). Further, as Still and Foxon noted, the document suggests, however does not prescribe appropriate technology, with WSAs needing to address several situations: (1) in urban areas and high-density residential areas, waterborne sanitation is considered the most appropriate solution; (2) in rural areas, on-site sanitation technical solutions are deemed appropriate; and (3) in intermediate areas – e.g., peri-urban – the WSA would need to consider the most appropriate technology and exercise caution when selecting waterborne options.

Since 1994, large-scale infrastructure programmes have been implemented to build VIPs to achieve national service delivery goals. Current estimates indicate that around 30% of the South African population rely on VIP toilets and their derivatives (Statistics South Africa 2013). Over two million VIPs and other on-site sanitation systems were implemented in South Africa after 1994, and many thousands reached capacity faster than anticipated (Figure 2). Many municipalities did not have operating and maintenance procedures, budgets or plans for VIP toilets, with some needing emptying as frequently as twice a month (Mjoli 2010; Still & Foxon 2012). A national audit of water and sanitation projects for the then DWAF (now Department of Water and Sanitation) indicated that at 60% of the facilities surveyed, municipalities were only conducting reactive maintenance, while 40% of municipalities had inadequate maintenance capacity (SALGA 2009).

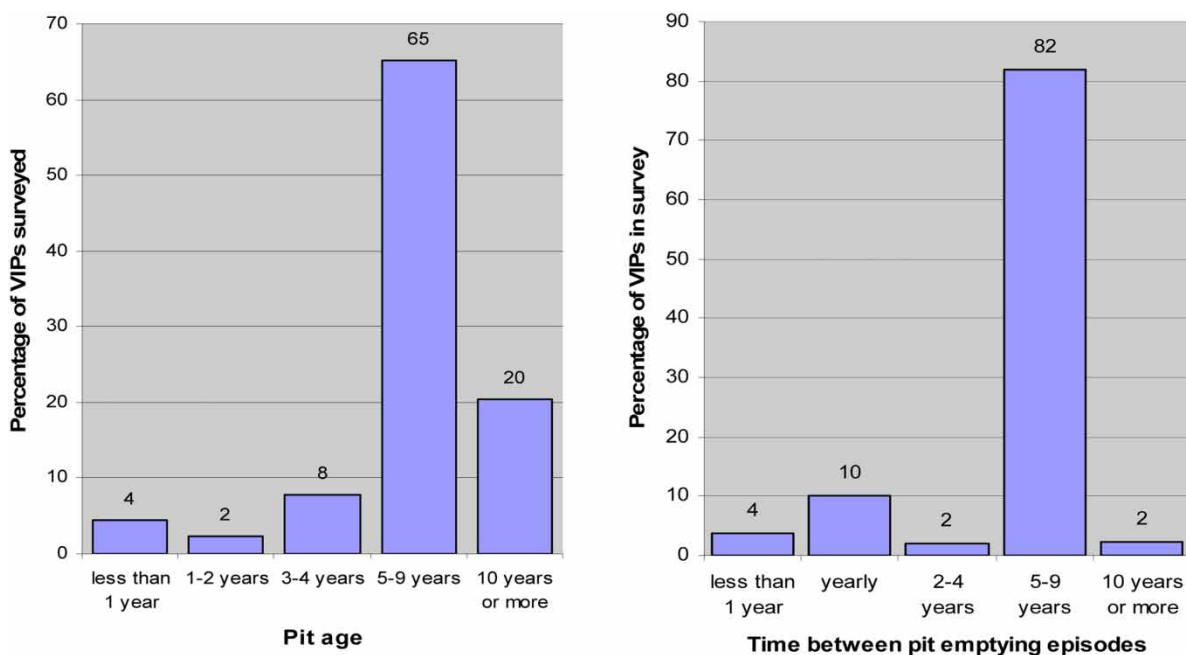


Figure 2 | Pit ages and emptying intervals required (Still & Foxon 2012).

In the early 2000s, the Water Research Commission (WRC) invested strategically in developing innovation around the FSM supply chain. At the same time, eThekweni Municipality, with the city of Durban as its core, was undertaking an emptying programme on all VIP latrines, 60,000 of which were inherited when its municipal boundaries were expanded. Many of the pits encountered during the programme were reported more than 10-years old and in urgent need of emptying

(Brouckaert *et al.* 2013), a task that could only be done manually due to the high detritus content (Still & Foxon 2012). Moreover, there were difficulties disposing of the emptied faecal sludge safely as the nearest municipal sewage treatment works could not handle the additional pollutant load.

To add to the complexity of the situation, technical knowledge of dealing with full pit toilets and the faecal sludge was limited. Vacuum tankers could not always be used and faecal sludge did not implicitly fall under existing sludge disposal guidelines (Still & Foxon 2012).

The result and response was an incremental research strategy by the WRC, in partnership with eThekweni Municipality and a number of research institutions, aimed at improving the knowledge base needed to support the development of strategies and innovative technical solutions to deal with dry sanitation. The aim was to provide a strong knowledge base and platform to these sanitation challenges, thus stimulating local innovations so that the lessons were applied in other municipalities facing similar difficulties. The three-pronged strategy aimed at: (1) understanding sludge accumulation rates in VIPs; (2) elucidating scientifically the processes occurring in VIP latrines and their variants; and, (3) developing pit emptying technologies. The results are summarised in Table 2.

Table 2 | Summary of research findings (Bhagwan *et al.* 2008; Bakare 2012; Still & Foxon 2012; Brouckaert *et al.* 2013)

Pits filling faster than their design life. The servicing interval of pits depends strongly on the presence/absence of detritus. It was predicted that VIP latrine capacity could be extended by 15 to 25 years by preventing detritus entering pits.

Pit additives. 21% of WSAs promoted or provided bio-enzyme additives to householders. There was no experimental evidence from either controlled laboratory or field trials that additives could reduce the rate of sludge accumulation or the volume of sludge in VIP latrines.

Pit latrines as storage vessels. The faecal sludge in VIP latrines had undergone significant stabilisation and was, therefore, not subject to the same treatment applications as fresh excreta. Aerobic biodegradability ranges from 50% at the top of the sludge heap to around 20% in the bottom half.

Faecal sludge poses a significant health risk. 60% of households analysed tested positive for *Ascaris*, while the examination of manual pit emptiers' face masks showed that exposure to parasitic helminths was high.

The cost of managing faecal sludges from full latrines is high. Sometimes it is comparable to the cost of installing new latrines.

The programme's findings showed the technical challenges of managing VIP latrines. With full waterborne sanitation expected to cost an estimated ZAR (South African Rand) 6 billion (USD 3 million) in capital infrastructure investment alone, other alternatives were sought (Macleod, N. pers.comm.). Outside the sewered network, indigent households were provided with urine diversion double-vault toilets (UDDTs), in which urine is separated from faeces. The urine percolates into a soak-away penetrating the soil, and the faecal sludge, and other anal cleansing and bulking material, collects in a vault under a pedestal. Once the first vault is full, the pedestal is moved over a second vault. It was thought that the faecal sludge in the standing vault would undergo dehydration and hence pathogen deactivation, allowing its contents to be emptied and buried safely. Source separation of the urine would also allow smaller volumes of faecal sludge to be emptied, transported and disposed of.

Around 80,000 UDDTs were installed in the eThekweni Municipality. Screened samples from 120 toilet vaults in the Municipality revealed, however, high levels of occurrence of both protozoan and helminth parasites (Trónnberg *et al.* 2010), indicating that complete pathogen deactivation was not occurring. Further, a survey of over 17,000 households in the municipality indicated low levels of satisfaction with the UDDTs, because of perceived smell in them and pedestal malfunctioning, as well as low usage located within the dwelling perimeter (Roma *et al.* 2013). These findings highlight the complexity of sanitation provision in which the service provider must match user needs and preferences to limited technical, natural and financial resources. Further, it pointed to the lack of suitable technology alternatives to deal effectively with faecal sludge on-site and render it harmless.

Globally, the research produced to date indicates the misalignment of sanitation infrastructure and its management (Koné 2010; Chowdhry & Koné 2012; Slabbert 2015; Louton *et al.* 2016). Sanitation programmes tend to be supply-driven, with very little thought afforded to user preferences, availability or resource recycling, operating and maintenance requirements, relocation and/or reuse of superstructure materials, superstructure cost reductions, and/or linking managing the systems to business opportunities (Bhagwan *et al.* 2008; Chowdhry & Koné 2012). The misalignment results in unreliable service and deterioration of the investment made (Koné 2010; Louton *et al.* 2016).

Climbing the sanitation ladder

The challenge in providing all households with basic sanitation is not just finding the right technology to suit the logistical needs, it is also social. Most indigent people in developing countries view flush toilets as a symbol of status and equality. In South Africa, many communities insist on having flush technology instead of dry toilets like VIP latrines – the government's recommended level of basic sanitation technology. This political pressure under technical constraints led WRC to develop an on-site pour-flush application. The technology is similar to Asian pour-flush systems but adapted to suit South African users: it needed a pedestal with a seat and a water seal, and had to flush excreta together with toilet paper and/or newspaper, use minimal water, and limit water wastage. An innovative P-trap design allowed the prototypes to use low flush volumes (2ℓ), and limits the detritus passing through the user interface into the leach pit. Prototypes were initially evaluated using the international MaP protocol (<https://www.map-testing.com/>) and then field-tested in a few rural households, which reported high user acceptance. The MaP test refers to Maximum Performance, and represents the number of grams of solid waste (soybean paste and toilet paper) that a particular toilet can flush and remove completely from the fixture in a single flush. Essentially, it is a test to failure. Such testing is independent, and is neither affiliated to nor controlled by any manufacturer or group. The system has since been tested more rigorously, with similar success reported in households and institutional settings across South Africa (WIN-SA 2015). Users have indicated that the toilet 'looks nice' and is 'safe', the latter suggesting that a fear element had crept into communities as a result of unfortunate incidents with children falling into pit latrines.

Recently, low-flush cistern upgrades have been produced due to demand and eThekweni Municipality has incorporated the toilet in government-sponsored housing schemes that are not close to the centralised sewerage network. While the toilet represents a climb up the sanitation ladder, as it is more advanced and has higher user satisfaction than pit latrines, the next logical step would be eliminating faecal sludges at the back-end of the toilet. This would shorten the management chain associated with it.

SANITATION GAME CHANGING

In 2011, the Bill and Melinda Gates Foundation's Water, Sanitation & Hygiene programme initiated the *Reinvent the Toilet Challenge* (RTTC) to address the limitations of current sanitation approaches.

The Foundation set the ambitious goal of developing the next generation toilet system within 5 years. To achieve this, grants were awarded to 16 research teams around the world to develop innovative technologies – based on fundamental engineering processes – for the safe and sustainable management of human excreta. The technical requirements set were that the system must: (1) protect public and environmental health, (2) recover valuable resources such as energy, water and nutrients, (3) operate off-grid without connections to water, sewer, or electrical lines, (4) cost less than US\$ 0.05 per user per day, (5) promote economic sustainability, and (6) be an aspirational product that will attract in both developing and developed country contexts.

More research teams have become involved since 2011, with a number of advances made with respect to sanitation treatment processes. The innovative, off-grid sanitation prototypes developed through the initiative focussed primarily on mechanical, physical and chemical processes, including liquid/solid separation, hydrothermal carbonisation, combustion and electrochemical treatment, to treat excreta almost immediately.

In RTTC's first phase, grantees provided scientific testing and validation of the processes, with the prototypes showcased at the 2012 RTTC Fair (Seattle, USA). The prototypes underwent rigorous testing and evaluation, optimisation and improvement, with demonstration-ready units showcased at the next RTTC Fair – 2014, Delhi, India. These prototypes are now being evaluated in India, China and South Africa, to establish market readiness, ensure durability and reliability, develop specifications and manufacturability, and understand issues relating to usage, including user acceptability and the re-use of beneficiated waste streams. The Foundation aims to establish a provision and servicing model similar to that for commercial household appliances to deal with the constraints of current approaches.

Through innovative design and treatment processes, the technologies developed under this initiative have the potential to address current sanitation limitations by eliminating pathogens on-site, recycling/re-using limited resources, meeting user experience and acceptability criteria, minimising environmental pollution, and enabling the linking of sanitation infrastructure to innovative management approaches. Treating human excreta at source, eliminates the need for sewers or, in the case of on-site sanitation technologies, having to find ways to manage faecal sludges (Figure 3). Less water is wasted because the technologies significantly reduce requirements for water or re-use/recycle it. Further, human excrement is transformed into by-products of potential economic value, allowing linkages to new business and service delivery models that have the potential to reduce the financial burden to municipalities. Such approaches not only challenge the way in which unserved areas are approached, but also the way in which water security and sanitation are managed in formalised areas using conventional technologies. In the developed world, water supply and sanitation have

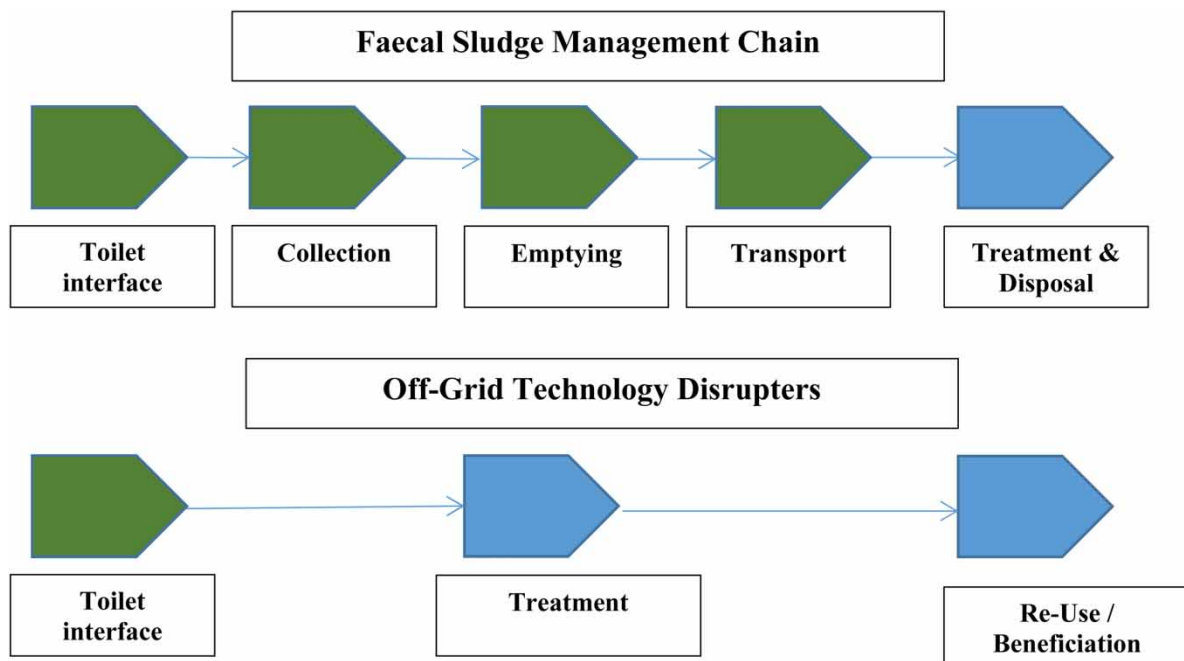


Figure 3 | Current and proposed approaches to sanitation. In linear FSM, any weakness in the management chain results in service disruption. In the alternative, the collection, emptying and transport cycle is reduced or eliminated by processing excreta off-grid into safe, potentially valuable by-products. Quality assurance is achieved through specification and manufacturing standards, which are in preparation.

followed a linear design trajectory – from achieving water supply, to sewered settlements, then drainage – to integrated urban water cycle management (Brown *et al.* 2009). The developing world appears to be following the same route. The off-grid solutions developed by the Foundation's funding could leapfrog this, enabling developing countries to mitigate water security and achieve sanitation provision, without additional water and/or energy, and create employment opportunities through new service, and operation and maintenance models.

CONCLUDING REMARKS

The sustainability of sanitation services relates to finance, people, institutions and technologies. Current linear approaches to sanitation, whether through fully waterborne or on-site systems, are not sustainable. Numerous studies have shown that sanitation infrastructure investment failures arise from poor consultation, poor understanding of needs, poor management, operation and maintenance, and lack of technological alternatives. This paradigm can be shifted, through innovation, towards more responsible use of water, energy and nutrients in towns and cities, while achieving the main aim of sanitation: protecting public health and the environment.

There is thus an opportunity to grow new services, operation and maintenance industries, using innovative products which offer the potential for smart supply chain management. The appliance-based model could yield growth opportunities for businesses manufacturing toilets and their parts, and incorporate the operation and maintenance component within the sanitation management model. This would enable the provision of the quality facilities and sanitation services that municipalities struggle to fulfil. In addition, there is the potential to recover valuable by-products which could open up other servicing models to ensure the sustainability of the approach. Developing countries should take advantage of this opportunity to leapfrog the linear design approach water and sanitation supply taken by developed countries.

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