14 Application of Anaerobic Digestion in Decentralized Faecal Sludge Treatment Plants

Swaib Semiyaga, Anne Nakagiri, Charles B. Niwagaba, and Musa Manga

Abstract

Over 80% of the population in low- and middle-income countries (LMIC) depends on on-site sanitation, largely pit latrines and septic tanks. Anaerobic digestion (AD) can stabilize the organic fraction of faecal sludge (FS) while also generating biogas to offset some energy needs at the treatment plant. This chapter examined the technical and operational feasibility, as well as opportunities for AD of FS. FS that has spent long time in containment systems produces less gas than the fresh one. Therefore, FS from container-based sanitation facilities can boost gas production in biogas facilities receiving aged FS. In addition, co-digestion with different organic waste substrates improves the quantity and quality of biogas production. However, a system for transportation, pre-treatment and storage of organic feedstock for co-digestion with FS should be examined against the backdrop of cost and benefits to determine whether the improved gas production matches with the required resource inputs. In conclusion, biogas is not the only driving factor for AD. Other benefits such as organic matter stabilization and environmental benefits such as pathogen and odour reduction contribute to

S. Semiyaga (✉) · C. B. Niwagaba
Department of Civil and Environmental Engineering, School of Engineering, College of Engineering, Design, Art and technology, Makerere University, Kampala, Uganda

A. Nakagiri
Department of Civil and Environmental Engineering, Faculty of Engineering, Kyambogo University, Kyambogo, Uganda

M. Manga
Department of Construction Economics and Management, School of Engineering, College of Engineering, Design, Art and technology, Makerere University, Kampala, Uganda

The Water Institute at UNC, Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

M. K. Meghvansi, A. K. Goel (eds.), *Anaerobic Biodigesters for Human Waste Treatment*, Environmental and Microbial Biotechnology,
https://doi.org/10.1007/978-981-19-4921-0_14

the driving factors for adopting AD of FS. The mineralized nutrient content in bio-slurry can be taken advantage of, although with care to avoid microbial health risks.

Keywords

Anaerobic digestion · Biogas · Co-digestion · Decentralized · Faecal sludge · Organic waste · Treatment plant

14.1 Introduction

There is appreciation in using anaerobic digestion (AD) as a step at treatment plants managing faecal sludge (FS) from communities or towns. Small-scale digesters are more practical for use in faecal sludge treatment plants (FSTPs) in low- and middle-income countries (LMIC) due to low complexity, low capital and maintenance costs as opposed to large-scale digesters at centralized wastewater treatment plants (Tayler 2018). Unlike on-site biodigester toilets, where fresh excreta (faeces and urine) are used as the feedstock in institutions and public places, biodigesters at decentralized scale receive FS previously stored in on-site sanitation facilities (pit latrines, public toilets, septic tanks, aqua-privies and container-based/portable toilets) and are expected to behave differently. The biodegradable characteristics of FS from these sources do not only vary with different technology options but also other geographical and environmental factors such as groundwater infiltration, emptying frequency, user habits, constituent materials, type, concentration of contaminants and location of sanitation facilities (Still and Foxon 2012). For example, biomethane potential (BMP) is very low in FS from septic tanks since it is partially stabilized but high from public and container-based toilets, where the FS retention period is short (Rose 2015). In addition, FS from septic tanks at the household level desludged after 5 years is expected to be more stabilized compared to that from septic tanks in public places such as schools and hotels, desludged in less than 1 year (Schoebitz et al. 2014). The difference in retention times causes variation in BPM of FS depending on the source. This makes AD of FS from containment technologies of varying retention times feeding the same decentralized digester technology (at treatment plant) complex. However, there is limited information on technical and operational feasibility, as well as opportunities for AD of FS at decentralized scales. This chapter presents the potential of AD technology at decentralized FS treatment plants by analysing the biodegradability characteristics of FS from different sources, BMP, co-digestion, operation and maintenance as well as management options of the produced slurry.

14.2 Faecal Sludge as a Feedstock

Faecal sludge treatment facilities mainly receive partially stabilized FS, which has stayed for varying durations in different types of on-site containments. However, considerable amounts of organics have been realized in various types of FS received at treatment facilities as reflected by the higher fraction of volatile solids in Table 14.1. The purpose of the AD is stabilization of the partially digested, fresh or raw FS, pathogen and odour reduction, as well as production of biogas energy and slurry.

The optimum pH for AD for high biogas yield ranges between 6.5 and 7.5 (Vögeli et al. 2014), which is generally the pH range for the various types of raw and partially digested FS. There is no need of adding chemicals to raise or lower pH for the operation of the plant. However, container-based FS exhibits low pH ranges,

Table 14.1 Characteristics of faecal sludge from various containments

	FS feedstock source			
Constituent	Septic tank FS	Pit latrine FS	Public toilet FS	Container-based toilet FS[a]
Moisture (%)	95–99	83–95	88–98	80–95
Total solids (%)	<3	5.3–19	2.94–11.94	4.6–9.5
Volatile solids (% TS)	45–76	41–69	70	65–75
pH	6.7–8	7.5–7.9	7.2	6.1–6.4
Total carbon (%)	NA	24.1	40.1	50–52
Total nitrogen (%)	1.0	2.1	3.7	4.8–7.3
Carbon-to-nitrogen (C:N) ratio	19–30	11.6	11.0	8.5–10
Methane yield (mL/g VS)	NA	49–199	NA	260–405
NH_4-N (mg/L)	120–1200	1853–9000	845–5000	396–5000
References	Heinss et al. (1998), Manga et al. (2016), Niwagaba et al. (2014)	Coetzee et al. (2011), Still and Foxon (2012), Rose et al. (2015), Semiyaga et al. (2017)	Heinss et al. (1998), Koné and Strauss (2004), Rose et al. (2015)	Rajagopal et al. (2013), Rose et al. (2015)

NA not available

[a] This is FS from container-based toilets having a younger age of less than 4 days

which necessitates mixing with FS from other containments to improve characteristics for a good biogas substrate. This can be achieved by introducing a mixing/buffer tank before the digester to aid in homogenization of FS from different containments.

Total solids (TS) for FS from most containments average >6%, which is required for unstirred fixed-dome digesters, in order to limit solids settling (Sasse 1988). In addition TS in the range of 5–10% is optimal for operating anaerobic digesters without addition of extra water (Nijaguna 2002). However, for TS > 4%, there is a need to have fixed-dome digester base slanting towards the middle for easy collection and removal of any settled sludge. The volatile solids (VS) of FS from various sources are >50% TS, which is required for application of fixed-dome digesters. FS temperature in most tropical countries is in the mesophilic range (20–40 °C), which is resistant to operational challenges since this can be achieved at minimal or no extra energy input.

The C/N ratio of FS from most containments is below the optimal requirement (16–25) for AD. This may lead to ammonia accumulation in the digester, which is toxic to methane-forming bacteria. Therefore, it may necessitate raising the C/N ratio during operation, through various ways such as co-digestion with organic feedstocks of a higher C/N ratio. FS can potentially be co-digested with other organic waste streams such as market wastes, municipal solid wastes, brewery waste or primary sludge to improve AD (Englund and Strande 2019).

14.3 Biomethane Potential for Faecal Sludge

Biomethane potential (BMP) measurements provide evidence for biogas production performance from substrates based on hydrolysis and degradation rates (Raposo et al. 2012; Hagos et al. 2017). BMP test is crucial before the full-scale design of anaerobic digesters to predict biogas production. However, since biogas production in real-time conditions faces design limitations, the expected values are lower than laboratory-scale values (Rose 2015). This is because the methane gas yields are under optimal conditions (such as mixing and constant temperature), whereas actual yields are reduced due to various uncertainties in full-scale operation.

BMP experiments, on the other hand, allow comparison between different substrates, and more reliable information can be obtained through setting up pilot-scale digesters (Englund and Strande 2019). FS presents higher theoretical BMP values when degradability is not accounted for. Therefore, fresh FS from container-based sanitation technologies presents higher BMP values, which is more suitable for AD, as compared to other sources of FS. Studies of different types of FS have indicated methane production completed within 10 days, implying that sludge holding times exceeding this period don't improve the yield of biogas (Rose 2015). However, a minimum hydraulic retention time (HRT) of 20 days has been reported for odour reduction (Englund and Strande 2019; Tayler 2018).

14.4 Co-digestion of Faecal Sludge with Organic Waste Streams

Co-digestion involves the use of more than one waste stream in anaerobic degradation, aimed at circumventing the limitation of using single substrates, thereby improving biogas production (Hagos et al. 2017). This is a promising technology in most cities or towns of LMIC, where management of different waste streams poses a number of challenges. AD process can co-manage more waste streams, improving biodegradability and nutrient balance.

14.4.1 Case Studies on Co-digestion of Faecal Sludge and Organic Waste Streams

Various researchers have determined the implications of co-digesting FS with other waste streams as summarized in Table 14.2. Majority of the studies reviewed were performed in laboratory experiments, with only one that used a field-installed biodigester. The experimental reactors were all batch fed and operated mainly under mesophilic conditions. The feedstocks/substrates added to FS in these studies included organic food waste, garden waste, cattle and poultry manure, sludge and effluent from wastewater treatment plant (WWTP). The performance/dependent variable for the experiments was mainly biogas generation.

From these studies, the volume of biogas produced increased when FS was digested with other wastes than when digested alone. Hoang and Nguyen (2020) noted better biogas quality when co-digested, where a high rise in composition of CH_4 was observed to reach 71.5%. The optimal biogas generation/yield is linked to feedstock type, co-digestion, particle size reduction, operational temperature, C/N ratio and pH. Hoang and Nguyen (2020) obtained a biogas yield of 13 mL/g dry matter (DM) when FS was digested alone, but the yield increased to 18 mL/g DM when FS was mixed with poultry manure (PM), cow manure (CM) and sewage sludge (SS). However, mixing two substrates produced more gas than mixing four substrates. For example, FS with PM produced a biogas yield of 28 mL/g DM, FS and CM produced 25 mL/g DM and FS with SS produced 25 mL/g DM.

Anaerobic digesters operating under thermophilic temperature ranges take shorter time to produce gas compared to those in mesophilic temperature range (Burka et al. 2021). The favourable pH range for AD is near neutral; hence, an initial drop in pH, resulting from acidogenesis and acetogenic oxidation, inhibits biogas generation. However, low pH can be solved through addition of sodium bicarbonate as a buffer (Afifah and Priadi 2017). Another product of acidogenic fermentation that often causes inhibition of anaerobic degradation is ammonia.

Overall, it can be deduced that while biogas can be recovered from FS, a co-feeding substrate is necessary for enhancing AD, thereby improving the quantity and quality of biogas recovery (Table 14.2). This is more so, considering the fact that FS undergoes partial stabilization during collection in on-site containment systems, resulting into a degraded quality with decreased biogas potential. Containments filling for longer time are more affected than those which are filled for shorter

Table 14.2 Case studies on co-digestion of faecal sludge and other waste streams

Nature of study	Inputs	Operating conditions	Key findings	References
Laboratory experiment	• Faecal sludge	• 51 L stainless steel reactor size	• Initial pH range of 5.2–6.3	Afifah and Priadi (2017)
	• Food waste	• Batch feeding, temperatures	• Ammonia was 240–504 mg/L (below the inhibition level)	
	• Garden waste	• 27–30 °C	• Gradual increase in biogas generated with higher values for higher sludge content (50% FS) 0.56 m^3 CH_4/kg VS	
		• 25–50% FS based on VS	• High reduction in VS and COD	
		• Buffer was applied on the 10th day	• A methane yield of 10–20-fold greater than the FS digested alone	
Laboratory experiment	• FS from septic tank	• 500 mL constantly stirring reactor vessels	• Biogas yield equalled 13 mL/g DM in 14 days	Burka et al. (2021)
	• Sewage sludge (SS)	• Thermophilic conditions (55 °C)	• Biogas yield for mixed substrates (FS + PM + CM + SS) reached 18 mL/g DM and 28 mL/g for FS + PM, 22 mL/g for FS + CM and 25 mL/g for FS + SS mixtures	
	• Cow manure (CM)	• Period was 14 days		
	• Poultry manure (PM)	• 95% moisture content of substrates		
		• 1:1 feeding ratio		
Laboratory experiment	• FS from pit latrine	• 200 L of plastic drum reactors	• A total of 285 L of biogas was recovered	Madikizela et al. (2017)
	• Anaerobic digester effluent at wastewater treatment plant (WWTP)	• Mesophilic temperature conditions (29 ± 2 °C)	• Biogas can be recovered from pit latrine FS, but a co-feed was necessary for AD to improve the quantity of biogas recovery	
	• Cow manure	• 1:2 mixture FS + WWTP effluent		
		• 2:1 mixture FS + WWTP effluent		
		• Cow paunch manure added in all the reactors		
Laboratory experiment	• FS from septic tank	• 4:1, 3:1 and 2:1 mix ratios (by weight) of FS to organic waste	• Highest biogas yield (514.3 L/kg VS) for 3:1 mix ratio	Phuong and Thai (2018)
	• Organic solid waste			

(continued)

Table 14.2 (continued)

Nature of study	Inputs	Operating conditions	Key findings	References
Laboratory experiment	• FS from septic tank	• 500 mL volume, continuous stirred reactors	• FS-specific methane yield from 269.3 N mL CH_4/g VS	An (2017)
	• Sewage sludge (primary sewage sludge and waste activated sludge (WAS))	• Mesophilic temperature (35 ± 0.5 °C)	• Only WAS digested	
		• Feeding ratio, WAS only; FS, WAS of 1:6, 1:3, 1:2 and 1:1 (VS content)	• Higher value 294.8 N mL CH_4/g VS in case of co-digestion, with a ratio of FS:WAS of 1:1 (VS content)	
		• pH range of 7.17–7.78		
Composite digester placed 1.9 m below the ground	• Faecal sludge (public and household toilets)	• Winter temperature of 16–18 °C and summer temperature from 30 to 32 °C	• Temperature raised to 35–38.2 °C, in 0–9 days thereafter, decreased to 32–33 °C after 30 days. Summer registered high temperature noted in summer	Hoang and Nguyen (2020)
	• Organic solid waste	• Organic waste sliced into sizes of 1–3 cm	• pH dropped from 6.5 to 6.8 within the first 6 days and raised after to 7.4	
		• 3:1 mix ratio (FS, organic waste)	• Largest and fastest biogas generation realized at higher temperatures (summer)	
			• Maximum daily biogas production obtained during summer and ranged from 2768 to 3670 NL/day (winter) compared to 3033–3917 NL/day during summer	
			• Methanogenesis took place when conditions were suitable for AD between the 13th and 25th day. The digester heated to 35–38 °C, pH was 7–7.4 and alkalinity was 2400–2900 mg $CaCO_3$/L	
			• CH_4 varied from 20.4% to 31.6% at the start to 64.4–71.5% mid-way and 67.3–69.2% towards the end	

(continued)

Table 14.2 (continued)

Nature of study	Inputs	Operating conditions	Key findings	References
Laboratory experiment	• Faecal sludge	• Glass digesters	• About 6.2 tonnes/DM of biomass per day	Krou et al. (2021)
	• Solid waste	• Normal environmental conditions	• 122 m^3 of biogas, of which 113 m^3 of methane could be produced per day	
			• The methane content was estimated at 65.6%	
Laboratory experiment	• FS from septic tank	• Hydrothermal pre-treatment (HTP) in a high-pressure vessel at 180 °C and 10 bars for 30 min	• Specific methane production (SMP) of STS reached 211.6 mL/g COD, ≈41.3% of the theoretical methane production (TMP, 350 mL/g COD)	Zhang and Li (2010)
	• Food waste	• 500-mL continually stirred reactor bottles	• After THP, SCOD increased from 960 to 2010 mg/L, 70% of organic matter remained in solid particles	
		• Operation temperature 35 ± 1 °C	• An increase in SMP to 250.6 mL/g COD (52.4% of the TMP) was noted	
		• Substrate ratios of FS: food waste = 1:0, 1:1, 2:1, 0:1 (based on COD)	• While screening the fine particles, the SMP increased to 274.9 mL/g COD	
			• Overall, methane yield increased owing to THP, although methane production rate didn't improve significantly	
			• Co-digestion of FW with filtrate after the THP of STS increased the SMP, and the values were 213.8 mL/g COD for the filtrate, 220.5 mL/g COD for the ratio of 2:1, 251.3 mL/g COD for 1:1 and 309.1 mL/g COD for only the FW	

(continued)

Table 14.2 (continued)

Nature of study	Inputs	Operating conditions	Key findings	References
Laboratory experiment	• Untreated primary sludge	• Batch digestion tests performed in 2.5-L digester filled to 80%	• Highest yield of biogas was from AUPS/ RCM and SUPS/RCM concoctions mixed in the ratio of 10:90 and 90:10	Hassan et al. (2022)
	• Biomass	• Mesophilic under 35 °C	• In all treatments, the biogas production increased suddenly within the first days of digestion, gradually decreasing thereafter	
	• Raw chicken manure	• Each glass was 2.5 L filled to 80% in all reactors	• Statistical significance was observed between biogas rates and low total coliforms (p 0.001) and faecal coliforms ($p = 0.002$)	
	• Fresh untreated primary sludge (UPS) collected from municipal wastewater treatment plant	• All reactors were gently mixed by hand for around 1 min/ day at the start of each biogas determination	• pH was optimum at 7.0, giving the best biogas products. A typical pH range for optimal biogas production is 6.5–7.6	
	• Raw chicken manure (RCM) • South Valley University (SUPS sludge)	• Six different mixing mass ratios of 100:0, 90:10, 50:50, 30: 70, 10:90 and 0: 100 were tested to obtain the best combination of untreated primary sludge		
Laboratory experiment	• Food waste (FW) septage were septic tanks	• Mix ratios FW and septage	• Yield in biogas from FW was 647–952 mL/ g VS 89–96 mL/g VS from septage	Prabhu et al. (2015)
		• Mix ratios were (FW: septage) 1: 1, 1.5:1, 2:1, 1: 1.5 and 1:2	• Co-digestion studies with FW: septage at 1: 2 ratio produced 2896 m^3/day of biogas	
			• FW alone, which lacked zinc, cobalt and iron produced less biogas	
			• Co-digesting septage and FW improved AD of FW at limiting values of Zn, Co and Fe	

time, where FS from CBS systems preferred for biogas production in decentralized FSTPs.

14.5 Anaerobic Digestion Products

The leading AD products (biogas and bio-slurry) produced from digestion and/or co-digestion of FS and other substrates such as organic solid waste, cattle, pig and buffalo dung have immense benefits. Biogas offers an alternative clean and modern energy source that can replace dirty biomass fuels, with the potential to contribute to poverty alleviation. Bio-slurry can boost agriculture production with recyclable sustainable nutrients. Utilization of both biogas and bio-slurry from AD can contribute towards alleviating climate change-induced impacts (Warnars and Oppenoorth 2014). The products of AD are discussed in the following sections.

14.5.1 Biogas Use Alternative

Biogas can be put to use in various ways such as cooking, lighting or driving engines of vehicles or other machineries. The latter is applicable for large-scale systems or treatment plants, where the produced heat can also be put to use. At decentralized FSTPs, biogas can be used to meet the cooking requirements of the workers at the plant and heat requirements for stabilization of equipment for the plant laboratory.

The biogas production patterns at the FSTPs do not match consumption. Gas usage mainly happens during the day, but production continues throughout the night. In cases of low biogas usage at the treatment plant, there may be a need to package the gas in gas storage bags to be used at a different location. However, biogas has a limitation of low energy density (6 kW h/m^3), which necessitates large storage volumes unless it is compressed. The option of storage in compressed medium to high-pressure gas cylinders is not feasible for decentralized FSTPs due to high costs involved (Vögeli et al. 2014).

In cases where packaging is not feasible and/or gas utilization patterns are interrupted such as non-functioning gas stoves, biogas needs to be flared in order to control methane release to the environment. Therefore, a gas burner for use in flaring needs to be considered in the design of FSTPs based on AD technology.

14.5.2 Bio-slurry Management and Uses

The effluent from the digester after gas production is known as bio-slurry or digestate. Like most digesters in developing countries, which operate under mesophilic temperature zone, the generated slurry at FSTPs still has high levels of pathogens; hence it cannot be used in the same ‘as generated’ state unless further treatment is done.

Bio-slurry has high water content; hence there is a need to be dewatered before use. Dewatering can be done using the common existing technologies such as sand drying beds. The liquid effluent from the drying beds percolates downwards through the filter media, while the solid fraction is retained on the beds, which is later dried. Dried bio-slurry has calorific value in the same range as FS; hence it can be put to similar uses such as production of fuel briquettes, soil conditioner, vermi-compost, animal feeds and protein-rich supplement or bricks for construction work (Semiyaga et al. 2015). However, cost (capital, operation and maintenance) assessment of the required technologies for various products needs to be considered, since this has been reported to be challenging in sustaining the decentralized plant operations (Massoud et al. 2009).

Where agricultural activities exist without food crops to be eaten raw, or in tree farming, bio-slurry can be applied without further treatment. It can also be applied in agriculture with deep row entrenchment. Furthermore, pathogens are not assimilated in plant material (roots, shoots, leaves or fruits). Therefore, health risks associated with the use of microbiologically contaminated bio-slurry can be averted by implementing a multi-barrier approach (WHO 2006) in combination with the sanitation safety planning approach (WHO 2016). The advantage with the use of bio-slurry in agriculture is that it contains plant nutrients, which are already mineralized and therefore readily available to the crops. This is as opposed to unstabilized organics, which, when applied in agriculture, must undergo several conversion processes before they are available to the crops. Moreover, slurry application in agriculture, as a replacement to synthetic fertilizers, not only replaces finite resources but also adds humic substances to soil. Humic substances are not present in synthetic fertilizers. The end result of using bio-slurry is to replenish soil fertility, which contributes to cycling of plant nutrients, leading to sustainable agriculture.

The liquid effluent stream after dewatering joins the liquid line of the FSTP, which is later discharged or reused after treatment. Liquid effluent is a plant nutrient-rich irrigation resource although it should not be applied on plants which are eaten raw such as vegetables and root crops such as cassava and potato, since the treatment system at most FSTPs does not eliminate viruses and bacteria. Therefore, the most practical means of managing liquid effluent stream is through disposal into the environment after treatment; hence the presence of a sink such as a wetland is crucial when locating a treatment plant, based on AD.

14.6 Case Studies on Decentralized Scale Anaerobic Digesters

Although available literature indicates the viability of AD, in sanitation, solid waste management and energy recovery, only a few deals with its application in FS treatment at the decentralized scale. This section provides an overview of twelve (12) documented case studies, which are limited to geographic areas where FS management is prominent, such as sub-Saharan Africa and South Asia. Nine (9) documented cases of AD plants are in operation at the full scale, and two

(2) are pilot scale, while one (1) is an experimental digester (Table 14.3). Most FSTPs have adopted a fixed-dome biogas digester, which is preceded by a screen chamber that receives the FS from the desludging vehicles. FS collected from pit latrines is reported to have high municipal solid waste content, which is problematic to AD processes. Therefore, application of screening stage before the digester unit at the treatment plant holds the key (Zziwa et al. 2016). Digesters handling FS should be positioned after the reception and preliminary treatment facilities. Ideally, the extraneous materials such as solid wastes and grit need to be removed by screening and grit removal units, since these waste streams do not contribute to the biogas production. In addition, FS after screening has particle sizes of less than 5 mm, which is reported to be in a range required to have onset of AD (Semiyaga et al. 2017).

After screening and/or grit removal, a homogenization/feeding tank is applied in a number of treatment plants to prevent shock loading of the digesters, since FS arriving at the treatment facility has varying characteristics. For example, at the Devanahalli (India), a treatment plant receives FS from septic tanks and soak pits into a feeding tank, where settling takes place. The anaerobic digester only receives the settled solid faction, while the liquid stream is treated in other proceeding units (Rao et al. 2020). The anaerobic digesters in this case are not stirred. On the other hand, the two case studies cited in China make use of continuously stirred tank reactors (CSTR) (Shikun et al. 2017). Stirring helps in shortening the hydraulic retention time; hence it can be ideal where large volumes of FS are to be digested. However, there is more energy involved in operation of the stirred reactors.

Most anaerobic digesters are reported to operate under mesophilic conditions, with the exception of the CSTR that operated either under mesophilic or thermophilic conditions. The biogas digesters vary in size with retention time of the FS ranging from 4 h (for the UASB) to 20–45 days in case of unstirred reactors. From the cases reported in Table 14.3, two value propositions are noted: (1) biogas that is often used for heating and lighting at the treatment plant and (2) bio-slurry that is processed to form a compost or soil conditioner. In one case (Nashik, Maharashtra, India), where FS and organic solid wastes are co-digested, the biogas is purified and used to generate electricity.

Finally, two cases reported successful operation and maintenance (O & M) of the plants by municipalities (Rao et al. 2020; Rath and Schellenberg 2020). However, some of the challenges cited from the O & M include non-operation of the plants to their full capacity owing to small volumes of FS collected from the communities. Commercialization of biogas generated presented a challenge, as its cost is found to be higher than the use of alternative energy sources. As such biogas is often used within the treatment plants. The sale of compost is also limited, which was attributed to limited farmlands within the plant location. Therefore it was opted for use in landscaping within the municipalities.

Table 14.3 Case study faecal sludge treatment plants using anaerobic digestion as a treatment step

Digester location	Type	Core technology	Capacity	Feedstocks	HRT	Value proposition	Institutional setup and revenue base	Other finding challenges/ recommendations	References
Devanahalli, Bangalore, India	Fixed-dome	Screening, feeding tank, biogas digesters, stabilization tank (ST), drying bed, co-composting unit, anaerobic baffled reactor (ABR) and filter, horizontal gravel filter (HGF) planted with macrophytes and percolation pit	6 m^3	Faecal sludge from septic tanks and soak pits	12–14 days	Compost and treated water	O & M contracted to Kam-Avida Enviro Engineers Private Limited	Operating below the capacity, occasioned by low demand for FS desludging from containments	Rao et al. (2020), Rath and Schellenberg (2020)
							Revenue from compost produced sales to farmers and support from the town municipal and BMGF	Collection constrained by low capacity of available municipal truck	
Beijing International Airport, China	CSTR, mesophilic, 625 m^3 comprising of 400 m^3 (main digester; +225 m^3 digestate storage)	Pre-treatment (screens and homogenization mixer), disinfection (pasteurization batch basin) and anaerobic digester	20 tonnes (average)	Faecal sludge	20 days	200–400 m^3/day of biogas, effluent and slurry use in nearby greenhouse	Owned by village committee. Revenue from sale of organic vegetables or fruits	Almost no smell reported	Shikun et al. (2017)
Beijing, China	CSTR, thermophilic, 180 m^3 × 2	Separation, pyrolysis, pulping, coagulation, composting, AD, liquid treatment (anaerobic, oxic and MBR)	300 tonnes of FS and 50 tonnes of kitchen waste (KW) per day	FS and kitchen waste	2 days	800–1500 m^3/day of gas, biodiesel and compost	Owned and operated by the local government.	Odour management by sealing and use of wooden bio-filter	
							Revenue from disposal fees for FW and KW and sale of biodiesel		
Chazanga, Lusaka, Zambia	Fixed-dome	Intake, anaerobic digester, settling tank, sludge receptor tank,	50 m^3	Pit latrine FS (from manual emptiers)	20 days	Biogas and soil conditioner	Owned by water utility company and managed by community-based	Failure of selling biogas to nearby houses (landlords unwilling to give	Soeters et al. (2021)

(continued)

Table 14.3 (continued)

Digester location	Type	Core technology	Capacity	Feedstocks	HRT	Value proposition	Institutional setup and revenue base	Other finding challenges/ recommendations	References
		unplanted drying bed, dried sludge storage, gravel filter and polishing pond with a soak pit					organization (Kanyama and Chazanga Water Trusts)	consent to tenants to get a gas connection)	
							Revenue from proposed sale of soil conditioner and biogas used within the FSTP	Higher gas proposed gas prices compared to other sources (coal and electricity)	
Upper Citarum, Indonesia	Pilot scale	Screening, equalization tank, anaerobic digester (tank prefabricated from PVC with metal frame support) and drying beds	1.4 m^3	Domestic wastewater and FS (5% FS loading)					Hastuti et al. (2021)
Kanyama, Lusaka, Zambia	Fixed-dome	Intake, anaerobic digester, settling tank, sludge reception tank, unplanted drying bed, storage area for dried sludge, gravel filter and polishing pond with a soak pit	50 m^3	Pit latrine FS (from manual emptiers)	20 days	Biogas and soil conditioner	Owned by water utility company and managed by community-based organization (Kanyama and Chazanga Water Trusts)		
							Revenue from proposed sale of soil conditioner and biogas used within the FSTP		

Warangal, Telangana, India	Fixed-dome digester and geo-bag (pilot demo)	Screening and homogenization	15 m^3			Biosolids use a soil conditioner	No current business model		
Brahmapuram, Kerala, India	UASB reactor	Sludge retention tank, UASBR, sludge drying beds (solid fraction)	30 m^3	Faecal sludge	4–5 h	Biogas used in heat exchanger to heat and keep UASBR at 37 °C	Revenue funding from sale of compost and FS discharge fees	Revenue from reuse is not feasible; thus focus is on generation	Rao et al. (2020)
Nashik, Maharashtra, India	Fixed-dome	Biodigester, pasteurization unit, biogas scrubbing, CHP, power grid	30 TPD of waste	Faecal sludge and organic waste		Purified biogas generates 2200–3300 kW h/day of electricity and soil conditioner	Financial support from the municipal council could benefit from selling soil conditioner		
Maseru, Lesotho	Fixed-dome	Sedimentation and floatation		FS mixed with organic solid waste					Müller (2009)
Kumasi, Ghana	Geo-bag digester	Pilot scale	8 m^3 volume in series			Biogas			Tayler (2018)
Antananarivo, Madagascar	Geo-bag digester	Geo-bag digester, upward flow anaerobic filter	4 no. each 40 m^3	Faecal sludge					
Grahamstown, South Africa	Modified plastic drums	Experimental setup	200 L	Faecal sludge, WWTP digestate, bovine paunch manure	45 days	Biogas		No recovery of biogas from only pit latrine FS	Madikizela et al. (2017)
								Biogas recovery with co-digestion	

14.7 Operation and Maintenance of Biodigesters at FS Treatment Stations

There is a need to develop and implement an operation and maintenance (O & M) strategy that includes a task schedule and allocation of responsibilities and having control mechanisms for proper checking of the completed duties. Some of the specific O & M considerations for anaerobic reactors at FSTPs start from feeding digesters, regular monitoring and periodic maintenance.

The anaerobic digester is fed regularly to maintain stable gas production; hence, the design has to be adequate for the routinely delivered FS quantities and co-digestion substrates (if any). The alternative organic wastes for co-digestion should be pre-treated to remove impurities (such as metals, glass and plastics) and reduce particle sizes to <5 cm. This is necessary to raise the surface area for microorganisms to access and degrade the material faster. This is relevant for AD, where the microorganisms are slow degrading.

For periodic maintenance purposes, solids that settle or accumulate at the digester bottom are not easy to remove, particularly in fixed-dome digester type. Tayler (2018) proposed periodic removal of the settled solids (sludge) using vacuum trucks, leaving the digester for several days to reduce risk from dangerous gases and then manually emptying the residual sludge. This can be achieved by considering design of two digesters operating in parallel. However, precaution should be taken by the workers to use appropriate personal protective equipment (PPE) with breathing apparatus.

Other general monitoring activities can be regularly checked, such as gas tightness of the pipes and dome, pipe blockages, slurry levels in the expansion chamber and biogas stove (where cooing is an option) (Vögeli et al. 2014).

14.8 Conclusions

Faecal sludge treatment plants in LMIC have a huge AD feedstock potential. This potential is driven by the majority of the population in these areas using on-site sanitation technologies, where FS is generated. Most of the existing FS treatment plants do not make use of the available FS feedstock to recover energy in the form of biogas. The characteristics of FS such as TS, pH, temperature and BMP depict potential for biogas production. The fresher the FS, the higher is the potential to generate large quantities of FS. AD will suit the treatment of FS, if other benefits from the process such as organic matter stabilization as well as reduction of pathogen and odours are aggregated. To achieve increased biogas production from FS, its low C/N ratio should be boosted by co-digestion with other organic waste materials. The logistics of collecting source-separated organic solid wastes and delivery to where the AD plant is located should be analysed in view of the costs involved and the benefits to be realized. The use of bio-slurry in agriculture, although advantageous, since AD mineralizes nutrient content, making it readily available to crops, is riddled with its pathogenic content due to insufficient sanitization occurring, in AD. The microbial health risks involved can be circumvented by applying in fertilizing crops not to be consumed raw, deep row entrenchment and implementation of multi-barrier approaches in combination with sanitation safety planning.

References

Afifah U, Priadi CR (2017) Biogas potential from anaerobic co-digestion of faecal sludge with food waste and garden waste. AIP Conf Proc 1826:020032. https://doi.org/10.1063/1.4979248

An VTH (2017) Bio-mathane potentail test for anaerobic c0-digestion of faecal sludge and sewage sludge. Vietnam J Sci Technol 55(4C):27

Burka MS, Basamykina AN, Kharlamova MD (2021) Technological features of biogas production while anaerobic co-digestion of faecal sludge, sewage sludge and livestock. IOP Conf Ser Earth Environ Sci 666(4):042052. https://doi.org/10.1088/1755-1315/666/4/042052

Coetzee MAA, Van Der Merwe MPR, Badenhorst J (2011) Effect of nitrogen loading rates on nitrogen removal by using a biological filter proposed for ventilated improved pit latrines. Int J Environ Sci Technol 8(2):363–372

Englund M, Strande L (2019) Faecal sludge management: highlights and exercises. J Chem Inf Model 53(9):1

Hagos K, Zong J, Li D, Liu C, Lu X (2017) Anaerobic co-digestion process for biogas production: progress, challenges and perspectives. Renew Sust Energ Rev 76:1485–1496. https://doi.org/10.1016/J.RSER.2016.11.184

Hassan M, Aboelenin SM, Soliman MM, Attia HF, Metwally KA, Salem HM, Khalaphallah R (2022) Biogas manufacture from co-digestion of untreated primary sludge with raw chicken manure under anaerobic mesophilic environmental conditions. Saudi J Biol Sci 29(4): 2969–2977

Hastuti E, Riyana R, Joy B, Supratman U, Pamekas R (2021) Integrated community onsite sanitation system for close loop faecal management. E3S Web Conf 249:01005. 1–10

Heinss U, Larmie SA, Strauss M (1998) Solids separation and pond systems for the treatment of septage and public toilet sludges in the tropics – lessons learnt and recommendations for preliminary design. EAWAG, Duebendorf

Hoang LP, Nguyen KT (2020) Application of composite biogas tank in anaerobic co-digestion faecal sludge and organic waste. In: Sustainable waste management: policies and case studies. Springer, Singapore, pp 517–526

Koné D, Strauss M (2004) Low-cost options for treating faecal sludges (FS) in developing countries - challenges and performance. In: IWA Specialist Group Conference on Waste Stabilization Ponds, 27 September - 1 October 2004, Avignon, France

Krou NM, Baba G, Akpaki O (2021) Estimation of the Amount of Electrical Energy Available From the Biogas Produced at the Faecal Sludge Treatment Plant in the City of Sokodé. TH Wildau Eng Nat Sci Proc 1:77–82. https://doi.org/10.52825/thwildauensp.v1i.13

Madikizela P, Laubscher R, Tandlich R, Ngqwala N (2017) Optimizing biogas recovery from pit latrine faecal sludge. In: 5th International Conference on Sustainable Solid Waste Management, pp 1–10

Manga M, Evans BE, Camargo-Valero MA, Horan NJ (2016) Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management. Water Sci Technol 74(12): 2795–2806. https://doi.org/10.2166/wst.2016.451

Massoud MA, Tarhini A, Nasr JA (2009) Decentralized approaches to wastewater treatment and management: applicability in developing countries. J Environ Manag 90(1):652–659. https://doi.org/10.1016/j.jenvman.2008.07.001

Müller C (2009) Decentralised co-digestion of faecal sludge with organic solid waste: case study in Maseru, Lesotho. In: Water and sanitation in developing countries. Government of Canada, Ottawa, ON

Nijaguna B (2002) Biogas technology. New Age International (P) Ltd, New Delhi
Niwagaba CB, Mbéguéré M, Strande L (2014) Faecal sludge quantification, characterisation and treatment objectives. In: Strande L, Ronteltap M, Brdjanovic D (eds) Faecal sludge management - systems approach implementation and operation. IWA Publishing, London, pp 15–42
Phuong HL, Thai NTK (2018) The potential of biogas recovery from anaerobic co-digestion of fecal sludge and organic waste. In: Achi C, Gedam V (eds) Utilization and management of bioresources. Springer, Singapore, pp 113–121. https://doi.org/10.1007/978-981-10-5349-8
Prabhu M, Waigaonkar S, Dube R, Walther D, Mutnuri S (2015) Anaerobic co-digestion of food waste and septage—a waste to energy project in Nashik city. Carbon Sci Technol 7(2):87–98
Rajagopal R, Lim JW, Mao Y, Chen CL, Wang JY (2013) Anaerobic co-digestion of source segregated brown water (feces-without-urine) and food waste: for Singapore context. Sci Total Environ 443:877–886
Rao KC, Velidandla S, Scott CL, Drechsel P (2020) Business models for fecal sludge management in India, vol 18. IWMI, New Delhi. https://doi.org/10.5337/2020.209
Raposo F, De La Rubia MA, Fernández-Cegrí V, Borja R (2012) Anaerobic digestion of solid organic substrates in batch mode: an overview relating to methane yields and experimental procedures. Renew Sust Energ Rev 16(1):861–877. https://doi.org/10.1016/J.RSER.2011.09.008
Rath M, Schellenberg T (2020) Decentraized wastewater and Fecal sludge management: case studies from India, vol 4. Asian Development Bank Institute, Tokyo
Rose C (2015) Developing a nutrient recovery process for recovering nutrients in anaerobic digestate in low income countries. Cranefield University, Cranefield
Rose C, Parker A, Jefferson B, Cartmell E (2015) The characterization of feces and urine: a review of the literature to inform advanced treatment technology. Crit Rev Environ Sci Technol 45(17): 1827–1879. https://doi.org/10.1080/10643389.2014.1000761
Sasse L (1988) Biogas plants. German Appropriate Technology Exchange (GATE) and German Agency for Technical Cooperation (GTZ), GmbH. http://www.borda-net.org/modules/wfdownloads/viewcat.php?cid=5
Schoebitz L, Bischoff F, Ddiba D, Okello F, Nakazibwe R, Niwagaba C, Lohri CR, Strande L (2014) Results of faecal sludge analyses in Kampala, Uganda (Issue April). http://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/EWM/Laboratory_Methods/results_analyses_kampala.pdf
Semiyaga S, Okure MAE, Niwagaba CB, Katukiza AY, Kansiime F (2015) Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: a review of technologies, practices and end-uses. Resour Conserv Recycl 104:109–119. https://doi.org/10.1016/j.resconrec.2015.09.001
Semiyaga S, Okure MAE, Niwagaba CB, Nyenje PM, Kansiime F (2017) Dewaterability of faecal sludge and its implications on faecal sludge management in urban slums. Int J Environ Sci Technol 14(1):151–164. https://doi.org/10.1007/s13762-016-1134-9
Shikun C, Lei Z, Mingyue Z, Xue B, Zifu L, Mang H (2017) Assessment of two faecal sludge treatment plants in urban areas: case study Assessment of two faecal sludge treatment plants in urban areas: case study in Beijing. Int J Agric Biol Eng 10(3):237–245. https://doi.org/10.3965/j.ijabe.20171003.3067
Soeters S, Mukheibir P, Willetts J (2021) Treatment technologies in practice: on-the-ground experiences of faecal sludge and wastewater treatment. SNV Netherlands Development Organisation, The Hague
Still D, Foxon K (2012) Tackling the challenges of full pit latrines. Volume 2: How fast do pit toilets fill up? A scientific understanding of sludge. WRC, Gezina
Tayler K (2018) Faecal sludge and septage treatment: a guide for low and middle income countries. In: Faecal sludge and septage treatment. Practical Action Publishing, Rugby. https://doi.org/10.3362/9781780449869

Vögeli Y, Lohri CR, Gallardo A, Diener S, Zurbrügg C (2014) Anaerobic digestion of biowaste in developing countries: practical information and case studies. Swiss Federal Institute of Aquatic Science and Technology (EAWAG)-SANDEC, Duebendorf

Warnars L, Oppenoorth H (2014) A study on bioslurry results and uses

WHO (2006) WHO guidelines for the safe use of wastewater, excreta and greywater. Volume 1: Policy and regulatory aspects. WHO, Geneva

WHO (2016) Sanitation safety planning: manual for safe use and disposal of wastewater, greywater and excreta. WHO, Geneva

Zhang Y, Li H (2010) Enhancing biogas production from septic tank sludge via hydrothermal pre-treatment and co-digestion with food waste, p 5–6

Zziwa A, Lugali Y, Wanyama J, Banadda N, Kabenge I, Kambugu R, Kyazze F, Kigozi JB, Tumutegyereize P (2016) Contextual investigation of factors affecting sludge accumulation rates in lined pit latrines within Kampala slum areas, Uganda. Water SA 42(3):490–495