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14. Frugal engineering solutions for recovery of resources from wastewater

Pamela Ceron-Chafla and Ralph E.F. Lindeboom

14.1. INTRODUCTION

This chapter describes how water resource management evolved in the Western world as a centralized linear system. Relatively large public and private corporations are driving innovation due to their main task of securing water availability and quality on a regional scale. This chapter will discuss how an innovation system has emerged in the Western world that successfully enabled water innovations in resource affluent settings and led to access to water supply and sanitation for the majority of its population. It will also discuss the limitations of the Western technical water innovation system in response to newly emerging challenges (Carlsson et al., 2002). The focus will then shift to how the technology developed within the Western technical innovation system has been translated to developing economies characterized by a high rate of urbanization and an attempt will be made to identify the limitations that result in not delivering the same results. The third part of the chapter will then highlight how people at the Bottom of the Pyramid (BoP) have historically relied on cultural heritage or indigenous innovations such as “Jugaad” for their personal or local decentralized provision of safe water. In the final part of this chapter we will bring together the opposite dimensions of these systems (centralized, linear and resource affluent versus decentralized, circular and resource constraint). Frugal innovation¹ is then presented as the confluence between “sustaining innovations” and Jugaad-like innovation. More importantly, it is highlighted as the source of frugal engineering solutions needed to solve one of the major 21st century global challenges, defined as UNSDG 6: equal access to sanitation and water supply by 2030.

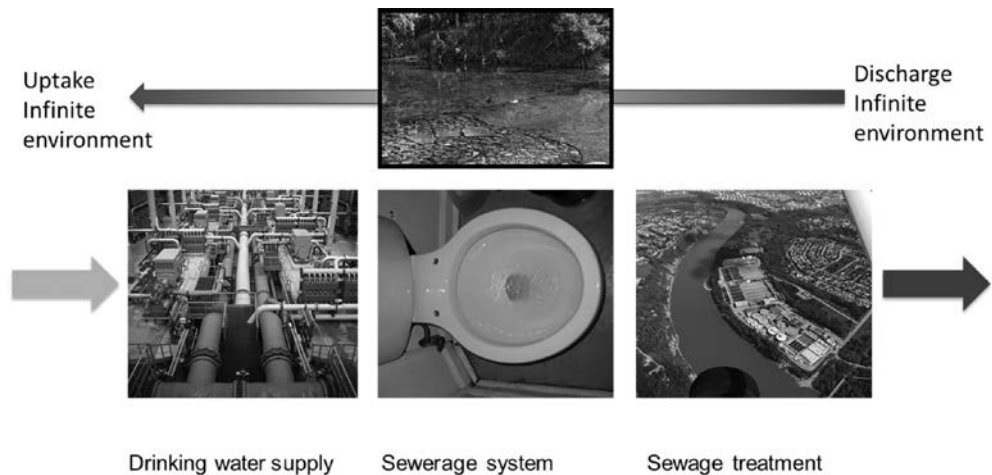
14.2. THE ORIGIN AND STATUS OF THE WATER SUPPLY AND SANITATION SYSTEM IN THE WEST

The development of the linear “Western” water system is characterized by a handful of large breakthrough innovations, described by Sedlak (2014) as Water 1.0, Water 2.0 and Water 3.0. The first crucial element (Water 1.0) was the integration of citywide planning and piped water distribution achieved by the Romans. In the 19th century, under the expansion pressure of large cities in the United States such as New York and Chicago, chlorination was introduced in centralized water supply systems to mitigate the outbreak of waterborne diseases. After further adoption of this approach, access to safe distributed water became the norm in the Western world (Water 2.0). Then, in the 20th century, planning of sewage conveyance and treatment systems was adopted in practically all cities, improving the larger water ecosystem (Water 3.0). These developments mostly took place during a resource-affluent period. At the time, all

global resources were at the disposal of the Western world given its colonial past and subsequently stronger economies compared with the Global South (Lempert and Nguyen, 2011).

It is therefore not surprising that the water supply and sanitation in our Western world currently also functions at the grace of access to abundant resources, which include a stable fossil-fuel driven electricity grid, an abundant, well-educated workforce and a centralized, well-maintained distribution and sewerage system. Potable water is typically harvested from a practically “infinite” environment, treated to improve its quality and then pumped to households via thousands of kilometres of piped distribution networks. Upon contamination it is discharged into a similarly extensive centralized sewerage system. There, it is often mixed with excess rainwater runoff, treated in centralized sewage treatment plants hidden in the outskirts of cities before being discharged into an “infinite” environment.

Over the past century, major infectious waterborne diseases have been practically eradicated from Western society, and it is often forgotten that the improved water supply and sanitation has been a key contributor (Sedlak, 2014). Access to sanitation and potable water supply has increased significantly in recent decades, with the richest countries reaching close to 95–100 per cent. It is therefore safe to assume that our “Western” linear water approach, as depicted in Figure 14.1, has been successful under local resource-affluent circumstances (Figure 14.1). Nonetheless, challenges remain, as roughly 60 million people in Europe and Central Asia still lack access to proper water supply and sanitation (WHO, 2019b).



Source: File:Reverse osmosis desalination plant.jpg by Jimjamjak is licensed under CC BY-SA 3.0. “” by Make Lemons is licensed under CC BY-SA 2.0. “Edmonton 2012” by jasonwoodhead23 is licensed under CC-BY 2.0. “Laceys Creek 1&” by Sheba_Also 43,000 photos is licensed under CC-BY SA 2.0.

Figure 14.1 Schematic visualization of the “Western” linear water supply and sanitation approach suitable for relatively low population density

Given the success of the Western water system, there is little incentive for further innovation and the majority of treatment plants spread throughout the West are highly similar. Treatment plants are typically large, treating all the municipal wastewater for tens of thousands popula-

tion equivalents. The municipal wastewater treatment systems very often consist of a primary clarifier, an aerobic biological activated sludge plant, followed by a secondary clarifier, after which the effluent is discharged into the environment. High-rate anaerobic systems, which are energetically more favourable, have been introduced, but their application is often limited to industry and/or relatively warmer climatic zones (van Lier et al., 2008).

Despite most sewage treatment plants still operating traditional activated sludge systems, the past decade has seen the introduction of more compact aerobic granular sludge systems. Those are now slowly penetrating the market, owing mostly to their lower surface area requirement and lower energy consumption (Pronk et al., 2015). Likewise, decentralization initiatives are garnering more attention and there is renewed interest in resource recovery (Zeeman et al., 2008). Nevertheless, most of these innovations are being introduced by or at least in cooperation with existing players in the field, i.e. within the existing innovation system. As a consequence, the four systemic problems that prevent systemic innovation as described by Wiczorek and Hekkert (2012) – actors, interaction, institutional and infrastructure – may play a role here. Institutionally, legislation in terms of quality and quantity is met using the current centralized physical infrastructure, which was built with a technical lifespan of over 30–70 years, and available knowledge of the actors (de Graaf and van der Brugge, 2010). There is a high amount of interaction between the actors, as they use practically the same physical infrastructure and share knowledge through, for example, the joint VEWIN (2018) and Unie van Waterschappen (2016) in the Netherlands or the AWWA in the USA. As a consequence, a lock-in effect is created in which the incentive to adopt “disruptive” innovations is marginal, leading to a situation in which so-called “sustaining innovations” are introduced that would neither risk upsetting the water quality nor the power balance in the existing innovation system (Reinhardt and Gurtner, 2015; Avelino and Rotmans, 2009).

It has been argued, however, that emerging challenges could result in required structural changes that could affect the power balance (Avelino and Rotmans, 2009). These challenges include extreme weather events, micro-pollutants and the prevalence of antibiotic resistant bacteria. In response to these challenges, there have been calls for renewed co-operation between various stakeholders, namely urban planners, civil and environmental engineers, public health experts and lawmakers (Sedlak, 2014). Decentralized treatment has been proposed and implemented in various initiatives for communities of several hundreds of households as one of the responses. The community-scale decentralized sanitation systems in the Netherlands are, however, still connected to a centralized potable water distribution system and discharge the effluent into the environment (Zeeman, 2008; Roefs et al., 2017). Examples of an almost completely closed municipal water cycle have only been achieved under specific circumstances where freshwater scarcity has become a societal issue, such as in Singapore and Windhoek (Lafforgue and Lenouvel, 2015). Both systems are large scale and it can therefore be argued that these systems are circular but not really decentralized. As they are operated by their respective public utility boards, innovation is still taking place within the existing innovation system.

One of the examples coming closest to a fully decentralized circular sanitation and water supply system can be found in the Concordia research station on Antarctica. There, the accessibility and local circumstances enforce full off-grid operation for 15 permanent residents (Lasseur, 2004). The design of this system happened in close co-operation with the Micro-Ecological Life Support System Alternative consortium of the transnational European Space Agency, which aimed to test their water recycling/life support system in a hostile,

remote environment (Bazley, 2011). These solutions are technically sound and suitable for decentralized circular operation in a resource-constrained environment. Nonetheless, they are deemed beyond reach for the BoP due to financial constraints. For example, the price of sending up 1 L of water or other resources into space exceeds tens of thousands of euros (Lasseur et al., 2005; Fairburn et al., 2017; MELiSSA Foundation, 2019).

14.3. THE LINEAR SYSTEM REACHING ITS LIMITATIONS IN THE MEGACITIES OF THE GLOBAL SOUTH

The success of the “Western” linear system and the UN’s focus on enabling access to water supply and sanitation has driven megacities in the Global South to adopt this same approach. Still, close to 2.0 billion people do not have access to any form of improved sanitation (WHO, 2019b) and 785 million lack access to safe drinking water supply (UN, 2019b). The implications of using systems designed for resource-abundant societies in a resource-constrained society are well described in research that has been conducted on resource affluence by Harlan et al. (2009) and Weinzettel et al. (2013). Over the past decades, many projects have been implemented in which technology that was developed in a “Western” socioeconomic context was copied step-by-step to solve “real”-world challenges in different socio-economic context. It shouldn’t come as a surprise that there are a multitude of examples that demonstrate the limitations of this strategy (Mackintosh and Colvin, 2003; McPherson and McGarry, 1987; Starkl et al., 2013). Moreover, it has been estimated that in 2016 over 1.8 million deaths were caused by inadequate water supply, sanitation and related waterborne diseases (UNESCO, 2020).

The following section describes several challenges found in urban and rural communities in the Global South. It aims to demonstrate the need to innovate beyond the traditional innovation derived from a resource-affluent water innovation system in order to fit a resource-constrained environment.

14.3.1. Limitations in Access to a Well-educated Workforce

As part of their responsibility to maintain groundwater and surface water levels and dyke integrity, the Dutch Water Boards employ a total of about 12,000 employees (Unie van Waterschappen, 2016). On top of that, drinking water companies in the Netherlands employ another 5,000 employees to ensure the proper operation of roughly 120,000 kilometres of a piped distribution network (VEWIN, 2018). Most of these employees would qualify under the category of a highly skilled labour force. When assuming an equal number of skilled employees per capita, 1,000 skilled employees would be needed per million inhabitants in a megacity in the Global South. This excludes the engineers needed to construct the physical infrastructure themselves.

For example, in a country such as India, with a high level of local educational opportunities for the middle class, the relative lack of interest in wastewater engineering is striking (Chaplin, 1999). As Chaplin (1999) argues, it appears that a large part of the middle class has been monopolizing state-provided sanitary services in order to differentiate themselves from the lower classes. It lies in the interest of the middle class to focus on more “respected” professions, such as medical doctor, pilot or programmer, that enlarge the difference from the lower class. More than providing the educational opportunities and technology, a change in mindset

is needed to help the megacities overcome the labour gap and thereby help them to become “water-wise” (Koop and van Leeuwen, 2015).²

14.3.2. Limitations in Access to a Stable Power Supply

The United Nations (2019a) reported that the rate of electrification has increased to 89 per cent in 2017. However, Andersen and Dalgaard (2013) point out that 50 per cent of African businesses see power outages as a constraint for their business. Power outages seem to occur more frequently in the Global South (Andersen and Dalgaard, 2013; Amadi, 2015) compared with “Western” countries (Klinger et al., 2014; Reichl et al., 2013). It can be assumed that the power supply for sufficient (waste)water treatment is also unlikely to be secured. Unfortunately, the dependence of conventional water treatment technology on a stable power supply in “Western” countries is high.

For example, the total power consumption of conventional wastewater treatment plants (WWTP) was estimated at 800 million kWh for the Netherlands in 2017 (CBS, 2019). About 20 per cent of this was generated at the WWTP sites from the production of biogas and/or other renewables. This demonstrates that the design of centralized “end-of-pipe” treatment plants still heavily relies on stable and centralized power supply, despite efforts in developed economies to increase the share of renewable energy. The majority of the power is consumed by compressors for aeration and the feed pumps in conventional WWTPs. Online monitoring and analytical laboratories that are used to analyse the wastewater characteristics require a much smaller supply but are sensitive to power outages. Although a power outage does not result in a direct health effect, such as when analytical equipment fails in hospitals, its usage has sensitivities to power outages similar to many medical devices used in hospitals (Klinger et al., 2014; Reichl et al., 2013).

14.3.3. Limitations in Access to Environmental Resources in Time and Space

For the relatively small population of a country like the Netherlands, which is situated in the delta of two main European rivers, water resources have always been abundant for the entire population. However, megacities in the Global South have a total number of inhabitants equal to the entire population of the Netherlands. In the Netherlands, the average person consumes roughly 125 L of potable water per person per day. When assuming equal per capita consumption for the megacities combined with the size of the urban population and the population density, annual water consumption (mm/y) in megacities is often larger than average global annual precipitation (mm/y) (Figure 14.2).

Despite not being adjusted for local and seasonal conditions, the magnitude of the challenge, especially for megacities in arid regions containing large informal settlements, cannot be denied. Data collected by NASA on the global³ precipitation patterns reveal the magnitude of human water consumption. On average, global annual precipitation is ~400 mm per year, but large fluctuations are present depending on season and climatic zone, due to which regional assessments are preferred (Rockström et al., 2014; Savenije, 2019). Annual precipitation in Delhi and Delft has been practically equal at 2.1 mm/d over the past 3 years, but in Delhi most of this precipitation fell during the monsoon season (Figure 14.3). Logistically, this has consequences and therefore the British colonizers expanded the naturally existing drainage

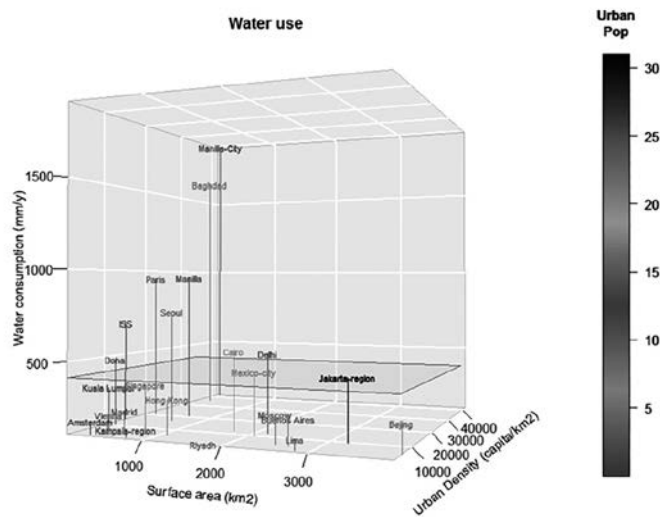
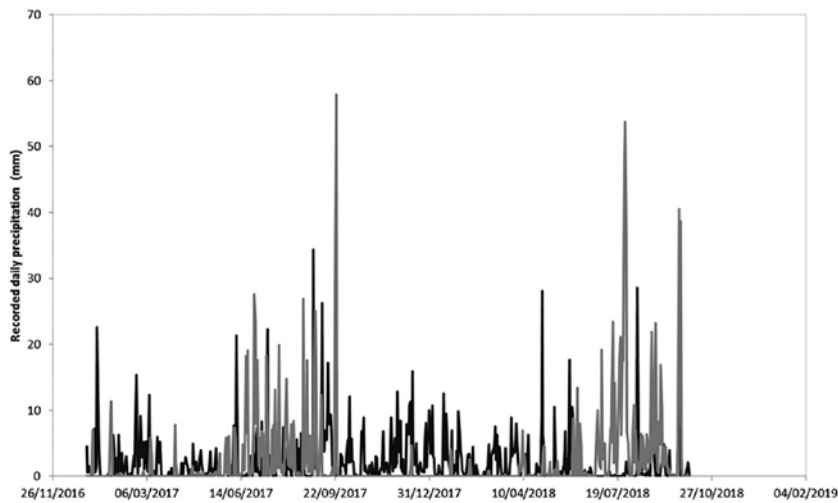


Figure 14.2 Total urban municipal water consumption (mm/year) in different global capitals plotted against surface area (km²), total population (capita) and urban density (capita/km²) assuming an average consumption of 125 L per capita per day. The plane represents the average global precipitation

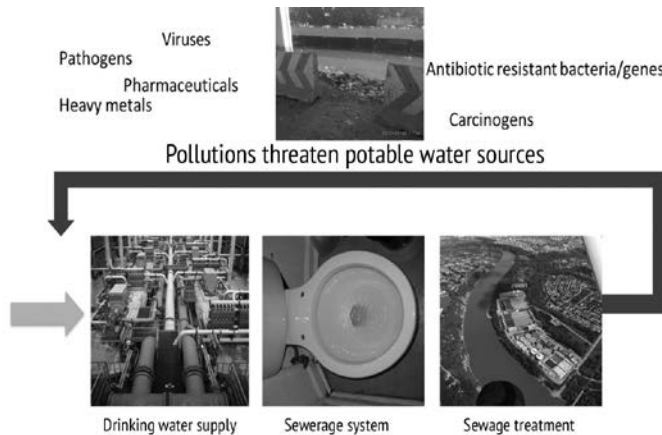


Source: NASA (2019).

Figure 14.3 Recorded rainfall (mm) at GPS coordinates in Delft (Latitude 52.022 Longitude 4.3256) and New Delhi (Latitude 28.5834 Longitude 77.2668)

pattern to prevent urban flooding, but only in the most important parts of the city. This division is currently still present in large Indian cities such as New Delhi (Chaplin, 1999).

In general, it can be assumed that cities that consume more water than the local annual precipitation will require a larger surface area to secure sufficient rainwater catchment (similar to river estuaries). Otherwise, those settlements will be forced to deplete groundwater reservoirs. Once the water has been consumed, a centralized distribution or conveyance network would need thousands of kilometres of pipes and channels in order to support this ever-increasing water demand. The Romans constructed aqueducts for this purpose (Water 1.0) (Sedlak, 2014). Nonetheless, the total water that needs to be transported into and out of megacities is an order of magnitude larger and can run into several million m³ per km² year in dense urban areas. In many situations, as in India or Malaysia, sewage or treated sewage effluent can make up a significant part of the river run-off. This is not a localized phenomenon since also in Europe the large rivers, such as the Rhine, consist to a large degree of treated sewage effluent (van der Weijden and Middelburg, 1989). Any pollutant that is not removed could end up accumulating in the local hydrological cycle or even in the potable water of downstream communities (Figure 14.4).



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Figure 14.4 Schematic visualization of the "Western" linear water supply and sanitation approach and the consequence of applying it in areas of high population density

The Netherlands, with about 17 million inhabitants living on >30,000 km², relies on more than 300 wastewater treatment plants with average capacities between 10,000–150,000 population equivalents (CBS, 2019). For the megacities of the Global South, a similar treatment capacity would have to be installed in cities (<4,000 km²), in which land/surface area is typically limited owing to the high population density.⁴ Typical Dutch treatment plants are deliberately built on the outskirts of the cities where the access to the environment allows for safe discharge. Following a similar strategy would be a much larger logistical challenge for the megacities of the Global South, owing to the high population density and land availability. As

a consequence, the challenges identified in the Western linear system are more pronounced in the megacities of the Global South. A frugal solution strategy could therefore help advancing in both.

14.4. TAPPING INTO THE CULTURAL HERITAGE – SOURCES OF JUGAAD-LIKE INNOVATION IN WATER

The Western world is a relatively young society compared with ancient societies in China, India, Africa, Latin America and Persia. Therefore, the focus on systemic innovation as described in conventional innovation literature (Wieczorek and Hekkert, 2012) risks excluding a plethora of cultural heritage or indigenous innovation types. Examples of these types of innovation include Jugaad (India), DIY (Anglo-Saxon world), Gambiarra, Jeitinho (Brazil), Systeme D (France), Jiejian Chuangxin (China) and Kanju, Jua Kali (Africa, Kenya), many of which have been described in previous chapters. Often, these types of innovation were developed by a person or a local community with limited access to resources on behalf of solving a personal or local community problem. As such, these innovations typically emerge from the informal economy and focus on sustaining a livelihood for people without other options.

Similarly to excluding cultural heritage innovations in most modern innovation literature, the approach proposed for Water 4.0 from a systemic “Western” innovation perspective would risk excluding the many innovative water solutions invented by people all over the planet over the last millennia. For any society aspiring to develop, water has always been a necessity (Clarke, 2013). Many examples exist of how water management systems helped sustain ancient communities in places such as India, Angkor Wat, Tikal or the Middle East (Fletcher et al., 2008; Lentz et al., 2018; Mithen, 2010; Taghavi-Jeloudar et al., 2013; Nair, 2004).

Despite the fact that these water management practices have often been forgotten, studying them would enable a better understanding of how local circumstances are key to developing sustainable water management practices (Pande and Ertsen, 2014). Since water is crucial for survival, even nowadays informal and local communities have developed many Jugaad-like inventions for ensuring a supply of water for personal survival. Due to the lack of resources, solutions will be well embedded in the local environment, but not directly suitable for broader implementation. Studying and making frugal those which employ systemic approaches is therefore proposed to develop modular and scalable solutions that can be adapted to the circumstances and thereby become suitable and cost-effective for the entire BoP.

BOX 14.1 CASE STUDY 1: ANAEROBIC DIGESTION TECHNOLOGY BUILDING ON CULTURAL HERITAGE INNOVATIONS FROM THE EAST

In the early stages of the research on Autogenerative High Pressure Digestion (AHPD),⁵ an approach was chosen in which biogas was allowed to accumulate in a pressure-resistant bioreactor. The aim was to build pressure biologically that could be used for upgrading the biogas to natural gas-quality and to replace the declining natural gas production from the Slochteren field in Groningen (Lindeboom, 2014). Despite the fact that anaerobic digestion had a strong foothold in the Western linear sanitation system, much of the innovation needed to operate the pressurized bioreactors had actually taken place outside the Western

sphere of influence

The true origin of the use of biogas probably dates back thousands of years. Historical records indicate that the ancient Assyrians, for example, used biogas to heat their baths as early as 3,000 years ago (Deublein and Steinhäuser, 2011). Pliny the Elder described dancing flames coming from the marshes and these lights were called *ignis fatuus* (foolish fire) by the Romans for their ability to lure people into the swamps. And Marco Polo described covered sewage ponds in China in the 13th century, despite official historical records pinpointing the 1920s as the start of biogas technology in China (Nianguo, 1984). After several European scientists such as van Helmont, Volta, Dalton and Henry discovered more of the characteristics of biogas between the 16th and 19th centuries, the earliest written record of an “industrialized” sewage digester is accredited to either the city of Exeter in 1896 or the Matunga Leper Colony in Bombay, India in 1897 (Gunnerson and Stuckey, 1986). Other records, however, argue that the Matunga Leper Colony operated the digester in the 1850s, well before 1896 (Buysman, 2009).

The pressure digester approach, despite adding some additional features due to the increased pressure, was very similar to the so-called “fixed (Chinese) dome digester” (Figure 14.5). This digester was invented by Luo Guorui in the 1920s and millions of its type are used in China and the Global South in general, largely due to a decree by Mao Zhedong in 1958 (Nianguo, 1984). It is noteworthy that another variation of the dome digester type widely adopted in the Global South is the Indian-designed floating dome digester (Gunnerson and Stuckey, 1986). Both systems seem to be more adapted to the available resources in rural areas and are “generic” in comparison with the “branded” Western-designed systems.

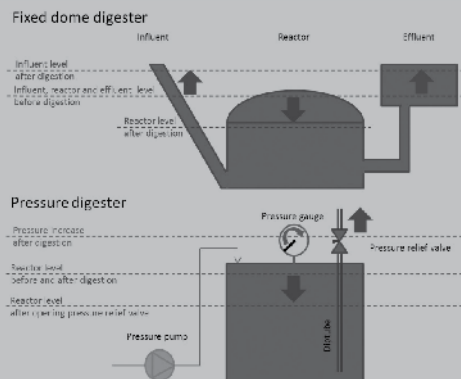


Figure 14.5 Simple schematic comparison of the pumping mechanism in a laboratory pressure digester and fixed dome digester as based on previous work (Lindeboom et al., 2012; Jegede et al., 2018)

High-quality but relatively capital-intensive autoclave bioreactors were purchased and used successfully to upgrade the biogas inside the reactor in multiple studies (Lindeboom et al., 2013; 2014; 2016). Even so, it can be considered unique to acquire sufficient funding to procure such sophisticated pressurized bioreactors. Despite the many opportunities currently available in pressure research, financial access to suitable equipment poses limits to the expansion of this research domain.

Therefore, the purchase of “commercially-available” alumina paintball bottles (suitable

up to 200 bar), as well as €50 manometers at a local paintball shop can be considered a significant step in reducing financial constraints for new pressure research. Subsequently, a special screw thread was required to connect a new head to the reactor to enable simultaneous liquid and gas sampling. The liquid sampling port was comparable to the systemic innovation represented by the so-called “dip tube” in the “branded” bioreactors that are commonly used (Ceron-Chafla et al., 2018) (Figure 14.6).

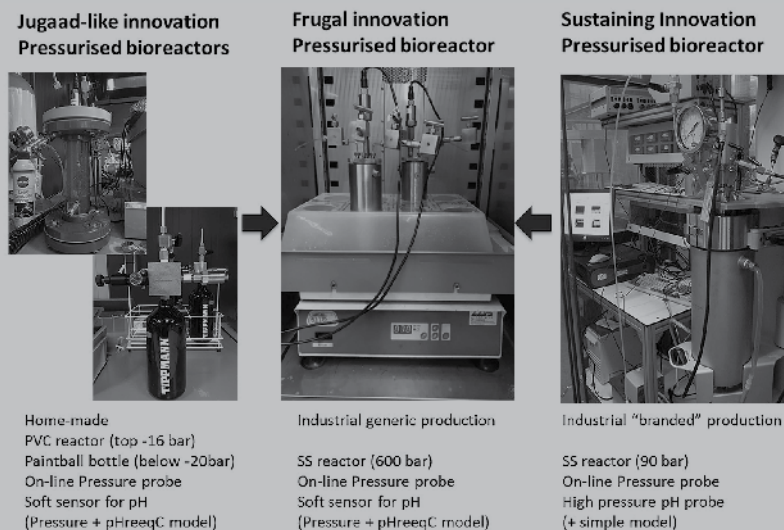


Figure 14.6 Overview of how laboratory experience with sustaining innovation, Jugaad-like innovation, resulted in the use of a hybrid frugal pressurized bioreactor

Another Jugaad approach was followed in order to reduce the cost of monitoring. Pressure-resilient pH probes are typically at least five times more expensive than conventional atmospheric pH probes and also the data logger can be capital intensive if commercial vendors are chosen. With the recent advance of the DIY low-cost Raspberry PI's and Arduino options, an alternative data-logging system was also introduced to significantly reduce the cost. The pH was measured using one medium pressure pH probe in a representative test reactor and the combined pressure, biogas CO₂-composition and pH data were modelled using the open-source software PhreeqC (Parkhurst, 1999). In this manner, the “soft-sensor” based on open-source software combined with a pressure probe and occasional gas composition enabled a substitution of the unconventional custom-made, high-pressure pH probes (Lindeboom et al., 2013). Altogether, overall reactor costs were reduced by almost a factor of 10 compared with the available state-of-the-art systemic solution, and the reactors were suitable for performing experiments similar to previous work.

It is important to point out the flexibility and independence provided by this monitoring system. Thanks to the use of a signal splitter bought online (€20), the signal of eight pressure reactors could be registered simultaneously using open-source code. In addition, the maintenance of this system is not reliant on specialized and authorized personnel, but on the researcher's know-how. Nonetheless, due to the very own nature of these “features”,

sometimes reliability can be compromised and fixing performance issues may become a time-consuming task.

To further validate the performance of the pH sensor, it was decided to use a commercially available pressure-resistant pH probe (max. 16 bar) coupled to a pressurized reactor. Keeping in mind system affordability, a Jugaad-approach was followed in the reactor construction. It was decided to use cheaper pressure-resistant materials (PVC) for reactor assemblage, since the pressure range for the operation was constrained by the pH probe resistance. An anaerobic pressurized reactor with online pH monitoring was built in-house in approximately two weeks from online purchased PVC and connection parts. The reactor was tested and performed satisfactorily in the pressure range and allowed gas and liquid sampling. Capital costs were decreased even further than with the alumina paintball bottles. Furthermore, this system is attractive due to its potential scalability, although constrained to available pressure-resistant probes and pH signal transducers.

Due to the manual labour, the paintball bottle reactors were less easy to duplicate and were eventually replaced by a set of industrially produced Chinese high-pressure reactors suitable for pressures up to 600 bar combined with the Arduino pressure-based reactor monitoring (Ceron-Chafla et al., 2020). This solution combines a Jugaad solution with the benefits of cost-effective industrial serial production and therefore is a systemic as well as frugal innovation (see Note 1). The anticipation is that these kinds of innovations make the pressurized anaerobic digestion research more accessible to a wider academic audience.

14.5. THE BEST OF A MULTIPOLAR WORLD: TOWARDS CIRCULAR FRUGAL SOLUTIONS

14.5.1. Frugal Solutions to Unlock Labour Potential

As argued before, water management for millions of people in megacities in the Global South will require a much larger well-educated workforce than is currently available (Eichengreen and Gupta, 2011). Since water is a basic need and can be a source of waterborne diseases, it is in the direct interest of the local community to ensure the water distribution and sewerage systems are well maintained. Following the “Notorious nine” theory of Gow and Morss (1988), the residents will need to feel a certain degree of ownership and responsibility in order to contribute and assist, keeping the communal services functional and thereby reducing the workload for the responsible authorities. The major pollution in rapidly growing cities with large informal settlements demonstrates that this sense of responsibility is insufficiently present if people are struggling to sustain their livelihood (Joy and Janakarajan, 2018).

Obviously, a well-educated workforce is addressed by education, but automation could also play a major role in reducing the required skills for local operators in case automatic and remote control options are considered. Especially in a context of low operator knowledge levels, a hybrid model of predictive control coupled to the IoT could prove a useful tool in ensuring continuous reactor performance. In this scenario, the conventional control systems are engineered by multinational companies and are not suitable for the BoP owing to the high capital costs in relation to the low cost price of water. The DIY revolution that has taken place over the past decade based on Raspberry PI, Arduino and open-source coding platforms such

as Python offer cost-effective possibilities for developing and designing control systems for the BoP.

BOX 14.2 CASE STUDY 2: FRUGAL SOLUTIONS AND COMMUNITY TRAINING TO PREVENT WATERBORNE DISEASES

Waterborne diseases, such as cholera, constitute a severe threat to the lives of low and middle-income citizens, especially on the African continent. In the particular case of the Democratic Republic of Congo (DRC), it accounted for roughly 25 per cent of reported cases on the continent in the period 2010–2017 (Tauxe et al., 2011). The prevention of cholera via improved sanitation and opportune health care at the primary attention level are areas where frugal innovation could play a significant role. Nonetheless, the market insertion of frugal technology to improve sanitation might be hampered if people are not aware of the benefits that a behavioural switch can bring to their quality of life. If local settings and traditional practices are not being considered in the value chain of products, lower acceptance rates could be expected. In consequence, the sustainability and success rate of frugal innovations in sanitation and health care heavily relies on community engagement.

The methodology known as Training of Trainers (ToT) (Yu et al., 2019) has been applied for the capacity building of local leaders in rural communities of DRC, as a way of tackling the spread of waterborne diseases. The methodology in itself shows a “frugal” nature due to:

- cost reductions: training local leaders in illness prevention and primary health care is more affordable compared with the deployment of specialized health workers to remote areas.
- concentration in core functionalities: waterborne disease prevention requires basic principles to be communicated and enforced: access to safe water (via boiling, chlorination, filtration), personal hygiene (handwashing), household cleaning and reduced open defecation. Additional “information” needs to be limited in order that the conveyed message is clear and will be effectively replicated.
- optimized performance level: community trainers need to be sufficiently engaged to guarantee a positive outcome of the intervention (reduced infection rate). As a reference case, in Haiti, during a cholera epidemic in 2010, the application of this approach decreased infection rates from 4 per cent to <1 per cent in three months (Hetherington et al., 2017). To further guarantee performance, monitoring and periodical evaluation of these interventions are critical in promoting accountability.

Community training might help decrease the inner resistance to the adoption of new practices and technologies in rural settings. For example, more people could be willing to purchase low-cost water purification devices if they recognize the importance of safe drinking water. Moreover, if suitable local credit systems are established, more people with financial limitations could have access. Local economies can be further supported when small enterprises helping to fight sanitation issues are locally assembled, e.g. soap making. In these settings, any innovation willing to improve sanitation needs to be characterized by simplicity, low maintenance and community acceptability. All these aspects can be significantly improved by local capacity building.

Setting up a complete ToT might exceed the capabilities of external frugal entrepreneurs trying to make an entrance into the sanitation field. Nonetheless, they should recognize the importance of these training programs for increasing community awareness. Concomitantly, they should try to identify themselves as key stakeholders if public offices or NGOs are implementing these initiatives. It is crucial that core values behind this ToT initiative, such as usage of local knowledge, local needs and context assessment, inclusion and empowerment and livelihood improvement, are incorporated into the design of “frugal innovations/interventions” (Figure 14.7). This can help reinforce the social sustainability aspect.



Source: Sun Mountain International – Ecuador.

Figure 14.7 Picture of a Training of Trainers workshop for capacity building in cholera prevention in the DRC

14.5.2. Frugal Autarkic Solutions to Overcome Power Outages

As previously discussed, power outages affect daily life in the megacities of the Global South (Amadi, 2015). Consequently, the design of a treatment plant cannot rely on a stable power supply from a central grid to aerate or pump water from one location to another. Several possibilities exist for providing a decentralized, off-grid power supply. The typical choice of installing sufficient photovoltaic cells and batteries (Olsson, 2012) and keeping the water treatment plant unaltered will produce a suitable water quality; however, it will most likely

not make the best use of available local resources and might rely on spare parts that cannot be easily resupplied.

Anaerobic Digestion (AD) technology has had a proven track record of biogas production, sanitary waste stabilization and biological pressure-driven pumping for millennia (van Lier et al., 2008; Lindeboom, 2014; Zeeman and Lettinga, 1999) as shown in Case Study 1. In contrast, conventional aerobic activated sludge processes typically cost energy. AD is therefore a particularly interesting technology to work on in a resource-constrained setting because limited capital-intensive resources are needed to produce biogas (an air-tight container). The chemical energy contained in biogas produced from municipal household waste(water) does not suffice to support an energy-intensive lifestyle from a resource recovery perspective. However, it could reduce the dependency of a STP on a central power grid, especially when combined with biogas engines or more innovative solid oxide fuel cells (Wasajja et al., 2020).

Most commercially available anaerobic digester configurations are designed for energy recovery and effluent discharge, and this opens up opportunities for ingenuity and innovative scientific contributions that enable water reuse (Lindeboom et al., 2012). At the same time, it is in our opinion surprising that commercial water treatment plants in sunny, resource-constrained regions are in practice often constructed without considering solar irradiation as a potential resource that could reduce energy consumption or enable water reuse. This is despite a solar potential of several kWh per m² per day and the availability of low-cost concentrated solar power technologies, such as mirrors and acrylic Fresnel lenses.

An interesting study by Mehr et al. (2017) indicates that without solar energy the auxiliary power consumption and heat demand of a conventional wastewater treatment plant would also exceed biogas production. However, the inclusion of concentrated solar power has a highly positive impact on the overall fossil fuel demand. According to the IRENA report (2018) on renewable energy, concentrated solar power is expected to drop below fossil fuel prices for electricity production in terms of Levelized Cost of Electricity (LCOE). With the cost of Fresnel lenses projected to drop to ~€5/m² thanks to mass production (Ervin and Judah, 2013) and Levelized Cost of Electricity generation CSP to \$0.06/kWh (Zhu et al., 2014; Bellos, 2019), the sun offers practically “infinite” possibilities for making wastewater treatment frugal.

BOX 14.3 CASE STUDY 3: FOCUSING ON THE “FREE” ENVIRONMENTAL RESOURCE WITH FRUGAL INNOVATION

Back in 2004, I went on an internship to the UNHCR refugee camps in Eastern Nepal to evaluate the performance of the parabolic solar cooking programme that was initiated by the Vajra Foundation with the aim of reducing deforestation and substituting the provided kerosene for cooking. Before travelling to Nepal, Rene Goverde and I travelled to Mount Abu to see the magnitude of the solar kitchens at the Brahma Kumaris’ Peace of Mind Centers (Lindeboom and Goverde, 2004). While in those days I was neither aware of frugal innovation nor of Jugaad innovation, in hindsight, my first experiences there were very good examples of frugal innovation. The industrial scale of cooking for thousands of people by using concentrated solar power for steam production in which local heritage and sociocultural settings were blended with German engineering and Indian ingenuity (Jugaad) (Sahoo et al., 2016) has inspired me ever since. (Ralph Lindeboom)

Two parts of the solar kitchen stand out for their ingenuity and cost-effectiveness: (1) a nail

functioning as a sundial and (2) a car windshield wiper motor.

1. The original design of the solar kitchen relied on a computer (Gadhia and Gadhia, 2006), in which the position of the earth versus the sun was modelled and would automatically position the mirrors in the right direction by driving an engine. The main concern, however, was that any mistake in the modelling or a computer crash would create a malfunctioning system. Since the computer was doing the work, no operator felt responsible for maintaining the system. A sundial consisting of a nail perpendicular to the surface area of the parabolic dish solved the issue, as the shadow created by the nail had to fall neatly in a circle around the nail. Based on this, the operators had a simple check based on which they could decide to reposition the solar dishes towards the sun.
2. However, this also resulted in additional labour for the operators, who had to go and check every 15–20 minutes. Manual repositioning towards the sun is the conventional method for the smaller 1.5 m² parabolic SK-14 models, but this is quite labour intensive for the larger systems (Gadhia and Gadhia, 2006). One heliostat typically has a surface area of 9–12 m² covered in mirrors with a stainless-steel frame. Therefore, the overall workload had to be reduced by a second frugal innovation.

Instead of using of a conventional engine, a local cost-effective Jugaad solution was incorporated, aimed at making the work of the operator in charge and his team easier, while reducing costs. By connecting the mirrors with bicycle chains and chain wheels and either a crank or a car windshield wiper motor, depending on the total number of heliostats (Gadhia and Gadhia, 2006). This success at the first solar kitchen in Gyan Sarovar, Mount Abu, in combination with the scalability of the solution, resulted in the approach being adopted in multiple solar kitchens in India and Burkina Faso (Otte, 2014) (Figure 14.8). This example thereby emphasizes, in the view of the authors, the difference between Jugaad and frugal innovation. The Jugaad ingenuity aimed at improvement of the personal situation of the first team of operators evolved by being scalable into a frugal innovation that was adopted in a global context.

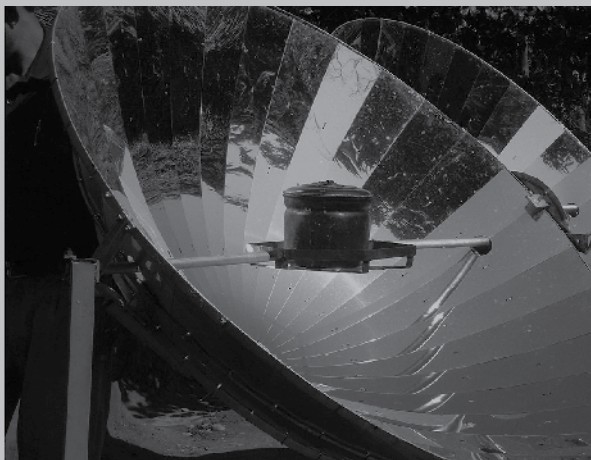
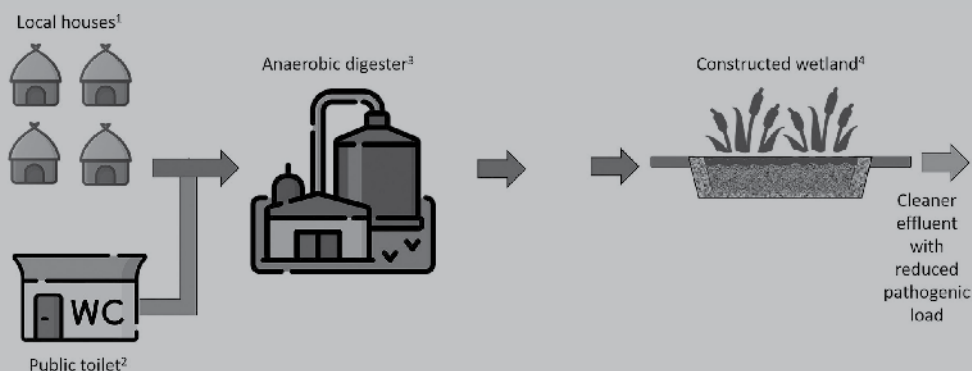


Figure 14.8 Pictures of a Scheffler-type parabolic solar kitchen at Mount Abu and SK-14 parabolic cookers at the Bhutanese refugee camps in Nepal

BOX 14.4 CASE STUDY 4: TACKLING WATERBORNE DISEASES WITH FRUGAL INNOVATION IN ANAEROBIC DIGESTION

According to the WHO, schistosomiasis is an acute and chronic disease of parasitic origin, characterized by immune reactions and significant organ damage. Infection occurs by the penetration of the larval form of blood flukes (trematode worms) of the genus *Schistosoma* (*S. mansoni* and *S. haematobium*) (WHO, 2019a). Transmission is associated with water contamination with human excreta due to poor sanitation. Of the reported cases requiring treatment, 90 per cent are located in Africa (WHO, 2017).

Decentralized wastewater treatment focused on pathogen reduction and inactivation could contribute to improved sanitation in rural communities that fight these diseases year after year. In particular, the usage of thermal inactivation and disinfection technologies could help reduce the pathogenic load inflicted on local water resources. Nonetheless, these technologies need to be affordable, reliable, low-maintenance and adapted to the local settings at the moment of implementation. It is important to inspire a new generation to design for a local resource-constrained context rather than follow the standard “Western” affluent design. Accordingly, students from the TU Delft course “Design of Drinking Water and Wastewater Treatment Plants” started analysing the local resource situation, i.e. abundance of solar irradiation and elevations in the terrain versus low accessibility to electricity, skilled labour and mechanical spare parts, for a village on Koome island in Lake Victoria (Suryanto and Kusumawardhana, 2020). A subsequent multicriteria analysis resulted in a treatment train consisting of an anaerobic dome digester, a gravel filter and a constructed wetland. Rotating parts could be substituted by the natural elevation of the terrain and biogas pressure. The sludge concentrated in the gravel filter could undergo a solar-based hygienization to ensure safe reuse. Although maintenance is minimized, workshops are needed to train local users.



Source: 1), 2) and 3) This cover has been designed using resources from Flaticon.com. 4) Wetland icon partially constructed with resources from Vectorified licensed under CC BY-NC 4.0 Licence.

Figure 14.9 Graphical representation of a proposed “frugal” treatment train for decentralized wastewater treatment with a focus on the reduction of pathogenic load, based on Suryanto and Kusumawardhana (2020)

Owing to its small size, the above-proposed system is likely to have a higher total cost of ownership, compared with current European full-scale filtration and disinfection costs (Hernández-Sancho et al., 2015). Nevertheless, improved water quality could promote savings in preventive chemotherapy, which is one of the current strategies for controlling the disease (WHO, 2019a).

The global pandemic Covid-19 has uncovered many disparities around the globe. It has highlighted the importance of self-sufficiency in a globalized context and has reminded us of the importance of proper sanitation and hygiene practices (Onsongo, 2020). Isolated places struggle daily for access to resources; consequently, to improve livelihoods there, the attention given to sanitation and health needs should follow a more flexible, holistic and decentralized approach.

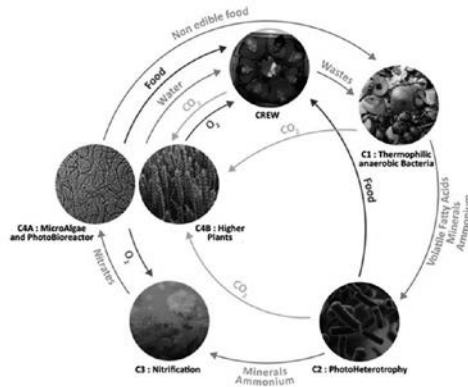
14.5.3. Circular Frugal Solutions to Unlock Access to the Environment

Given the surface area covered by megacities (Figure 14.2) the construction of thousands of kilometres of piped water distribution and sewerage systems is required if wastewater treatment plants have to be built on the outskirts of the city, similar to the linear system. As large parts of the cities have already been constructed, it would require the clearing of vast urban areas in order to construct the required underground piping network to make the environmental resources available for the entire urban population. For this same reason of reducing the investment costs for replacing the underground network, i.e. this “limited resources” constraint, the Dutch Water sector increasingly focuses on treatment and resource recovery at the source (Roest et al., 2015). Over the years, this “resource recovery” approach has been picked up in various parts of our society, but it has also come with an ever-increasing expectation pattern. This should, however, be carefully put into context to avoid raising the impression that profits can be easily made by selling energy, nutrients and chemical intermediates derived from wastewater.

In the life support concept, however, full resource recovery is not an economic question, but cannot be avoided as, in space, resources to support life are absent or at least scarce (Lasseur et al., 2005). Furthermore, this concept differentiates itself from the terrestrial alternatives as the human population is not considered a separate part of the environment. From this life support system engineering perspective, humans are considered equally a reactor unit, like any microbial reactor, and face constraints with respect to the use of personal care products and food, for example (Clauwaert et al., 2017). A similar approach has been introduced in the City As A Spaceship (CAAS) concept (Fairburn et al., 2017) in which human excrement becomes the environmental resource for water, energy and nutrients for neighbouring urban residents.

By closing the resource cycles, the cities will be able to exert much more control over their interaction with their surroundings and function like an independent spaceship, located on Earth. New resources will only be taken in to make up for the efficiency losses in the several processing units. Nevertheless, these solutions have not reached the BoP, due to the technical systemic and capital intensive nature of the proposed approaches. Moreover, such an extensive degree of control over the residents will be hard to achieve in megacities characterized by a significant informal economy.

As described earlier by Gow and Morss (MELiSSA Foundation, 2019), residents will need to feel a certain degree of ownership and responsibility in order to contribute and achieve this



Source: Diagram courtesy of MELiSSA Foundation.

Figure 14.10 Schematic overview of Micro-Ecological Life Support System Alternative in which humans are an integrated part of the engineered environment (MELiSSA Foundation, 2019)

through a bottom -up approach. If urban waste management would be organized bottom up, it could offer an opportunity for residents in the informal urban sector to earn their livelihood. Likewise, the reuse of many residual organic waste sources from urban farms or parks, such as empty fruit bunches from oil palms, sugar cane bagasse from sugar cane or elephant grass, could serve as input for many new products (Andersson, 2017). Moreover, manure from city farming could not only serve as a source for additional biogas, but also be used to develop decentralized manure refineries for N and P recovery, minimizing the need for transporting fertilizer into the city (Pradhan and Kumar, 2014). A bottom-up approach evolved naturally in Agbogboshie, Ghana, for the recycling of e-dump waste material (Ezejiofor et al., 2014), with similar situations occurring elsewhere (Mehta et al., 2015), all of which are associated with health risks. There is thus a great need for new incentives that connect indigenous innovation in resource recovery to systemic innovations, such as the City As A Spaceship concept, from the bottom up. This approach could help to protect the BoP workers while providing them with a livelihood and thereby closing the urban and/or rural metabolism.

14.6. CONCLUSIONS

This chapter has described the major innovations that resulted in the centralized water supply and sanitation system in the Western world. The success of this system depended on the availability of abundant resources. Owing to emerging challenges, new innovation is being adopted, but the focus remains on resource-affluent societies. In order to achieve UNSDG6, the successful Western system is often translated to the Global South without non-financial resource limitations being taken into account in terms of access to the environment, a well-educated workforce and a stable power grid. This chapter has emphasized how all people, whether at the BoP or in ancient cultures, have shown remarkable potential for water innovations. To a large extent, this “indigenous innovation” has been neglected in pursuit of implementing

“sustaining innovation” developed for resource-affluent societies. The last part of the chapter introduced “frugal innovation” as an approach that builds upon both the systemic approach of “sustaining innovations” and adaptability to resource constraints of “indigenous innovations”. We then showed how open source coding combined with cost-effective sensing and smart automation can help in overcoming limitations in a well-educated workforce and improve the adoption of frugal water technologies (Case Study 1). Second, we highlighted the importance of community engagement in increasing awareness and the success rate of adoption of frugal innovation in sanitation (Case Study 2). Third, we discussed the off-grid energy revolution that is taking place in the Global South and is largely driven by frugal innovations such as PV and CSP. The adoption of such a technology offers opportunities to adapt the systemic Western water approach to overcome limitations that power outages pose to providing equal access to water supply and sanitation (Case Study 3). Furthermore, we addressed how the design process could start with an assessment of local available resources in order to develop a new generation of decentralized, cost-effective wastewater treatment technology to tackle waterborne diseases (Case Study 4). Finally, we introduced circular biological life support concepts, in which humans are an inseparable part of the engineered environment, as a source of inspiration. Their incorporation could help overcome limitations in access to environmental resources in time and space, both in resource-affluent and resource-constrained societies.

NOTES

1. Frugal or Jugaad innovation, is often defined “as doing more with less resources by ingenuity and creativity” (Radjou et al., 2012). Jugaad innovation: think frugal, be flexible, generate breakthrough growth. But as is described in this chapter it would be highly useful to distinguish between Jugaad-like, frugal and innovations that sustain the existing innovation system; i.e. sustaining innovations.
2. Water-wise is defined as: “These cities apply full resource and energy recovery in their WWT and solid waste treatment, fully integrate water into urban planning, have multi-functional and adaptive infrastructures, and local communities promote sustainable integrated decision making and behavior. Cities are largely water self-sufficient, attractive, innovative and circular by applying multiple (de)centralized solutions...” (Koop and van Leeuwen, 2015).
3. Glocal = is the “simultaneous occurrence of both universalizing and particularizing tendencies in contemporary social, political, and economic systems” (Roudometof, 2015).
4. It is noteworthy that the population density of the International Space Station is on par with that of megacities, despite having a crew of only a handful of astronauts.
5. In reference to 2008, when Ralph Lindeboom started his PhD on AHPD in the sub-department of Environmental Technology at Wageningen University, the Netherlands, and in co-operation with Bureau BV.

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